Comparative Studies on Microstructure, Mechanical and Pitting Corrosion of Post Weld Heat Treated IN718 Superalloy GTA and EB Welds

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Abstract. In the present study, an attempt has been made to weld Inconel 718 nickel-base superalloy (IN718 alloy) using gas tungsten arc welding (GTAW) and electron beam welding (EBW) processes. Both the weldments were subjected to post-weld heat treatment condition as follows -980°C /20 min followed by direct aging condition (DA) as 720°C/8 h/FC followed by 620°C /8 h/AC. The GTA and EB welds of IN718 alloy were compared in two conditions as-received and 980STA conditions. Welds were characterized to observe mechanical properties, pitting corrosion resistance by correlating with observed microstructures. The rate of higher cooling ranges, the fusion zone of EBW exhibited discrete and relative finer lave phases whereas the higher niobium existed laves with coarser structure were observed in GTAW. The significant dissolution of laves were observed at 980STA of EBW. Due to these effects, the EBW of IN718 alloy showed the higher mechanical properties than GTAW. The electrochemical potentiostatic etch test was carried out in 3.5wt% sodium chloride (NaCl) solution to study the pitting corrosion behaviour of the welds. Results of the present investigation established that mechanical properties and pitting corrosion behaviour are significantly better in post weld heat treated condition. The comparative studies showed that the better combination of mechanical properties and pitting corrosion resistance were obtained in 980STA condition of EBW than GTAW.

1. Introduction
The precipitation hardened Inconel718 (IN718) belongs to nickel based superalloy group is extensively used in turbines, rocket motors, spacecrafts, nuclear reactors etc., due to its better combination of mechanical properties and corrosion resistance behavior at elevated temperatures (~650°C). The precipitates γ’ (Ni₃Al) and γ” (Ni₃Nb) contributed the strengthening mechanisms [1-5]. At above 650°C exposure, the detrimental delta- Ni₃Nb phase formed by the phase transformation of γ” phase [1-2]. Many studies [6-10] stated that niobium segregation, intermetallic lave phases formation and liquation cracking could develop in either FZ (or) HAZ of welded IN718 alloy. Thus, several studies were employed on IN718 alloy welds by using various welding methods [7,9,11,12]. The severity of these associated issues are lesser in EBW when compared to GTAW due to its higher cooling ranges and lower heat inputs. As high energy welding process by electron beam welding showed higher efficiency in its mechanical
properties without any deterioration effects, it is recognized as better welding operation for Inconel718 [G.D Janaki ram (2004), C.A.Huang et al. (2007)]. Weld ability of Inconel-718 is quite good as compared to other Ni-based super alloys. It shows greater resistance against solidification cracking and strain age cracking [John N. Dupont et al. (2009), J.Gordine (1971)]. However, it is reported that this alloy is prone for segregation of alloying elements, formation of intermetallic laves phase [G.D. Janaki ram (2004), Ch].Radhakrishna et al. (1997), G.M. Reddy et al.(2009)] in the weld fusion zone and HAZ liquation cracking [J.Gordine(1971)]. The detrimental effects faced in welding processes have been overcome with considerable usage of PWHT [13 - 16]. The present study is aimed to compare the gas tungsten arc welding (GTAW) and electron beam welding (EBW) of IN718 alloy in as-received and post weld heat treated -1080STA conditions. The IN718 alloy weldments were subjected to several characterizations to examine the relation between structural-mechanical property relationships. Potentio-dynamic polarization test was conducted to evaluate the corrosion resistance behavior of both the weldments.

