# AN APPROACH FOR EFFECTIVE JOINING OF DISSIMILAR METALS USED IN SUPERCRITICAL BOILERS

**A Thesis Submitted**
**In Partial Fulfillment of the Requirements**
**for the Degree of**

**DOCTOR OF PHILOSOPHY (Ph.D.)**

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**December, 2021**

## Synopsis

The objective of this research work is to resolve the long-standing techno-scientific issue of joining dissimilar steels (T23-to-T91) in supercritical boiler through judiciously selected welding parameters (filler wire selection in particular) in a cost-effective Gas Tungsten Arc Welding (GTAW) process so as to develop an efficient joint in view of obviating type-IV failure in the heat affected zone at boiler operation temperature (571°C) by enhancement of joint strength with necessary microstructural modification, thereby achieving 100% joint efficiency.

The chronological shift from subcritical boiler technology (Temperature < 540°C, Pressure: 16.5 MPa) to supercritical boiler technology (Temperature: 565°C-580°C, Pressure: 24.8 MPa) enhances the boiler efficiency from 35% to 46%. Indeed, it eventually provides a cost effective and readily available option to reduce $CO_2$ emission per unit of electricity generated through enhancement in power plant efficiency by combined increase of temperature and pressure so that less coal is burnt per MWh generated. In this regard, the joining between T23 steel to T91 steel tubes (dissimilar steel joining) becomes eventual in a modern supercritical boiler. However, it is quite unfortunate to note that the dissimilar steel joining in boiler has long been recognized as an area of potential problem (since the year 1935), primarily due to type-IV failure through heat affected zone (HAZ). Indeed, the research work carried out so far to resolve this issue lacks fundamental insight and necessary scientific advancement. The majority investigations carried out till date is merely backed up with microscopic level characterization (optical microscopy and scanning electron microscopy) along with hardness measurement. No in-depth microstructural analysis at submicroscopic level has been carried out for necessary structure-property correlation. Most importantly, the tensile test at boiler operation temperature has not been carried out to explore techno-scientific insight keeping different regions of weldment intact. In this regard, a thorough literature survey indicates a possible futuristic attempt of using Ni-based filler wire in GTAW process which is expected to restrict carbon diffusion so as to arrest type IV failure while joining dissimilar steels (say, joining T23 to T91) in a supercritical boiler.

Accordingly, in the present research work three approaches have been taken up for joining T23 to T91steel tubes. Since Ni-based filler wire is costlier to Fe-based filler wire,

in first two approaches Fe-based filler wires of lower matching type (ER90S-G) and higher matching type (ER90S-B9) are respectively used in the GTAW process of fusion welding. In third approach, a Cr containing Ni-based filler wire (ERNiCrFe-7A) is used in the GTAW process to join T23 to T91 steel tubes. It is further noteworthy to mention that although Ni-based Inconel type filler wire is costlier to the Fe-based filler wires; the overall process is still expected to remain cost-effective, since the heat input required for joining by Ni-based filler wire is much lower due to its lower liquidus temperature than the Fe-based filler wires. The novelty of this work primarily stems from using a new kind of filler wire (Ni-based alloy containing Cr) so as to augment chromium diffusion (instead of carbon diffusion) to negate the formation of carbon-depleted zone, primarily responsible for type-IV failure. Moreover, the resultant solid state diffusion phenomenon is dealt with fundamental error function-based analytical treatment at atomistic level. In particular, a special focus is provided to fundamental insights and scientific advancement to adopt most advanced characterization techniques for exploring structure at submicroscopic level and associated phenomena. This is further backed up with thermodynamic perspective and supporting evidences of type-IV failure negation provided by advanced characterization techniques up to the level of FEG-TEM based IFFT analysis. Of course, on technological perspective, the in-depth scientific analysis is supported with one of the most critical tasks of performing tensile test at boiler operation temperature and thereafter executing advanced characterization techniques keeping different regions of weldment intact.

Once GTAW welding of T23 to T91 steel tubes are executed followed by post weld heat treatment and standard radiography test, small samples are machined out from the weld joint region, consisting of weld metal and HAZ and both the base metals. These specimens are at first examined under the Optical Metallurgical Microscope, Scanning Electron Microscope (SEM) equipped with EDS detector, Field Emission Scanning Electron Microscope (FESEM) equipped with EDS detector and X-ray diffractometer. Furthermore, microhardness test (across the weldment) and high temperature tensile tests are carried out to ascertain the hardness and high temperature tensile properties, respectively. The tensile fractured surfaces are examined in FESEM to understand the failure mode in correlation with microstructure and properties. Furthermore, HAZ near weld zone in T23 side (otherwise type-IV failure location) of the high temperature tensile

tested specimens are examined in different characterization units; namely, FESEM equipped with EDS detector, Atomic Force Microscope, X-ray diffractometer, transmission electron microscope equipped with field emission gun (FEG-TEM) and electron backscattered diffraction (EBSD) analysis.

