Dissimilar Metal Welds used in AUSC Power Plant,
Fabrication and Structural Integrity Issues

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ABSTRACT. In the current era, the Advanced Ultra Super-Critical (AUSC) plants have been used to substantially increased efficiency with environmental protection. AUSC components boiler header, re-heater and super-heater tube etc. are fabricated by using advanced materials to join by the welding process. Any failure of the power plant can lead to grave consequences, not only of substantial financial losses but additionally immensely treasured and irreparable human life loss. In this review, the dissimilar metal welds (DMWs) have many issues such as metallurgical issue, cracking, carbon migration, welding electrode selection, creep properties, suitable welding process and structure integrity issues which enhanced the failure of weldments. The results of our review showed that DMWs of AUSC power plant are joined by activated flux Tungsten Inert Gas (A-TIG) and Pulse A-TIG process to increase the productivity and cut the significant fraction of cost. However, A-TIG process with Post Weld Heat Treatment (PWHT) improved the mechanical properties and high-temperature creep resistance properties of DMWs. This state of the art is encouraged the researchers about the enormous future scope.

1. INTRODUCTION

Among all traditional energy sources, the coal remains the most important source of electricity in India. Recently, the AUSC power plants are developed all over the world with high efficiencies to improve human living standard. Hence, the most successful approaches to increase the efficiency of the power plant is developed the advanced materials. The material development for AUSC was initiated in 1998s by COMTES700 USA project started by China in 2011. Further, India started the AD700 project in 2012 with the development of new materials as shown in Fig 1 [1].

Figure 1. Materials used in SC, USC and AUSC boiler [1].

The selection of materials for AUSC components is based on high temperature creep properties, sufficient weldability, and industrial availability. The ferritic / martensitic steels such as ASME Gr. 91,
92,122 etc. are used in the thick section while super austenitic stainless steel as TP316 H, 304 H, TP321 H, TP347 H etc. and the Ni-base Alloys as 800 H, IN 617, 617 B, 740 H, 718 etc. are used in thin section of boiler but undoubtedly nickel alloy is more costly compared to the ferritic / martensitic steel [2].

Recently, the AUSC power plants in India are used various materials as shown in Table 1. The DMWs are mostly adopted in AUSC boiler headers, super-heaters and re-heater pipe or tube joined to make the whole system by welding together the components for transport the fluid [3].

| Elements      | TP23 | TP91 | Super304H<sub>Cu</sub> | Super347H | IN 617 | IN 740H | IN718 |
|---------------|------|------|-------------------------|-----------|--------|---------|-------|
| Carbon (C)    | 0.04-0.10 | 0.07-0.14 | 0.07-0.13 | 0.0681 | 0.05-0.15 | 0.048 | 0.026 |
| Manganese (Mn) | 0.10-0.60 | 0.30-0.60 | 1.00 max | 2.03 | 1.0 max | 0.240 | 0.085 |
| Phosphorous (P) | 0.03 max | 0.02 max | 0.040 max | - | 0.015 max | <0.001 | 0.009 |
| Sulphur (S)   | 0.01 max | 0.01 max | 0.01 max | - | 0.01 max | 0.001 |
| Silicon (Si)  | 0.50 max | 20-0.50 | 0.30 max | 0.62 | 1.0 max | 0.005 | 0.102 |
| Nickel (Ni)   | – | 0.40 max | 7.50-10.50 | 9.39 | 44.5 min | Bal. | Rem. |
| Chromium (Cr) | 1.90-2.60 | 8.50-9.50 | 17.00-19.00 | 20.06 | 20.0-24.0 | 25.36 | 17.49 |
| Molybdenum (Mo) | 0.05-0.30 | 0.85-1.05 | – | 0.27 | 8.0-10.0 | 0.005 | 2.96 |
| Cobalt (Co)   | – | – | – | – | 10.0-15.0 | 20.04 | 0.102 |
| Copper (Cu)   | – | – | – | 2.50-3.50 | – | 0.5 max | 0.025 |
| Niobium (Nb)  | 0.02-0.08 | 0.06-0.10 | 0.30-0.60 | 0.44 | – | 1.56 | 5.03 |
| Titanium (Ti) | 1.45-1.75 | 0.02 max | – | – | 0.6 max | 1.36 | 0.905 |
| Tungsten (W)  | 0.20-0.30 | 0.18-0.25 | – | – | – | – |
| Aluminium (Al)| 0.03 max | 0.07 max | 0.003-0.030 | – | 0.8-1.5 | 1.39 | 0.572 |
| Boron (B)     | 0.006 max | – | 0.001-0.010 | – | 0.006 max | – |
| Iron          | Balance | Balance | Balance | Balance | 3.0 max | 0.23 |

