IOP Conf. Series: Materials Science and Engineering **330** (2018) 012030 doi:10.1088/1757-899X/330/1/012030

Effect of PWHT on Microstructure, Mechanical and Corrosion Behaviour of Gas Tungsten Arc Welds of IN718 Superalloys

Dilkush[1], Raffi Mohammed[2], G Madhusudhan Reddy[4], K Srinivasa Rao[3]

[1]Department of Metallurgical & Materials Engineering, RGUKT, Nuzvid
[2]Department of Metallurgical & Materials Engineering, NIT Andhra Pradesh
[3]Department of Metallurgical Engineering, Andhra University, Visakhapatnam
[4]Defence Metallurgical Research Laboratory, Hyderabad, India.

Corresponding author E-mail: dilkush@rgukt.in

Abstract. An attempt has been made to perform Gas tungsten arc welding (GTAW) on IN718 superalloy plates with 3mm thickness. Though base metal is having better combination of properties, the welding operations on IN718 alloy resulted in significant drop in its corrosion resistance and mechanical behaviour. The present work aims to improve corrosion resistance and mechanical behaviour of the welds with suitable post weld heat treatment (PWHT).The structural-property relationship of the weldments are judged by correlating the microstructural changes with observed mechanical behaviour and pitting corrosion resistance of the welds in as-received, direct aging (DA), 980STA, 1080STA conditions. Microstructural studied by scanning electron microscopy (SEM) and optical microscopy (OM). Potential-dynamic polarization test conducted to study the pitting corrosion resistance in 3.5%NaCl solution. The present work results established that the better combination of mechanical properties and pitting corrosion resistance were obtained at 980STA than as-received, direct aging (DA),1080STA conditions of GTA welds of IN718 alloy.

1. Introduction

The Inconel 718 (IN718) is a Nickel based superalloy, it is extensively used in various areas of application as aerospace, marine, nuclear, oil & gas industries at elevated temperatures due to its better mechanical properties and high resistance to corrosion. The IN718 alloy consists of other alloying elements with Fe, Cr, Mo, Al, and Ti for developing the strengthen mechanism .Nickel based superalloy i.e., Inconel718is formed by the solid solution and precipitation of second phases due to the application of different heat treatments. The presences of the precipitates gamma-prime γ ' (Ni_3Al) and gamma –double prime γ” (Ni_3Nb) are the major source for developing the hardening mechanism [1].Welding is the main fabrication method used for joining structural components. Most of the conventional fusion welding processes showed the better results, but still severe problems are in notice like solidification cracking, microfissuring in the HAZ, segregation of niobium and formation of brittle intermetallic laves phases. However the elemental segregation by niobium and further formation of inter-metallic laves phases as ((Ni, Fe, Cr)$_2$ (Nb , Mo, Ti)) which are rich in Nb with brittle in nature will depletes the matrix during solidification of weld metal and facilitates crack initiation and propagation [2,3].In the latest generation of nickel based super alloys which are precipitation-strengthened by γ″-gamma double prime strengthened IN718 alloy, the strength contributing alloying elements Ti and Al are replaced by Nb. The process of dispersion of the precipitates γ″- Ni_3Nb in austenite phase is one the cause to overcome the occurrence of strain-age cracking, at the same time the problems like solidification cracking susceptibility and liquation cracking are raised[4,5].As per the view of researchers, niobium which segregates into the interdendritic regions resulting in the higher solidification cracking susceptibility which drastically decreases the weld metal's solidus temperature range[6].In industrial point of view, double aging treatment is in practice on IN718 alloy welds. Similarly in critical applications PWHT's are performed than double aging treatments [7] .The post weld heat treatments are advisable to adopt for reducing the severity of the effect of formed brittle intermetallic lave phases and the segregation of the alloying elements like niobium in fusion zone. The present work is aimed to weld IN718 alloy plate of 3mm thickness using gas tungsten arc welding process (GTAW) to evaluate the changes in microstructures to correlate with observed mechanical and corrosion behavior of IN718 welds. Considerable post weld heat treatments were performed on welds to remove the element segregation and avoid formation of brittle laves phases. The structural – property relationship of the PWHT samples is judged by the correlation of microstructure, mechanical and corrosion behaviors of the welds.

2. Experimental Details

The working material IN718 with 3mm thickness plates were taken with a chemical composition shown in Table1. A fusion welding process of gas tungsten arc welding (GTAW) was performed on IN718 plates with optimized welding parameters shown in Table 2 by using similar IN718 filler wire. GTA welded plates were undergone to Non-destructive testing (NDT) for evaluating the soundness of the weld joints after conducting the welding operations. Considerable post weld heat treatments (PWHT) were done in following conditions as (1) Direct aging treatment (DA): 720^0C/8h/furnace cooling followed by 620^0C /8h/air cooling (2) Solutionizing treatment at 980^0C (20 min) /AC followed by DA condition (980STA) (3) Solutionizing treatment at 1080^0C (20 min) /AC followed by DA condition (1080STA) to remove the element segregation, liquidation cracking and avoid formation of brittle lave phases. The schematic representation of thermal cycles of above PWHT conditions as shown in Figs.1-3. GTA weld of IN718 alloy is shown in Fig. 4. After the welding, the weldments were prepared by mechanical grinding and followed by polishing with grit papers and emery papers. The metallographic specimen was etched by mixed acid solution (2mL HF + 20mL HNO_3 + 76mL H_2O + 100mL Hcl) to reveal the microstructures. Microstructural characterization was carried out by LEICA (DMI3000 M) optical microscope. The mechanical properties were studied by microhardness measurements using a Vickers micro-hardness tester, testing load was 0.5Kg and dwell time was 15s. The unsmooth surfaces of the GTAW joints were wiped off for all the characterization studies. Potentio-dynamic curves was employed to find out the corrosion behavior of GTA welds of IN718 in all conditions with respective zones .The test was performed in 3.5wt% of NaCl solution by using a potentiostat.