2. Experimental Work

Inconel718 plates were subjected to perform gas tungsten arc welding (GTAW) and electron beam welding (EBW) processes with 200×80×3mm dimensions. Table 1 was listed with elemental composition of IN718 alloy. The welding parameters employed for GTA and EB welds were listed in Table 2 & 3 respectively. After welding operations, the GTA and EB welded plates were undergone to non destructive testing (NDT) for evaluating the soundness of the weld joints. Electric discharge machine (EDM) was used to cut the welded plates for specimen preparation to conduct various characterizations. These specimens were subjected to mechanical grinding, polishing and cleaning with acetone. The present study is aimed to evaluate both the GTA and EB welds in two conditions- as-received and post weld heat treated condition (PWHT). The PWHT in this work was 980STA condition - 980°C/20 min /air cooling followed by DA condition -720°C/8h/furnace cooling followed by 620°C /8h/air cooling to remove the element segregation, liquidation cracking and avoid formation of brittle lave phases. The schematic representation of thermal cycle for 980STA condition was shown in Figs.3. The etching agent used for the metallographic specimen to reveal the microstructure of the weldment was (2mL HF + 20mL HNO3 +100mL HCl+76mL H2O). Microstructural characterization was carried out by using the optical microscope model - LEICA (DMI3000 M). Vickers micro-hardness tester was used to measure the mechanical properties of the weldments using a testing load of 0.5Kg and dwell time was 15s. Hardness measurement was carried out at intervals of 0.05 mm across the interface and 0.5 mm along the base metal. Potentio-dynamic polarization test was carried out to evaluate the corrosion behavior of GTA and EB welds as-received and 980STA conditions in 3.5wt% NaCl solution.

| Material         | Composition |
|------------------|-------------|
|                  | C | B   | S   | P  | Si  | Ti  | Al  | Mo  | Nb  | Cr  | Ni  | Fe  |
| IN718 alloy      | 0.02 | 0.003 | 0.002 | 0.005 | 0.12 | 0.97 | 0.51 | 3.13 | 5.08 | 18.2 | 53  | Bal |
| Filler wire (IN718) | 0.05 | 0.005 | 0.015 | 0.015 | 0.35 | 0.65 | 0.45 | 2.80 | 4.75 | 17  | 50  | Bal |
Table 2 Optimized welding parameters used for conventional GTA welding process

| Welding parameter     | Selection |
|-----------------------|-----------|
| Current               | 110 A     |
| Speed                 | 6 mm/s    |
| Voltage               | 18 V      |
| Heat input (J/mm)     | 330       |

Table 3 welding parameters used for EB welding process

| Welding parameter     | Selection |
|-----------------------|-----------|
| Current               | 47 mA     |
| Speed                 | 750 mm/min|
| Voltage               | 55 kV     |
| Heat input (J/mm)     | 103       |

Fig. 1 Gas tungsten arc welded IN718 alloy plate

Fig. 2 Electron Beam welded IN718 alloy plate

Fig. 3 Thermal Cycle of Post weld solution treatment (980STA)
3. Results and Discussion

3.1 Microstructural Studies

3.1.1 Inconel 718 Superalloy (IN718). The microstructure of the base metal in 980°C solution treated condition is shown in Fig.4. Fine austenitic grains (ASTM 8-9) with twins were seen in the microstructure with much number of grains. At the grain boundaries, fine spheroidal delta phase was observed predominantly. At the twin boundaries and around the carbide particles, the presence of delta phase was also observed.