2. Problems associated AUSC dissimilar metal welds

2.1 Metallurgical problem and Imperfection during welding

The performance of DMWs in service basically depends upon the quality of weldments. The weld defects such as cracks, cavities, solid inclusion, incomplete fusion, unacceptable contour, arc strike etc. are causes failure of DMWs in service at high temperature [4]. Many researchers were reported that
failure occurred in the welded joint due to metallurgical deterioration. The nickel base alloys showed laves phase (ϒ) in grain boundaries (GB) which reduced the fatigue strength and increased the yield strength due to ϒ combined with Cr and precipitates undesirable M23C6 phase[5]. Similarly, Austenitic steels is showed NbC, TiC and ϒ phase which improved the creep strength of welded joints but ϒ phase increased the solidification cracking sensitivity. The weldment solidification modes of steels are calculated by Cr_eq/Ni_eq ratio. However, Verma et al. [6] were studied constitution diagrams such as Schaeffler, WRC 1992 and Pseudo binary (Fe-Cr-Ni) diagram as shown in Fig. 2. For similar and dissimilar metals joint, these diagrams can be used to predict the microstructure of the DMWs.

![Figure 2. Constitution diagrams for dissimilar metal joining to predict the weld microstructure by Schaeffler, WRC-92 and Pseudo binary (Fe-Cr-Ni) diagram [6].](image)

Further, Fu et al. [7] were reported that when Cr_eq / Ni_eq ratio is less than 1.2, thus the microstructure showed fully austenitic and there is no δ-ferrite in an equilibrium condition. The main constituents Cr, Mo, V, W, Co, N, Nb, B, Ni, C etc. are added to improve the mechanical properties in ferritic and martensitic steels. The W, Co increased the austenite phase and reduced the δ-ferrite phase in the steel [8]. The contents C, N are showed more solubility in austenitic steel than ferritic steel. The formation of laves such as Fe2(W, Mo) increased the hardness and short term creep properties in the steel weldment due to increase the lower critical temperature 810-825°C or reduced the martensitic start (Ms) temperature at 390-400°C. However, the V, Nb constitutes is formed MX phase which increased the corrosion and reduced the fracture toughness of the steel joints. The creep and fatigue properties of the steels are reduced when δ-ferrite increased in the weldment. Further the formation of δ-ferrite in WM and HAZ is calculated by using the Kaltenhauser ferrite factor (KFF) and Schneider Ferrite factor (SFF) Eq. (1) and (2) [9-10].

$$KFF = Cr + 6Si + 4Mo + 8Ti + 2Al + 4Nb - 2Mn - 4Ni - 40(C+N) \quad (1)$$

$$SFF = Cr+2Si+1.5Mo+5V+1.75Nb+0.75W-Ni-0.5Mn-30C-25N-0.3Cu \quad (2)$$

Also, Ramkumar et al. [11-12] were studied the microstructure of DMWs between the metals Nickel alloys (IN 718), martensitic steel (AISI 416) and Austenitic steel (316 SS). They were reported that the Nb and Mo secondary phase found in the heat affected zone (HAZ). In sequence, the laves phase (Ni3Nb) with inclusion (FeS, MnS) was observed in the fusion zone (FZ) and the partially melted zone (PMZ). However, Dev et al. [13] were reported that the microstructure of weldments also showed δ-ferrite. Similarly, Ramkumar et al. [14] was investigated the DMWs of IN718 / SS 316L and found the Cr and Ni content in HAZ with the unmixed zone (UMZ). Additionally, Pavan et al. [15] were studied the microstructure of DMWs between IN 617 / SS 304 L. They were reported that Cr, Mo, C, Si contents found in the FZ and PMZ, which increased the M23C6 precipitation in the weldment. Along with, Falat et al. [16] were investigated the microstructure of DMWs T91 / TP316 H. It was reported that the weld metal (WM) consisted of Nb, Ti, and carbide phase (MC). Similarly, Mittal et al. [17] were found martensitic phase in WM and HAZ of T91 / 347 H DMWs. Briefly, the mechanical properties and service life of DMWs are influenced by phases, which developed the microstructure heterogeneity.
2.2 Cracking in AUSC welds