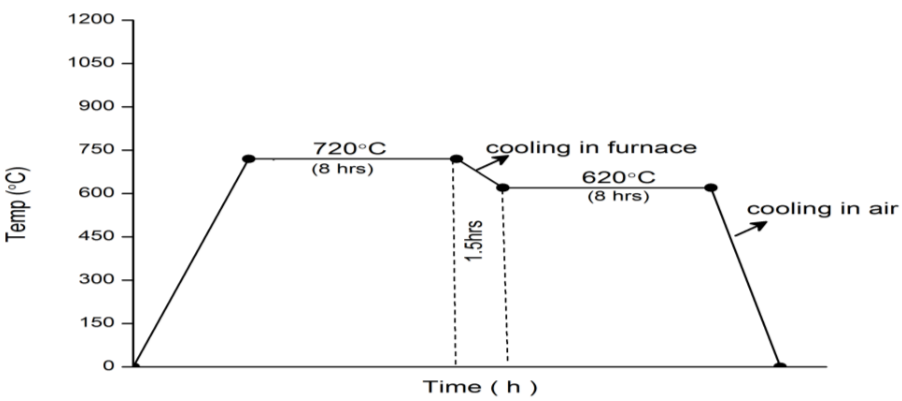


Fig.1 Thermal Cycle of DA treated condition

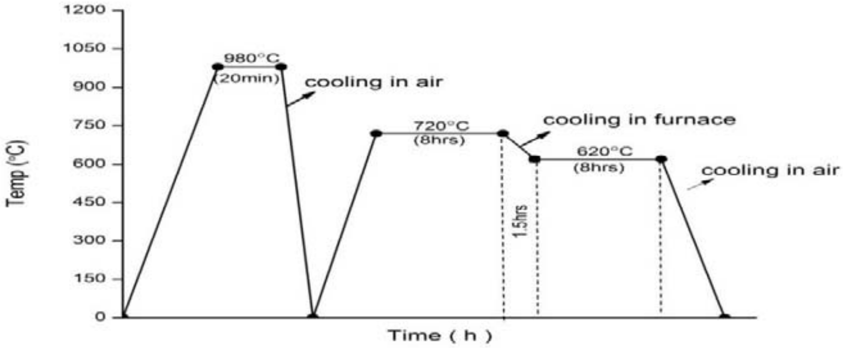


Fig.2 Thermal Cycle of 980STA treated condition

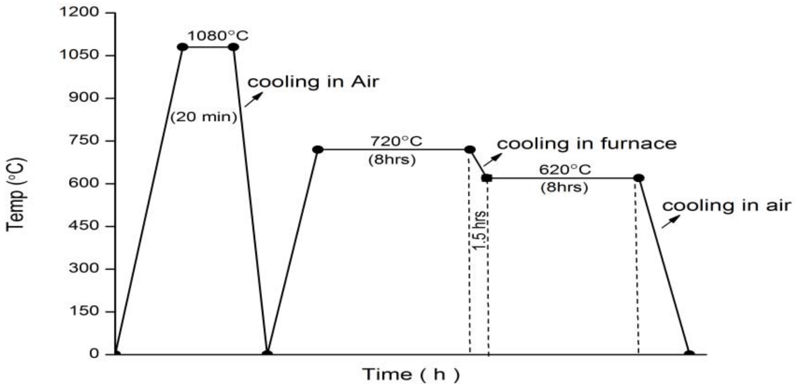


Fig-3 Thermal Cycle of 1080STA treated condition

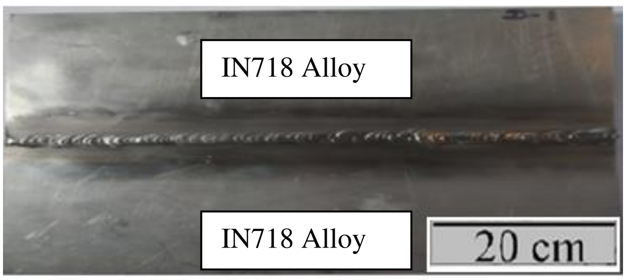


Fig 4 Gas tungsten arc welded IN718 alloy

Table 1 Composition (Wt %) - Filler wire and IN718 alloy

Material	**Chemical Composition(Wt. % Elements)**											
	P	S	B	C	Si	Al	Ti	Mo	Nb	Cr	Ni	Fe
IN718 alloy	0.005	0.002	0.003	0.02	0.12	0.51	0.97	3.13	5.08	18.2	53	Bal
Filler wire (IN718 alloy)	0.015	0.015	0.005	0.05	0.35	0.45	0.65	2.80	4.75	17	50	Bal

Table 2 Optimized welding parameters used for conventional GTA welding

Welding parameter	**Selection**
Current	110 A
Speed	6 mm/s
Voltage	18 V
Polarity	DCEN
Electrode	Thoriated W, 2 mm dia
Shielding gas	Argon
Heat input (J/mm)	330

3. Results and Discussions
3.1 Microstructure studies
3.1.1 Inconel 718 Superalloy (IN718):

IN718 super alloy consists of fine equiaxed twin banded austenitic grains in the matrix. Fig 5 shows the presences of number of primary carbides with MC type which are dispersed randomly in γ matrix. These primary carbide particles are known to be rich in Nb, Ti and delta phase on the grain boundary was also observed. The serious issues like a brittle interdendritic laves formation, microfissuring, segregation of secondary particles was not observed in the base material of IN718 alloy. The modifications in required aspects of metallurgical and mechanical properties by which the impact will be there on its corrosion resistance can be improved by suitable ageing treatments.