3.1.2 Microstructural Studies of GTA & EB welds of IN718 alloy. The base material is much stronger when compared with solid state and fusion state welding operations like GTAW, LBW, EBW, FSW etc.. Though IN718 alloy is best for welding among all nickel based superalloys, few detrimental defects such as formation of brittle continuous laves network, segregation of niobium alloying element, solidification cracking etc., are the major concern issues observed. These defects effect the relation between structural – mechanical property drastically. The controlling and monitoring of segregation can be maintained by weld cooling rates. Fig 5(a) & (b) showed optical macrostructure of IN718 alloy GTA welds and EB welds. The lower heat inputs and relative higher cooling rates are employed in EBW than GTAW. The fusion zones shows dendrite structure with the interdendritic regions consists of lave phases in both the fusion welding processes of GTA and EB welds. Due to the higher cooling ranges, the fusion zone of EB welds exhibited discrete and relative finer lave phases where as in GTAW the higher niobium existed.
laves with coarser structure are the results observed. The optical microstructure and scanning electron microstructure of GTAW and EBW in both as-received and 980STA conditions were shown in Figs.6-13. Post weld heat treated 980STA condition resulted in significant dissolution of lave phases, segregation of Nb and need like $\delta$ (Ni$_3$Nb) phase precipitation around them. Post weld heat treated 980STA condition in EB welds results showed that noticeable reduction in segregation and finer lave phases that to small quantity was observed in EBW than GTAW. The combined effects of lower heat inputs and higher cooling rates in welding operations and applied solution treated with aged conditions resulted in $\delta$ phase precipitation by dissolving the lave phases and segregation of alloying elements. The literature on welding processes of IN718 alloy solutionizing treatments said that the formed $\delta$ phases were retained in the microstructure under 980°C critical temperature. The PWHT at 980°C leads to partial dissolution of lave phases but not eliminated completely from the fusion zone of the weldments. The $\delta$ phase precipitation (860-995°C) around partially dissolved laves [19 - 21].Therefore on heating beyond the $\delta$-solvus temperature (~995°C) can dissolve the $\delta$ phase. The literature stated that the solution treatment at 1080STA of both weldments base zone resulted in grain coarsening and complete dissolution of delta phase. But the unfavorable condition of grain coarsening taking place in 1080STA condition suggested considering for lesser solution treated and aged at 980STA. The significant dissolution of the Nb-enriched lave phases were also observed at 980°C solution treated and aged (980STA) and without any coarsening of grains in base metal of the weldments. This leads to improve their mechanical and corrosion resistance behavior with relative microstructural morphology.

![Fig. 6 Optical microstructure of IN718 alloy-as received GTA weldments (a) FZ (b) HAZ and (c) BMZ](image-url)
Fig. 7 Optical microstructure IN718 alloy-980STA treated GTA weldments (a) FZ (b) HAZ and (c)BMZ

Fig. 8 SEM images of IN718 alloy-as received GTA weldments (a) FZ and (b) HAZ.

Fig. 9 SEM images of IN718 alloy-980STA treated GTA weldments (a) FZ and (b) HAZ.
Fig. 10 Optical microstructure of IN718 alloy-as received EB weldments (a) FZ (b) HAZ and (c) BMZ

Fig. 11 Optical microstructure of IN718 alloy- 980STA treated EB weldments (a) FZ (b) HAZ and (c) BMZ

Fig. 12 SEM microstructures of IN718 alloy- as received EB weldments (a) FZ and (b) HAZ
3.2 Mechanical Studies

3.2.1 Microhardness of GTA & EB Welds of IN718 alloy:

Microhardness results of GTA and EB welds in both as-received and PWHT- 980STA condition with respective zones were given in Tables 4 & 5 and in figs.14 & 15. In as-received condition, the hardness of the fusion zone (FZ) was lower than the heat affected zone (HAZ) and base metal zone (BMZ) due to the presence of segregation of alloying elements and formation of laves network during weld metal solidification resulted in inferior mechanical properties. By applying post weld solution treatment (980STA), the observed fusion zone hardness was significantly increased when compared with the fusion zone in as-received condition in both the weldments (GTAW and EBW). The fusion zone of as-received condition, niobium present in dendrite core regions is significantly lower than the base metal. For the $\gamma'$ precipitation the amount of niobium available in the weld matrix is significantly lower than the base metal. The nature of precipitation is affected by the imbalance caused in the weld matrix chemistry as a result of segregation [22] and it is also influenced by the relative amounts of titanium, aluminum and niobium present in the matrix [23]. The tendency of hardness as BMZ > HAZ > FZ has been observed in as-received and 980°C solution treated and aged condition of both GTAW and EBW. The significant hardness increase was observed in fusion zone of 980STA condition in both the welds. The effective reduction of segregation diffusion and resolving them from brittle laves particles into the matrix has increased the precipitation of strengthening phases resulted in significant hardness increase in FZ of 980STA condition. These results interprets that better mechanical properties were achieved at 980°C solution treated and aged (980STA) condition of electron beam welding (EBW) rather than gas tungsten arc welding (GTAW) process.