2.2.1 Hot cracking

Hot cracking have been found recently in weld metal (WM) and heat affected zone (HAZ) of nickel base alloys and austenitic steels. It is appeared during weld solidification or metal liquid inherent in between two solid grain boundaries. Kou et al. [18] were reported that nucleation and grain growth causes the hot cracking due to thermal stress and strain. Naffakh et al. [19] were studied the cracking susceptibility in DMWs of AISI 310 / IN 657 and found the Ti-rich phase, and segregation causes the solidification hot cracking. However, Sayer et al. [21] were examined the DMWs between nickel base alloy (IN825) and austenitic steel (AISI 321). They were reported that rich Ti-phase and low δ-ferrite promoted the solidification hot cracking. In sequence, Xin Ye et al. [33] were reported that sensitivity of hot cracking increased in IN 718 due to crater developed in the weld center by longitudinal and transverse micro-segregation by laves phase.

2.2.2 Hydrogen Induced Cracking (HIC)

HIC also known as cold cracking because, low-temperature (200 to 1000°C) martensite phase and hydrogen are combined and developed cracking in the HAZ. The various sources of hydrogen are moisture, oil, grease and shielding gas. Besides, the flux assisted SMAW, FCAW, SAW and GTAW or GMAW process with H2 shielding gas introduced the hydrogen in WM. The hydrogen atom and molecules diffused and dissolved into the WM during welding process. The atoms of hydrogen easily penetrate the weld voids and caused cracking, blistering and hydrogen embrittlement. The hydrogen is transferred from high temperature (Tf) of the WM to low temperature (Tb) of the HAZ. Therefore, HAZ austenite converted into martensite because the ferrite is low solubility of hydrogen during welding. The combined effect of hydrogen and martensite caused a crack and developed HIC in HAZ as shown in Fig. 3 [22].

![Schematic representation of diffusion of hydrogen from WM to HAZ](image)

The HIC susceptibility of steel is predicted by carbon equivalence (CE) in Eq. (3). The HIC susceptibility of the steel increased when CE value is high.

\[
CE = \%C + \frac{\%Mn}{8} + \frac{\%Si+Cr+Ni}{15} + \frac{\%Cu+Mo+}{} \tag{3}
\]

Pandey et al. [23] were reported that hydrogen embrittlement increased when diffused hydrogen content more than 6.21ml/100 in WM. In sequence, the tensile and flexural strength of WM decreased when deposited WM content is a higher volume of hydrogen 12.54 ml / 100. However, Saini et al. [24] were found martensite in HAZ of P92 steel, then martensite phase increased the HIC susceptibility. Further, the HIC on AISI 4137M exhibited some evidence of hydrogen embrittlement during slow strain rate tests. Zhou et al. [25] were investigated the corrosion behavior in H2S medium of DMWs of X60 / IN 625 and found high corrosion in FZ due to hydrogen embrittlement.
2.2.3 Stress corrosion cracking (SCC)

The SCC is considered combining interaction of the material, tensile stress-strain and corrosive environment as shown in Fig. 4. The SCC occurred trans-granular or branching type in HAZ into extent in BM due to C or Cr depletion.