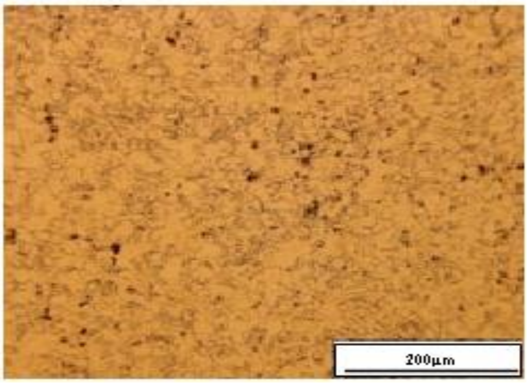


Fig 5 Optical Microstructure of IN718 alloy

3.1.2 GTA welds of IN718

The microstructural phases in the GTA weldments of IN718 alloy in as welded and PWHT conditions were discussed as follows: Fig. 6 reveals the microstructures of IN718 alloy -GTA weldments in as received condition ,Fig. 7 reveals the microstructures in direct aging condition (DA): 720^{0}C/8h/furnace cooling followed by 620^{0}C /8h/air cooling, Fig.8 & 9 reveals the microstructures in solutionizing treatment at 980^0/20 min /air cooling followed by DA condition (980STA) and another solutionizing treatment at 1080^{0}C/20 min /air cooling followed by DA condition (1080STA) in respective FZ, HAZ and BMZ. In as-received condition, the segregation of Nb and the prolonged Laves phase presence in interdendritic regions which is due to interdendritic Nb segregation was observed in fusion zone. The observations showed the coarse dendritic structure of the grains and formation of microfissuring at the HAZ, twin bands and MC type carbides in BMZ. Due to the heat inputs of the GTA welding process is higher and lower cooling rates. The role of post weld heat treatments (PWHT) is high in dissolving the elements segregation and laves network dissociation. The almost complete reduction of laves concentration and improve hardness was observed in fusion zone of 1080STA condition and significant amount of dissociation of the long connected chain like morphology of lave phases was observed in 980STA.Figs. 10-13 shows the results of scanning electron microstructure of GTA welds in following conditions (a) as-received (b) direct aging (c) 980STA (d) 1080STA in respective FZ, HAZ and BMZ to correlate with microstructural behavior.

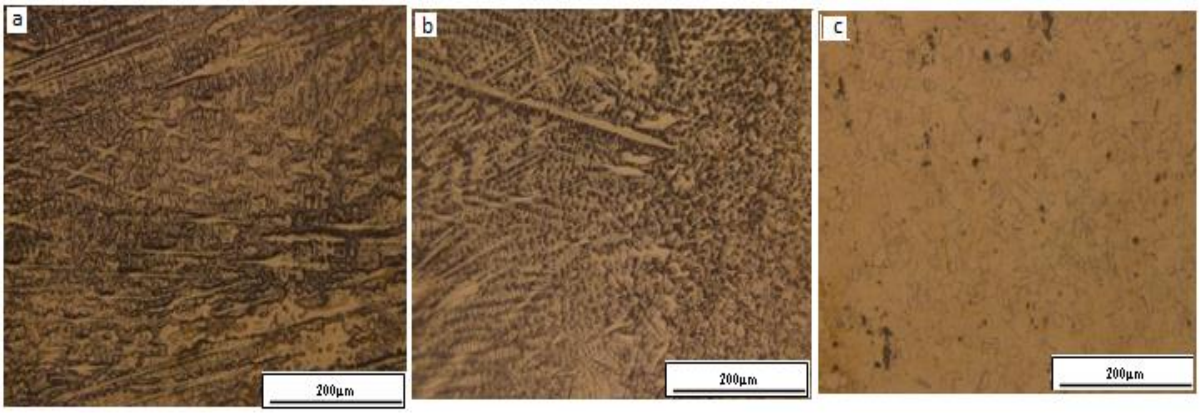


Fig. 6 Optical microstructure of IN718 alloy-as-received GTA weldments (a) FZ (b) HAZ and (c) BMZ

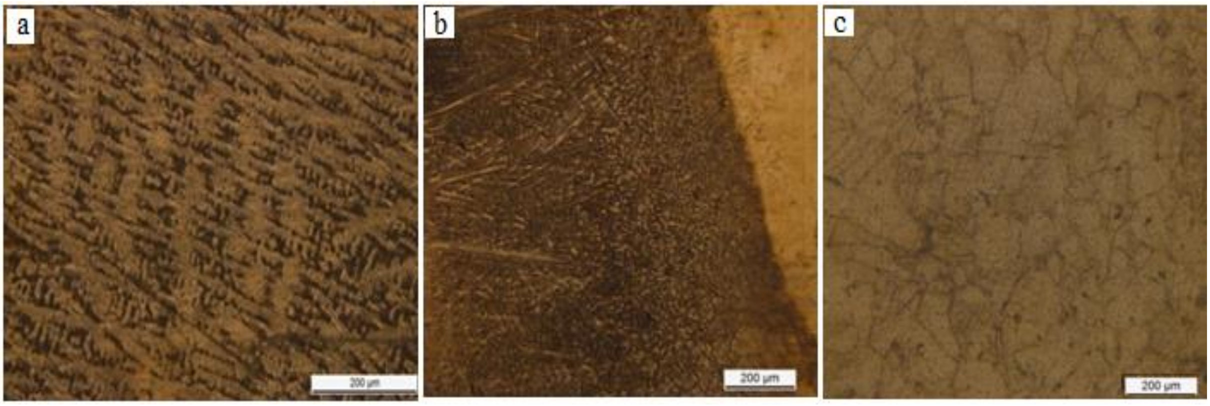


Fig. 7 Optical microstructure of IN718 alloy-DA treated GTA weldments (a) FZ (b) HAZ and (c) BMZ