In the first approach, while joining T23-to-T91 steels by GTAW process using lower matching iron-based filler wire (ER90S-G), the microstructure evolved in the weld metal comprises of various alloy carbide precipitation in α-iron based matrix of a combined 'polygonal'-plus-'lath' morphology. On a gross scale, the base metal and HAZ part along T23 side exhibit carbide precipitates in α-ferrite based matrix. Furthermore, a tempered martensite matrix containing carbide precipitates are identified in the T91 side of base metal and HAZ. In particular, the HAZ near weld zone in T23 side consists of clustered $Cr_{23}C_6$ particles around cavity at the junction of α-ferrite grain boundaries. The accumulation of dislocation loops around $Cr_{23}C_6$ particles is also identified. In view of the microhardness traverse curve across the weldment, the hardness variation in each similar domain of the weldment is confined to a narrow range (160-171 HV along T23 side and 195-202 HV along T91 side). Incidentally, the HAZ near weld zone in T23 side appears to be the weakest location in the weldment possessing the lowest hardness value of 160 HV. Indeed, the highest hardness (219 HV) across the weldment is exhibited by the weld metal due to hard carbides being dispersed in α-iron based matrix of a combined 'polygonal'-plus-'lath' morphology. The HAZ near weld zone in T23 side, the region of lowest hardness consisting of clustered $Cr_{23}C_6$ particles around cavity at the junction of α-ferrite grain boundaries, is eventually found to be the location of failure during the high temperature tensile test carried out at the boiler service temperature (571°C). Quite a reasonable high temperature tensile strength (mean UTS of 318 MPa) coupled with a modest ductility (%Elongation = 6) is exhibited. However, joint efficiency appears to be less than 100% as exemplified with the occurrence of failure from the HAZ near weld zone in T23 side; thereby not providing a complete solution for type-IV failure.

While joining T23-to-T91 steels by GTAW process using higher matching iron-based filler wire (ER90S-B9), except a little variation in the weld metal part, the overall evolution of microstructure, hardness variation and high temperature tensile properties

closely follow that observed for joining with lower matching iron-based filler wire. The weld metal exhibits a tempered martensite matrix possessing lath morphology along with various dispersed carbides. On a gross scale, the base metal and HAZ part of the weldment in T23 side primarily consist of α-ferrite along with carbide precipitates. Furthermore, the overall structure of the base metal and HAZ part in T91 side corroborates carbide precipitates in tempered martensite matrix. Again, in the HAZ near weld zone along T23 side, $Cr_{23}C_6$ particles are found to be clustered around cavity formed at the junction of α-ferrite grain boundaries. Furthermore, dislocations are found to be accumulated around $Cr_{23}C_6$ particles. While the microhardness traverse curve across the weldment is introspected, the HAZ near weld zone in T23 side is identified as the location possessing the lowest hardness value (159 HV). However, the variation of hardness in either similar domain is restrained to a narrow range ((159-170 HV along T23 side and 198-203 HV along T91 side), thereby indicating some accomplishment in the adopted process of joining. Moreover, the weld metal, corroborating a microstructure of dispersed alloy carbides in tempered martensite matrix, possesses the highest hardness (244 HV). Again, the HAZ near weld zone in T23 side is identified as the site of failure while the weldment is subjected to tensile test carried out at the service temperature of supercritical boiler (571°C). The high temperature tensile strength obtained is quite noteworthy (mean UTS of 319 MPa); while the ductility obtained is a modest one (%Elongation = 8). In any case, the failure from the HAZ near weld zone in T23 side exemplifies less than 100% joint efficiency. Therefore, a complete solution for type-IV failure is not obtained.

Henceforth, while joining T23-to-T91 steels by GTAW process using Cr containing Ni-based (Inconel type) filler wire, the microstructure originated in the weld metal typically consists of all five feasible characteristic growth patterns of Ni-based solid solution matrix along with distributed precipitate phases (either CrNi or σ-phase). The morphological variations of Ni-based solid solution matrix with regard to the five characteristic growth patterns are typically the planar, cellular, cellular dendritic, columnar dendritic and equiaxed dendritic. Excluding HAZ near weld zone, the base metal and majority parts of HAZ primarily consist of either carbide precipitates in α-ferrite based matrix (in T23 side) or tempered martensite matrix containing carbide precipitate (in T91 side). Most importantly, the HAZ near weld zone in T23 side typically exhibits coherent σ-phase