Figure 4. Conjoint interactions material, stress-strain and environment in SCC [54]

The constituent phases Fe-Ni, Fe-Cr, MₓO₄ (M=Ni, Cr, Fe) are produced intergranular SCC in AUSC materials at high temperature. The surface corrosion with stress-strain initiated the micro-cracks due to dislocation or defects then micro-voids coalesced and produced the cracking on surface or grain boundaries [26]. Dong et al. [27] were investigated the SCC behavior in DMWs of SA508 Cl. 3 / Alloy 52M with high pressurized water and found the reason of SCC due to Cr depletion and strength mismatch in fusion zone (FZ). Zhu et al. [28] were examined SCC of DMWs 316 L / 52M in borated and lithiated water solution. The cracking is occurred in FZ with mixed mode nature as well as trans-granular and intergranular. Hence, Vidyarthi et al. [29] were found the pitting corrosion in weld interface of DMWs between IN 718 / 316 L and P91 / 316 L which developed the stress corrosion cracking.

2.3 Segregation

The segregation is found in DMWs due to insufficient mixing and dilution of filler metal with BM during welding. Hence, Soyal et al. [30] were reported that the segregation occurred due to differences in liquids temperature of weld metal and base metal. Moosavy et al. [20] were found the segregation of Ti rich phase in inter-dendritic FZ region and developed the PMZ with laves phases in DMWs of IN 718 / IN 500. Similarly, Ramkumar et al. [31] were found the Mo, Cr micro-segregation in the FZ of DMWs IN 718 / IN 625. Further, Vashistha et al. [32] were found the C, Cr segregation in DMWs of austenitic stainless steel 304 SS / 201 SS.

2.4 Carbon Migration

The carbon migration occurred in the weld interface during PWHT or service at high temperature. Kulkarni et al. [34] were investigated the DMWs of ferritic steel P91 / P22 microstructure with carbon diffusion as welded and PWHT condition. Hence, the carbon migration mechanism reported that carbon migrated from high to low-level Cr zone and developed carbon enriched (dark) and carbon denuded (light) region. The migrated carbon combined with Cr and Mo particles which developed Fe₃C, MX, and Mₓ₂C₆ phases in both sides of carbon enriched interface zone as shown Fig. 5. Further, Jahanzeb et al. [35] were reported that microhardness heterogeneity developed due to carbon migration in DMW of 316L / SS400 steel.
2.5 Selection of filler wire

Recent, the AUSC materials are mostly joined by using GTAW, pulse TIG, SMAW or combination of two (hybrid) process. The selection of suitable filler metal for DMWs is very critical due to the difference in composition, thermal properties and mechanical behavior of BM. Some researchers are used the filler wire in DMWs as shown in Table 2.

Table 2: Filler metal composition (in wt. %) with welding process for DMWs.

| Process   | Filler               | C    | Si  | Mn  | Ni  | Cr | Co | Al | Ti | Fe | Other | Ref. |
|-----------|----------------------|------|-----|-----|-----|----|----|----|----|----|-------|------|
| TIG       | IN A                 | 0.10 | 1.00| 3.0 | Rem | 15 | -  | -  | -  | 12 | A     | [20] |
| GTAW/     | ERNiCr-3 (IN82)      | 0.035| 0.30| 3.0 | 72.6| 20 | -  | -  | -  | 3.0 | B     | [17] |
| SMAW      | ERNiCr-1             | 0.05 | 1.0 | 3.0 | 70  | 16.5| -  | -  | -  | 6.50| C     | [35] |
| GTAW/     | ENiCrFe-3 (IN182)    | 0.015| 0.10| 2.8 | 72.6| 19.6| -  | -  | 0.37| Bal.| Nb-2.68| [36] |
| SMAW      | ENiCrFe-1            | 0.08 | 0.75| 3.5 | >62 | 17 | -  | -  | <11| Bal.|         | [55] |
| GTAW/GMA  | ERNiCrCoMo-1         | 0.06 | 0.10| 0.1 | Bal.| 22 | 11 | 1.3| 0.3| 0.5 |       | [36] |
| TIG       | ERNiCrMo-3 (IN 625)  | 0.1  | 0.50| 0.5 | 64  | 22-23| -  | 0.4| 0.4| Bal.| D     | [21] |
| TIG       | ERNiCrFe-1 (IN65)    | 0.05 | 0.5 | 1   | Bal.| 23 | -  | 0.2| 1.1| 23  | E     | [21] |
| Pulse TIG | ERNiCrMo-10          | 0.012| 0.05| 0.55| Bal.| 22.4| 0.22| -  | -  | 2.5 | F     | [56] |
| TIG/P-TIG | ER2553               | 0.015| 0.35| 1.25| 6.32| 25.85| -  | -  | -  | Bal.| G     | [13] |
| P-TIG | ERNiCu-7 | 0.02 | 0.13 | 3.61 | 62.8 | - | - | 0.1 | 2.55 | 0.78 | H |
|-------|----------|------|------|------|------|---|---|-----|------|------|---|
| P-TIG | ENiCrMo4 | 0.00 | 0.05 | 0.52 | 57.8 | - | - | - | Bal. | 1    |