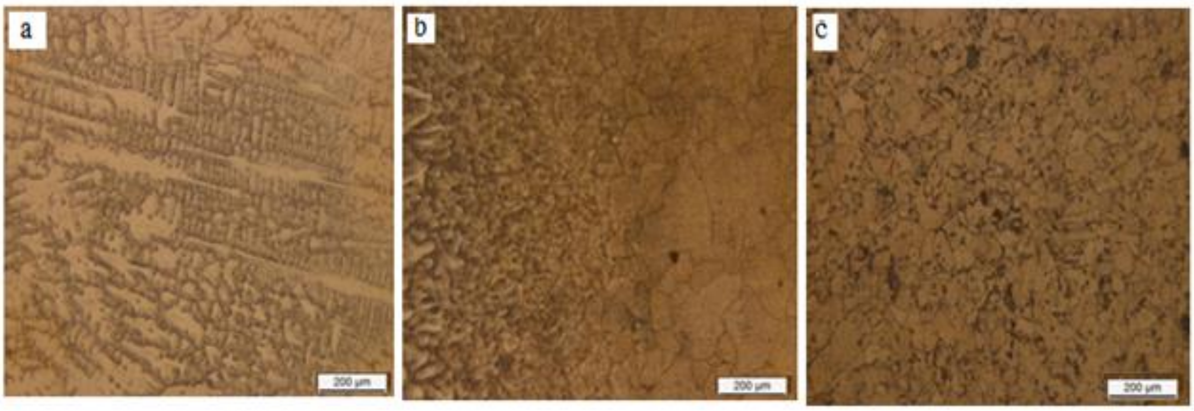


Fig. 8Optical microstructure of IN718 alloy-980STA treated GTA weldments (a) FZ (b) HAZ and (c) BMZ

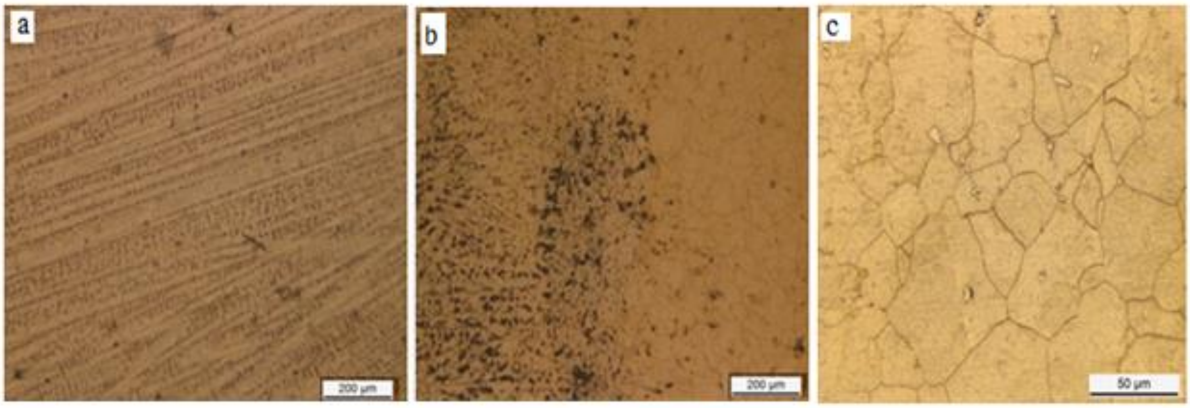


Fig.9 Optical microstructure of IN718 alloy-1080STA treated GTA weldments (a) FZ (b) HAZ and (c) BMZ