precipitates in α-iron based matrix. The evolution of such a novel microstructure, during the process of fusion welding with Cr containing Ni-based filler wire, is a consequence of the diffusion of chromium from the molten weld pool to the adjacent heat affected zone (HAZ near weld zone) and subsequent cooling followed by post weld heat treatment. The evolution of coherent σ-phase precipitates in α-iron based matrix is substantiated with advanced characterization techniques, an error function-based analytical approach of ascertaining diffusion phenomenon together with the authentication of the thermodynamic feasibility of highly negative Gibbs free energy change for σ-phase evolution. Furthermore, with regard to the microhardness traverse curve across the weldment, the lowest hardness (158 HV) across the weldment is identified at the centre of the weld metal region. The weld metal, being a solid with Ni-based matrix, is expected to be a bit softer as compared to Fe-based solid microconstituents around. While contemplating on the Fe-based regions, the T91 side exhibits relatively higher hardness (in a range of 199-204 HV) as compared to the hardness (range: 163-172 HV) possessed by the T23 side. This is primarily due to the presence of harder tempered martensitic matrix along the T91 side as compared to the relatively softer α-iron based matrix of tempered bainite along the T23 side. Furthermore, within this domain of Fe-based regions, the HAZ near weld zone along T23 side possesses the lowest hardness (163 HV). In any case, the Ni-based (Inconel type) weld metal, being a heat resistant material is expected to retain significant strength at high temperature as per standard literature. Therefore, even if possessing the lowest hardness (158 HV), the failure does not occur through weld metal region during high temperature tensile test. Most interestingly, unlike joining by Fe-based filler wires (either 'lower matching' or 'higher matching' type), the high temperature tensile failure does not occur through HAZ near weld zone along T23 side (though possessing a low initial hardness of 163 HV), primarily due to the evolution of coherent σ-phase that resists grain boundary sliding at the time of high temperature tensile deformation. This leads to the attainment of 100% joint efficiency which is exemplified with the T23 base metal region as the location of failure during high temperature (571°C) tensile test exhibiting a reasonable percentage elongation (21) and ultimate tensile strength (332 MPa) values. This eventually indicates toward a complete solution for type-IV failure.

Almost similar mode of failure is identified while using both the Fe-based filler wires (lower matching and higher matching type), HAZ near weld zone being the weakest zone that consists of clustered $Cr_{23}C_6$ particles around cavity at the junction of α-ferrite grain boundaries. In these cases, during high temperature tensile deformation, $Cr_{23}C_6$ particles are pushed with grain boundary sliding and finally are clustered around the cavity formed thereby, where the converging grain boundaries tend to meet. The presence of clustered $Cr_{23}C_6$ particles along with cavity promotes a cleavage mode of failure that does not allow a high ductility to be achieved. However, still a modest ductility (6-8% Elongation) is retained due to the presence of soft α-ferrite matrix which promotes a dimple mode of failure. Significant high temperature strength of 318-319 MPa (though lower than 100% joint efficiency) is still obtained due to dislocation accumulation around $Cr_{23}C_6$ particles. Indeed, while using Cr containing Ni-based (Inconel type) filler wire, the evolved σ-phase, being coherent with α-iron based matrix (substantiated by low misfit parameter and low coincidence index), readily resists the sliding of α-ferrite grain at high temperature. This negates the process of failure from HAZ near weld zone, which is the otherwise location of catastrophic failure of boiler tube while using matching Fe-based filler wires. As a consequence, the failure has occurred from T23 base metal region providing 100% joint efficiency. In concurrence to the significant high temperature strength and large ductility exhibited, the failure is found to occur through transgranular dimple rupture mode. The dimple rupture essentially takes place via microvoid coalescence in the α-ferrite based solid solution matrix.

Therefore, the use of Fe-based filler wire (either higher matching or lower matching) in a cost effective GTAW process for dissimilar steel (T23-to-T91) joining may be ascribed to provide just a 'partial success' of joining due to non-attainment of 100% joint efficiency (as failure occurs from HAZ region) with a modest tensile ductility, but with a reasonable high temperature tensile strength. However, for the first time in the last ninety years, the use of Ni-based (Inconel type) filler wire containing Cr in GTAW process has envisioned a new pathway of joining dissimilar steel (T23-to-T91) in a supercritical boiler with attainment of 100% joint efficiency, as failure occurs from the base metal region. As a consequence, significant high temperature tensile strength (332 MPa) and large tensile

ductility (21% Elongation) are obtained to completely obviate type-IV failure. In this regard, a new fundamental conceptualization is elucidated for the first time that enumerates the evolution of coherent σ-phase during the process of welding by virtue of diffusion of Cr from molten weld pool to the HAZ near weld zone and subsequent cooling followed by post weld heat treatment. The presence of σ-phase readily resists the sliding of α-ferrite grains during high temperature tensile test, thereby negating the process of failure from HAZ near weld zone. Moreover, although Ni-based Inconel type filler wire is costlier to the Fe-based filler wires; the overall process is still expected to be cost-effective, since the heat input required for joining by Ni-based filler wire is much lower due to its lower liquidus temperature than the Fe-based filler wires.