\[ A: Mo - 1.5, Nb - 2.5, Cu - 0.5, B: Mo - 0.30, Nb - 2.6, C: Cu < 0.5, Nb + Ta - 1.5 - 4.0, D: Cu - 0.5, Nb - 3.6, Mo - 9.2, P - 0.015, E: Cu - 2, Mo - 3.5, F: S - 0.001, Co - 0.22, V - 0.01, W - 3.34, Si - 0.05, Cu - 0.2, G: Cu - 1.56, P - 0.02, S - 0.005, H: Cu - 29.94, S - 0.004, P - 0.003, I: Cu - 0.26, V - 0.041, W - 3.98, S - 0.004, P - 0.007 \]

Dupont et al. [49] were reported that IN 622 produced better solidification cracking resistance than IN 625 due to dilution of Mo, Nb, \( \sigma \) phases, which increased the solidification temperature range. Further, Sayyar et al. [50] were reported that IN625 and ER347 filler developed the Nb-Mo-Ti rich phase with better hot cracking resistance but Mo phase developed MGBs. Thus, Wu et al. [50] were reported that the 310 SS showed high sensitivity of solidification cracking (SC) but IN 82 and IN 617 are developed hot cracking in WM due to low melting point secondary phase. Similarly, Dev et al. [11-13] were reported that ERNiCrMo-4, ER2553 and ERNiCu-7 witnessed the Mo, Nb phase with segregation and MGBs. Also, Pandey et al. [21-23] were found the certain variations in material chemistry of buttering due to Ni-Fe alloy buffer layer and enhanced the solubility of Nb and Ti content due to increased Fe content in DMWs of SA508Gr3Cl1 / SS316 L. Moreover, Mateshakker et al. [52] were reported that AWS ER 347 and 316 L consumables enhanced the Cr and Mo phase with \( \delta \)-ferrite, which decreased the mechanical properties and corrosion resistance. From open literature, it is clear that selection of filler for DMWs is not standardized yet.

3. Creep characteristics for AUCS power plant

Recently, AUSC plant boiler and turbine section are designed with high creep rupture strength with allowable stress and time 100000 - 500000 h at high temperature. The creep rupture data for long-term creep for ferritic, martensitic, austenitic steels and nickel base alloys with operating temperature versus stress at 100000 h are shown in Fig. 6 [37].

![Figure 6. Application ranges of creep rupture for various materials [55].](image)
DMW in T91 / TP316H at temperature range 600-650°C with stress 60-140MPa and fracture occurred at T91 HAZ side due to micro-void coalescence at grain boundaries. However, Shin et al. [39] investigated fracture during creep in DMWs 740 H / P92 for parameter range 650 °C / 80 MPa and 700 °C / 35 MPa. It was concluded type IV cracking occurred at P92 side in CGHAZ due to poor grain boundaries strengthening by carbides. Along with, Matsunaga et al. [40] were studied the creep behavior of P91 / AISI 316 at stress 40 - 80 MPa and temperature 590 - 625°C and reported that cavities nucleated at the top surface of the weld joint in the form of micro-cracks. The DMWs are mostly damaged in the outer surface of joint due to high creep strain appeared at the interface surface.

4. Structural integrity assessment issues

The structural integrity is considered scientific margin between safety and disaster for improved the life of existing structure by rehabilitation. Recently, the structural integrity assessment procedure has been based on the reliability of the structure stand in high temperature. However, the UK power generation industries developed the R6 procedure for defect assessment. The BS 7910 procedure is used for detecting the discontinuities in components used in high temperature and improved by the addition of SINTAP for assessing the structural integrity[42]. Moreover, Rathod et al. [43] were used FITNET, R6, SINTAP and BS 25 for analysis the yield strength ratio (YSR), plastic instability strength (PIS) and SENB toughness test in the DMWs of SA 508 / 304 LN. The structure integrity assessment are available for single joint. Recently, the DMWs design consideration very critical and essential for remnant life prediction of the plant with new testing and fabrication procedure.