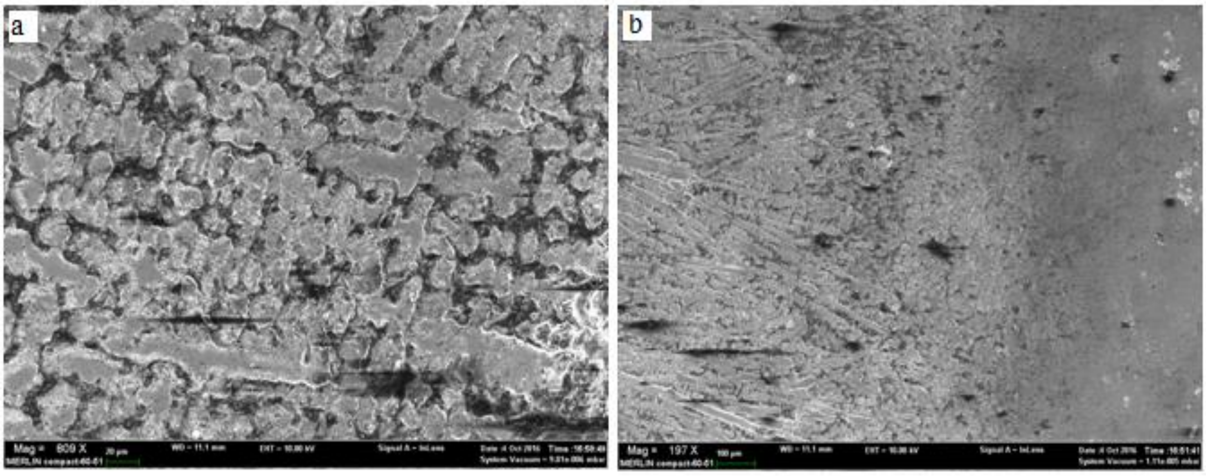


Fig.10 SEM images of IN718 alloy-as-received GTA weldments (a) FZ and (b) HAZ

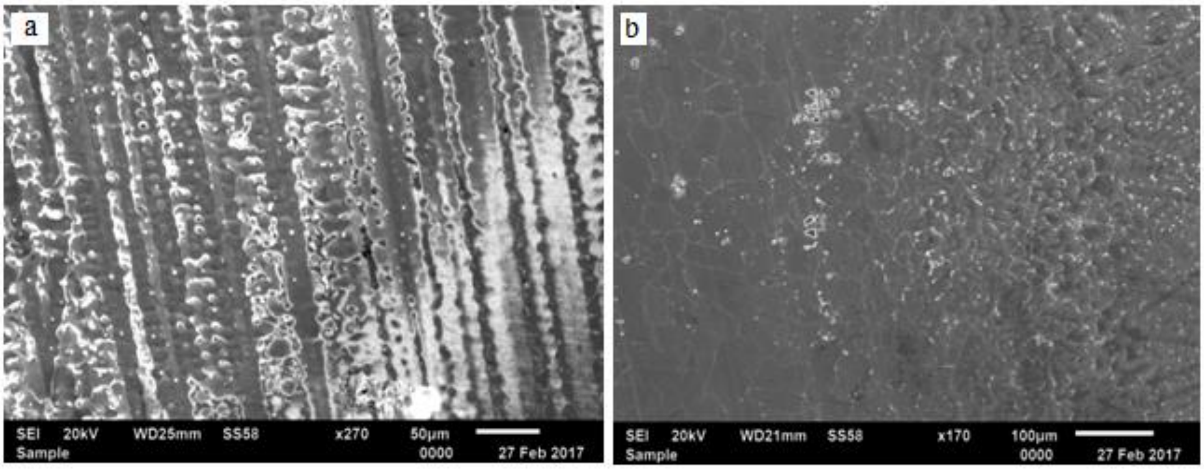


Fig.11SEM images of IN718 alloy-DA treated GTA weldments (a) FZ and (b) HAZ

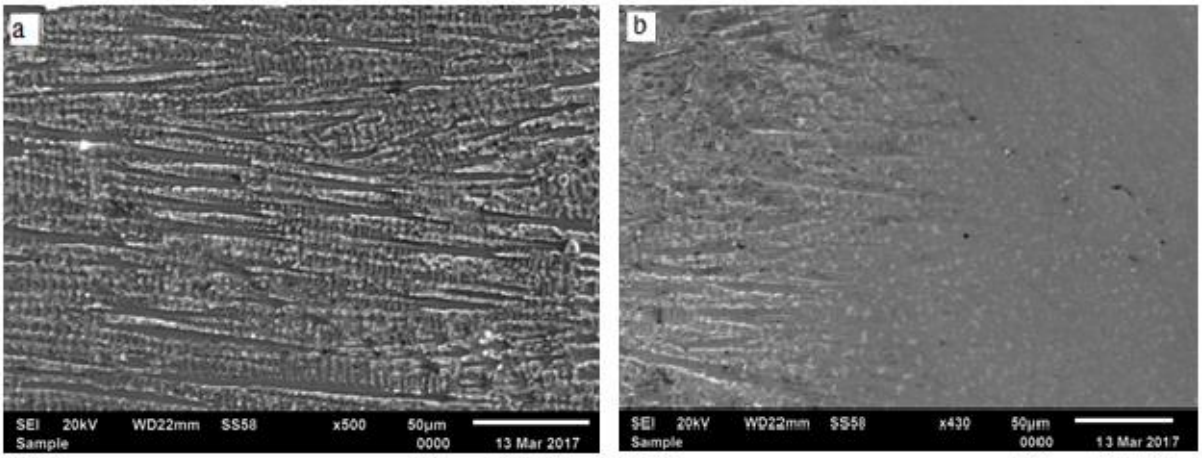


Fig. 12 SEM imagesof IN718 alloy-980STA treated GTA weldments (a) FZ and (b) HAZ

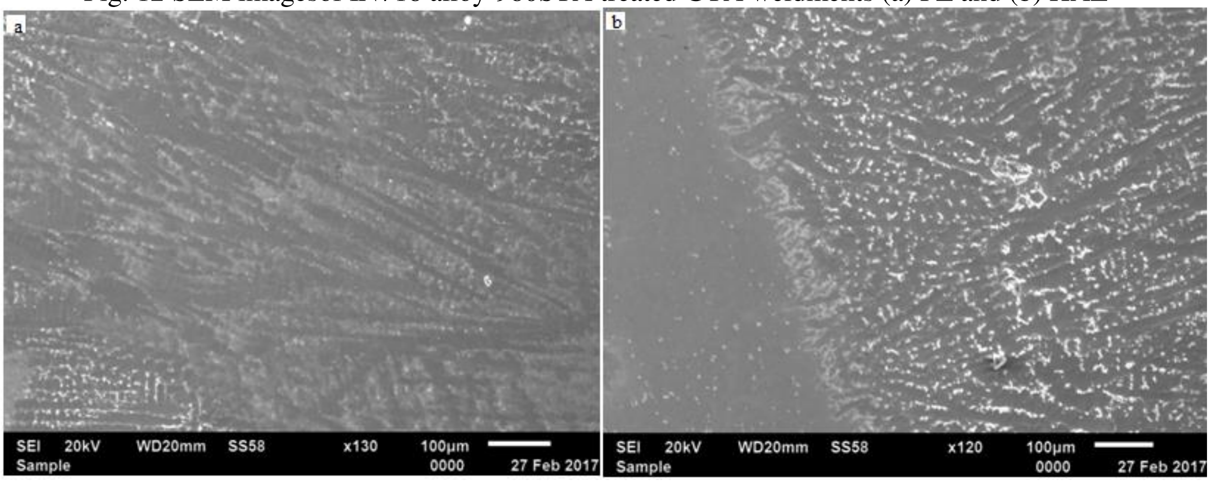


Fig. 13SEM imagesof IN718 alloy-1080STA treated GTA weldments (a) FZ and (b) HAZ

Few researchers Gordine [1970 and 1971] have observed PWHT effects on GTA weldments at the range between 925^{0}C to 1150^{0}C. At 925^{0}C to 980^{0}C temperature ranges as post weld solution treatments given insignificant results about dissolution of laves network, but were found to result in needle –like delta precipitation around laves network. The results showed that at 1090^{0}C almost the dissolving of laves network in the matrix takes place. The present studies established that the PWHT involvement leads for promoting the element segregation diffusion and resolve them from brittle laves particles in the matrix. Increased precipitation of strengthening phases lead to a significant increase in the resulted fusion zone mechanical properties of post weld heat treated condition compared to as received GTA weldments. The high reduction of elemental segregation and consequent brittle, intermetallic lave phases in fusion zone was observed in 1080STA than 980STA condition but an undesirable condition in 1080STA condition, that the grain coarsening was observed in microstructural morphology in the base metal zone of the weldment.