Table 4 Microhardness measurements on GTA welds of IN718 alloy

| Specimen condition | Vickers Microhardness measurement values (VHN) |
|--------------------|-----------------------------------------------|
|                    | Base zone | Heat affected Zone | Fusion zone |
| As welded           | 305       | 280                | 284         |
| 980STA             | 518       | 501                | 485         |
Fig 14 Vickers Microhardness measures of Gas Tungsten arc welding of IN718 alloy

Table 5 Microhardness measurements on EB welds of IN718 alloy

| Specimen condition | Vickers Microhardness measurement values (VHN) |
|--------------------|-----------------------------------------------|
|                    | Base zone | Heat affected Zone | Fusion zone |
| As welded           | 333       | 286               | 299         |
| 980STA             | 529       | 514               | 511         |

Fig 15 Vickers Microhardness measures of Electron beam welding of IN718 alloy
3.3 Pitting corrosion studies

The weldments of both GTAW and EBW showed lower mechanical and corrosion resistance behavior without prior heat treatments. In Ni-Cr group superalloys, the solution treatment at 1050°C was found to result in the significant refinement of grain size by resolving the detrimental effects and finally improve the mechanical and corrosion properties. However, at 1200°C and above temperature exposure gives a rapid increase in the grain growth which turns in decrease the protective passive layer formed by chromium carbide. This leads to drastic decrease of mechanical properties and corrosion resistance behavior of nickel based alloy weldments [24].

Potentio-dynamic polarization testing was carried out to study the pitting corrosion resistance in 3.5 wt% of sodium chloride (NaCl) solution with respective FZ, HAZ and BMZ of both GTA and EB welds in as-received and 980STA conditions. The polarization curves of GTA welds in two conditions were depicted in figs 16 (a) & (b) and respective conditions of EB weld in figs 17(a) & (b). Pitting corrosion resistance is significantly better in base metal than welding and PWHT conditions. It is due to formation of secondary precipitates and its distribution in the fusion zone. During the heat treatments to the welds, the increasing tendency of corrosion resistance in STA condition was observed due to the carbides precipitation and reduction in segregation of alloying elements. Fusion zone is enriched with metallic carbide at the grain boundary with Cr7C6 in PWHT condition. Corrosion resistance is given by the passive layer formation with chromium carbide. Improved pitting corrosion resistance of the post weld heat treated condition is attributed to the redistribution of strengthening precipitates in the matrix. Results of the present investigation established that pitting corrosion resistance is significantly better in post weld heat treated conditions of both the welds. The comparative studies showed that the superior pitting corrosion resistance is exhibited in 980STA condition of EBW than GTAW.

| Zone/Region       | Base metal zone (mV) | HAZ (mV) | Fusion zone (mV) |
|-------------------|----------------------|----------|------------------|
| As received condition | -250.75             | -268.12  | -274.57          |
| 1080STA condition   | -239.1              | -253     | -258             |

Fig. 16(a) & (b) Potentio-dynamic Polarization curves of GTAW in 980STA condition
Table 7 Tafel experimental data of EB welds

| Zone/Region | Base metal zone (mV) | HAZ (mV) | Fusion zone (mV) |
|-------------|----------------------|----------|------------------|
| As received condition | -183 | -190 | -205 |
| 1080STA condition | -169 | -171 | -177 |

Fig. 17 (a) & (b) Potentio-dynamic Polarization curves of EBW –IN718 alloy in 980STA condition

4. Conclusions

1. The presences of columnar grains at heat affected zone, dendritic structure with distribution of laves phase in the fusion zone is observed in as welded condition of GTA welds, whereas the finer and relatively discrete Laves phases were observed in EB welds of IN718 alloy.
2. The novel idea of using post weld solution treatment at 980STA condition in both the welding processes of GTAW and EBW, resulted in significant microstructural changes by reducing prolonged lave network phases and consequent niobium segregation in EB welds, also with its welding parameters.
3. Results of the microstructural changes established that the 980°C solution treated and aged (980STA) condition in both weldments (GTAW and EBW) showed drastic enhancement of its mechanical properties and best response to pitting corrosion resistance when compared with as-received condition of EBW than GTAW in aqueous solution.
4. The present work investigations showed that the best approach for enhancing the better combination of mechanical properties and related pitting corrosion resistance behavior can be obtained by adopting post weld heat treatment at 980STA condition. The 980°C solution treated and aged (980STA) condition of EBW exhibited better results than GTAW of IN718 alloy.

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