5. The effect of Welding process and heat treatment on mechanical properties

The AUSC components are fabricated by using fusion welding process such as gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), shielded metal arc welding (SMAW), Submerged arc welding (SAW). Recently, the researchers are diversified toward advance welding process as activated flux or autogenous A-TIG and pulse TIG process with selecting suitable parameters. Verma et al. [44] were studied the effect of the SMAW process parameters on DMWs of DSS 2205 / 316 L. The hardness and tensile value decreased as heat input increased. Further, Wang and Mittal et al. [54-17] were reported that GTAW process provided better mechanical properties than SMAW process in DSS 2205 / 16 MnR. and, T91 / 347 H dissimilar joints. Along with, Rathod et al. [36] were investigated the effect of Ne - Fe buffer layer by using GTAW, GMAW, SMAW process with heat input 1.11, 2.46 and 3.47 KJ/mm respectively. It was reported that fracture toughness, weld strength and ductility of the GMAW is higher than SMAW process. Further, Naffakh et al. [23] were reported that WM with heat input 5.93 KJ/mm by GTAW process was showed better the hardness 240 HV, tensile strength 450 MPa and impact strength 121 J than hybrid process. Further, Vashistha et al. [31] were studied the effect of heat input (HI) of GTAW 0.34, 0.38, 0.48 KJ/mm and SMAW 0.72, 0.81, 0.97 KJ/mm process on the DMWs of AISI 304 / AISI 201 steel. It was concluded that the GTAW process was produced better mechanical properties. Moreover, Pavan et al. [15] were studied the effect of the TIG process on DMWs of SUS 304 H / IN 617. It was found the hardness and impact strength better in WM than base metal (BM). It was concluded that TIG process suitable for AUSC boiler. Likewise, Ramkumar et al. [14-47] were studied the effect of continuous current CCGTAW and pulse current PCGTAW process on the mechanical properties of DMWs as IN 718 / AISI 316 L and SAF 2207 / IN 825. The PCGTAW was showed better tensile strength and impact toughness than CCGTAW. Likewise, Ramkumar et al. [11-12] were reported that joint efficiency of activated Flux A-TIG found higher than autogenous TIG such as 85% and 77% in DMWs of IN 718 / AISI 416. Also, Karthick et al. [44] were studied the effect of PWHT 760 °C / 2h on mechanical properties of P91 / 316LN. The notch tensile strength and impact toughness of WM and HAZ in P91 side was found higher 580-590MPa and 116-90J respectively. Further, Falat et al. [19] investigated the effect of PWHT 750 °C / 1h and found low creep strength with types IV cracking in HAZ. Similarly, Zang et al. [45] were reported that. WM of P92 / IN 617 showed
better impact strength, tensile strength and hardness values after PWHT. Pandey et al. [10] were analyzed the effect of flux A-TIG process with PWHT on DMWs of P91 / P92. It was found that the tensile and impact strength increased after PWHT. Similarly they were reported that hardness of both welding processes after double PWHT 760 °C / 2h increased. Further, A-TIG process provided better mechanical properties than M-TIG [48] Even so, from the above section, it is clear that DMWs compatible with single and hybrid welding process with PWHT for evolution of microstructure and mechanical properties point of view, but in the case of creep properties with A-TIG and Pulse TIG, a lot of work is needed.

6. Conclusions

The DMWs of AUSC power plant is joined by hybrid or multi-pass welding process, these processes are developed some critical issues in DMWs, and decreased the productivity. However, A-TIG provided the superior results and cut the significant fraction of cost. The high-temperature properties of DMWs can be improved by suitable PWHT with A-TIG and pulse TIG process. Further, a structural integrity assessment procedure for DMWs of AUSC Power plant will be developed to adopt by the scientific community. This state of the art is encouraged the researchers about the enormous future scope.

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