3.2 Hardness studies

The results of Vickers micro-hardness measurements are shown in Fig. 14 and given in Table 3. The measures were taken in all four conditions with respective zones as FZ, HAZ and BMZ. The mechanical property in terms of hardness infusion zone (FZ) was observed lower than heat affected zone (HAZ) and base metal zone (BMZ) in as-received condition. The inferior mechanical properties in the GTA weldments were observed due to the presences of segregation of niobium element and brittle continuous laves network in the fusion zone. By applying PWHT, the results showed a noticeable increase in fusion zone hardness in 980STA condition than direct aged and as-received conditions. The tendency of hardness as BMZ > HAZ > FZ has been observed in as-received, direct aged and 980STA conditions. But due to the effective reduction of segregation and resolve the brittle laves particles into the matrix through precipitation strengthening mechanism leads to a significant increase in fusion zone hardness of 1080STA unlike remaining conditions. The coarsening of grains at the base metal zone is unfavorable in 1080STA condition, due to this reason the drop of hardness was observed in BMZ of the weldments.

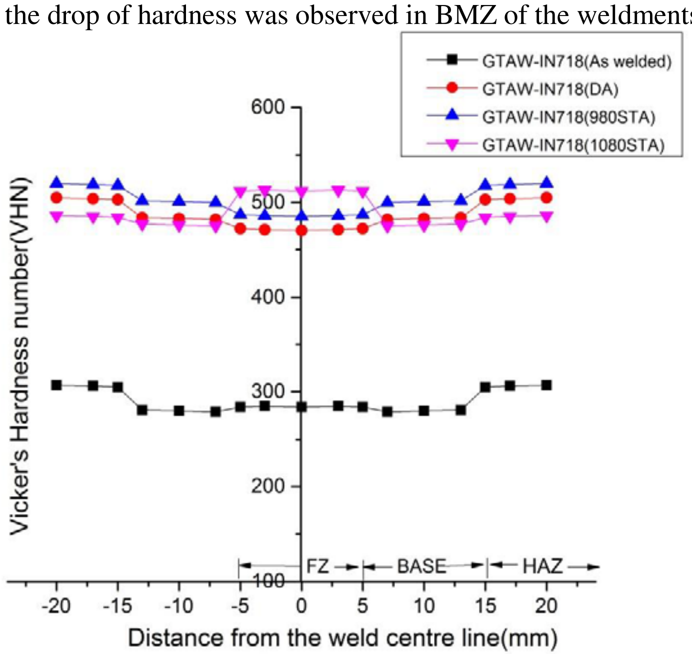


Fig. 14 Vickers Hardness survey of gas tungsten arc welding of IN718 alloy

Table 3 Micro-hardness values of IN718 alloy GTA welds

Specimen condition	Vickers Micro-hardness values (VHN)		
	BMZ	HAZ	FZ
As received	305	280	284
Direct aged	503	483	470
980STA	518	501	485
1080STA	485	476	512

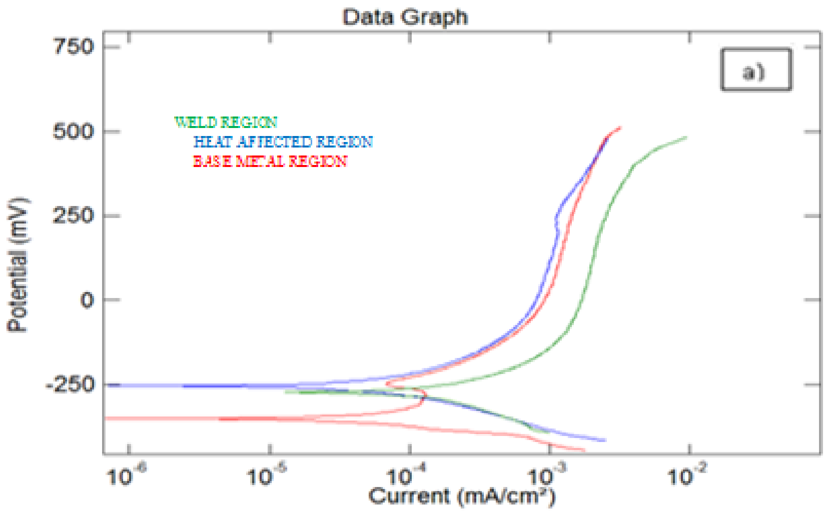
3.3 Pitting Corrosion studies

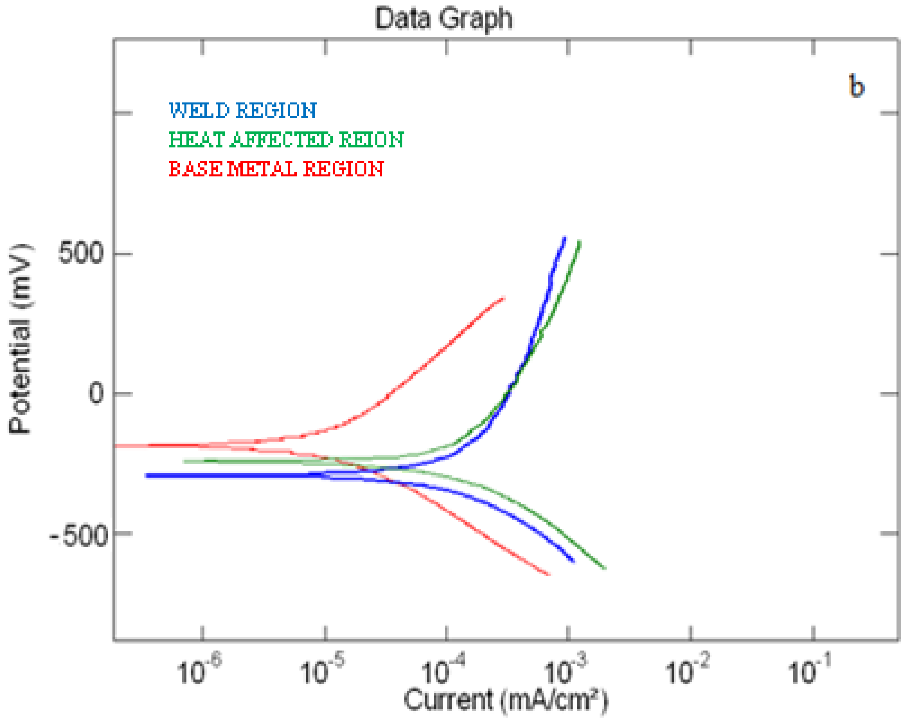
The applications of IN718 alloy mainly require high corrosion resistance, along with creep and high tensile strength. So it is important to investigate the corrosion behavior of IN718 alloy welds in aqueous solutions. The corrosion rates are different for different zones - fusion zone (FZ), heat-affected zone (HAZ) and the base metal zone (BMZ). Electrochemical behavior of GTA welds of IN718 alloy were evaluated by subjected to potentio-dynamic polarization. This electrochemical tests were conducted on all the respective zones as fusion zone, heat affected zone and base metal zone for four considered conditions of the GTA welds in as-received, direct aged, 980STA and 1080STA. The polarization curves of GTA welds of various conditions are depicted in fig 15. The susceptibility of materials to corrosion is revealed by corrosion potential acts as a static indicator of electrochemical corrosion resistance. In general, materials that exhibit high corrosion potential offers higher corrosion resistance [8].Table 4 gives the results of Tafel values of IN718 GTA welds in 3.5 wt% NaCl solution at 30 ^{0}C.The passivation behavior in anodic branch of the polarization curve of Inconel 718 can be attributed to the high chromium contents in its chemical composition [9].

The variation in the microstructural and mechanical properties of the GTA welds in as-received, direct aged, 980STA, 1080STA conditions took place due to the involvement of post weld heat treatments. This impact will be on the corrosion resistance ability of the welds in the respective conditions. The usual corrosion and pitting corrosion resistance are very sensitive to post weld heat treatments. The increase tendency of corrosion resistance is raised in the DA and STA conditions due to the carbides precipitation and reduction in segregation of the alloying elements during the heat treatments of the welds. The ranking for pitting corrosion resistance (Epit) in considered conditions with respective fusion zone on comparison states the following tendency as 1080STA>980STA>DA>as-received. The results showed that the pitting corrosion resistance of BZ is higher than that of FZ in as-received, direct aged (DA) and 980STA conditions. But similar tendency is not observed in 1080STA condition, the corrosion resistance of FZ is higher than that of BZ. Due to the unfavorable reason of growth of the grains took place in base zone of 1080STA condition which leads to drastic decrease of its pitting corrosion resistance. Grain boundary at fusion zone is enriched with metallic carbides with $Cr_{23}C_6$in PWHT conditions. $Cr_{23}C_6$ formation helps in preventing grain boundary sliding. The passivation layer $Cr_{23}C_6$ gives corrosion resistance even at tensile load applications.

Table 4 Tafel values of IN718 GTA welds in 3.5 wt% NaCl solution

Zone/Region	Base metal zone (mV)	HAZ (mV)	Fusion zone (mV)
As received condition	-250.75	-268.12	-274.57
Direct aged condition	-247	-261	-269
980STA condition	-239.1	-253	-258
1080STA condition	-261.5	-259.02	-234.37

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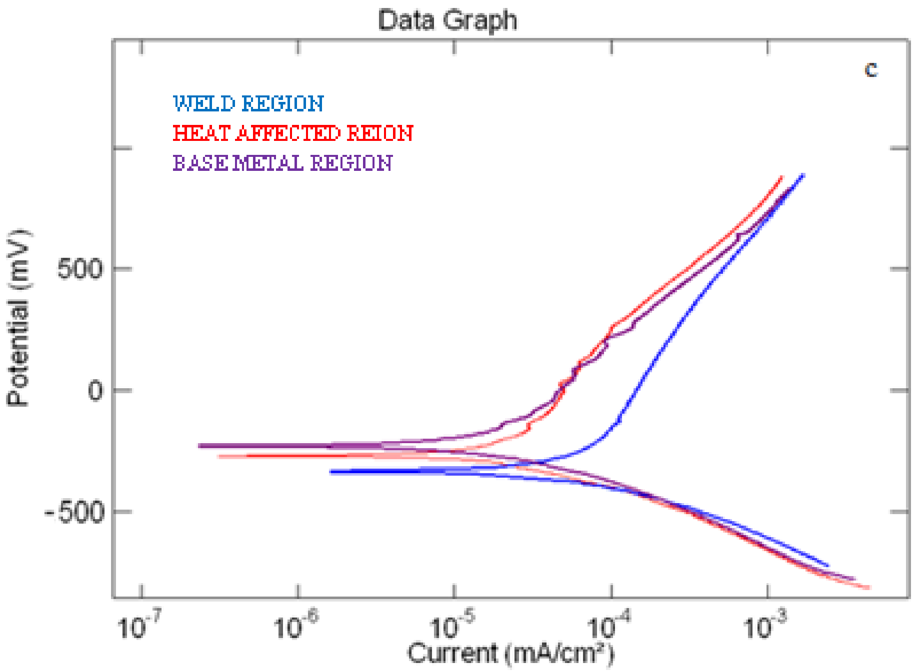
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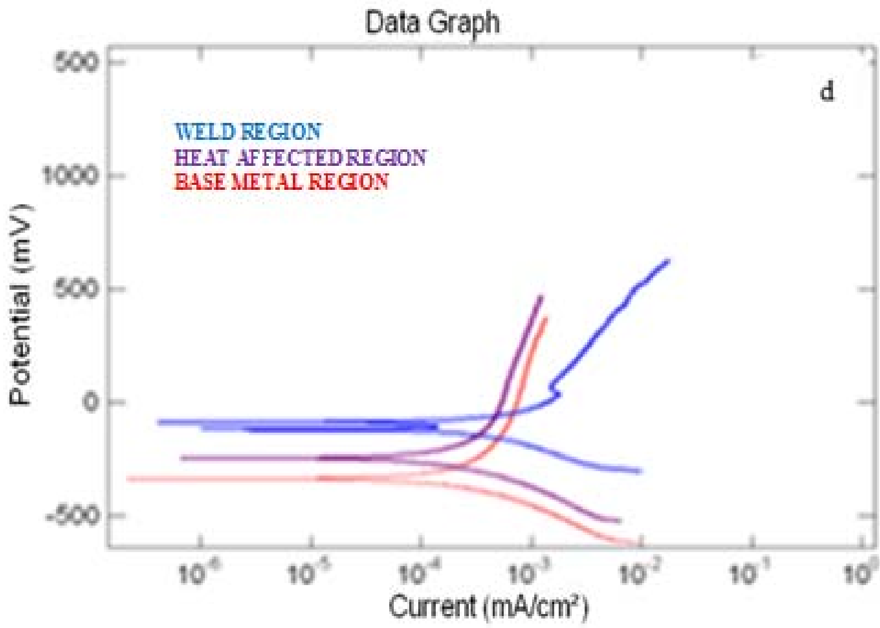

Fig.15. Potentio-dynamic polarization curves of GTAW – IN718 alloy (a) As-received, (b) Direct aged, (c) 980STA and (d) 1080STA conditions in 3.5%NaCl solution

4. Conclusions

1. GTA welds of IN718 alloy resulted in microfissuring and coarse columnar grains at heat affected zone, and the continuous laves network distribution with dendritic structure in fusion zone were observed in as-received condition.

2. The segregation of alloying element niobium and prolonged laves network was slightly higher in as received condition of GTA weldments when compared with direct aged (DA) condition and as a result it effects the mechanical properties and corrosion behavior of the welds.

3. Post weld heat treatment (PWHT) on IN718 GTA welds shows better strength than as received condition and DA treated condition. The 980STA condition shows some significant reduction in niobium element segregation and partial dissolution of continuous laves network when compared with as received and DA conditions. But uniform Nb distribution throughout the matrix and almost significant amount dissolution of laves network was observed infusion zone of 1080STA condition.

4. The mechanical tendency in terms of hardness reported as BMZ >HAZ >FZ in as-received, direct aged and 980STA conditions. But due to the effective reduction of segregation and resolve them from brittle laves particles into the matrix by the precipitation strengthening mechanism leads to a significant increase in fusion zone hardness in 1080STA, unlike remaining conditions. But the coarsening of grains at the base metal zone is unfavorable in 1080STA condition, due to this reason the noticeable drop of hardness was observed in BMZ of the weldments.

5. Pitting corrosion resistance is significantly better in base metal than welding processes. It is due to formation of secondary precipitates and its distribution in the fusion zone. Pitting corrosion resistance in the weldments was improved by the adoption of post weld heat treatments and better results were observed at 980^{0}C solution treated and aged condition.

6. Overall studies showed that, the better combination of mechanical properties and pitting corrosion resistance of gas tungsten arc welds of IN718 alloy were obtained in 980STA condition. At 980STA condition significant promising results were exhibited.

Acknowledgements

The authors gratefully acknowledge the Director to utilize welding facilities for our research work in Materials Joining Group, Defence Metallurgical Research Laboratory (DMRL) - Hyderabad, India and for their continuous support to publish this work.

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