Chapter 9

Summary and Conclusions

9.1 Summary

Ultra super critical (USC) power plants are under development worldwide to improve the efficiency and thereby to reduce the CO₂ emissions. As the steam parameters are continually increased further, the first attempt to develop high efficiency USC steam generator has failed mainly due to the break down in superheater and reheater tubes. Hence, material development, selection and qualification are critical to the success of these efforts.

Austenitic stainless steels are the most suitable and cost effective materials for the finishing stages of superheaters and reheaters of the USC boilers. Super 304H austenitic stainless steel containing 2.3 to 3 (% wt) of copper is a recently developed grade for use in superheaters and reheaters of USC boilers. Super 304H belongs to 18 % Cr – 9 % Ni system with additions of Copper (Cu), Niobium (Nb), and Nitrogen (N) for precipitation strengthening.
Stainless steels resist general corrosion but are susceptible to localized corrosion such as pitting, and stress corrosion cracking (SCC) in chloride environments. Production of USC boilers requires lot of welding operations. Welding alters the microstructure, phase composition, induce residual stresses, and can affect the mechanical and corrosion properties of materials in contrast to the information of the characteristics of the productionized steel.

In this work a feasibility study to join super 304H by friction welding has been carried out and the microstructural characteristics and mechanical properties of friction welded super 304H austenitic stainless steel tube joints, fabricated using optimized parameters was evaluated. The extent of properties evaluation of friction welded joints is limited in this work, as the occurrence of flash inside the tubes may lead to operational problems in boilers.

Super 304H weld joints were fabricated using CC-GTAW and PC-GTAW processes, both autogenously and with matching filler with Argon as shielding and purging gas. Effect of GTAW processes and filler addition on weld microstructure, room temperature (RT) and high temperature tensile properties (550 °C, 600 °C, and 650 °C), stress corrosion cracking behaviour, and cyclic polarization behaviour of super 304H was evaluated. The important findings obtained from this investigation are listed below.
9.2 Conclusions

(i) Super 304H was successfully welded using friction welding process and the joint exhibited higher tensile strength than the parent metal. The failure occurred at close to the weld interface with a shear like fracture. An empirical relationship incorporating the friction welding parameters was also developed to predict the tensile strength of friction welded super 304H tubes at 95% confidence level.

(ii) In case of GTAW joints, the autogenously fabricated CC-GTAW and PC-GTAW joints resulted in weld metal with austenite matrix and δ ferrite. Boron was found to segregate along the intercellular boundaries to form low melting eutectic and (Fe,Cr)$_2$(C,B)$_6$ borocarbides in autogenous welds. Current pulsing (PC-GTAW) was found to be beneficial in reducing the volume % of eutectic film segregation in weld metal of autogenous joints.

(iii) In case of filler added GTAW joints, the increased Mo, Nb and N addition to filler, suppressed the segregation and precipitation of coarse borocarbides by formation of (Nb,Mo)C clusters or (Nb,Mo) carbonitrides and retained elemental B within the matrix to increase the hardenability of the joint.

(iv) Autogenous GTAW of super 304H resulted in joints with inferior room temperature tensile strength compared to filler added GTA weld joints. PC-GTAW joints of
both autogenous and filler added joints exhibited marginally higher tensile strength (1 %) and ductility than the CC-GTAW joints.

(v) Yield strength, tensile strength and elongation of super 304H parent metal decrease with increase in test temperature. The strain hardening capacity (Hc) of the parent metal increases up to 600 °C and decreases at 650 °C. Three empirical relationships were used to fit the stress-strain curves, such as Hollomon, Ludwik and Afrin and their strain hardening exponent values was found. Ludwik strain hardening exponent value is higher than that of the Hollomon and Afrin’s strain hardening exponent values.

(vi) K-M plots of super 304H parent metal for all test temperatures was characterised by two stage hardening behaviour, with stage III represented by a rapid decrease in strain hardening rate followed by stage IV with relatively constant strain hardening rate. K-M plots of super 304H parent metal shift to lower stresses, with increase in temperature, indicating that the material is temperature sensitive to tensile hardening. The reduction in elongation with increase in test temperature for all joints of super 304H was attributed to the annihilation of dislocations at high temperatures, aided by the recovery process.

(vii) The PC-GTAW joint (both autogenous and filler added) exhibited higher tensile strength and ductility (percentage of elongation) than the CC-GTAW joints at
elevated temperatures. Filler added PC-GTAW joint exhibited higher tensile strength at elevated temperature than other GTAW joints of super 304H.

(viii) SCC resistance of super 304H stainless steel and filler added CC-GTAW joints was determined using constant load SCC test in boiling MgCl₂ solution. It was found that the SCC resistance of super 304H was deteriorated by welding due to the detrimental microstructural changes in the HAZ of the joint and the residual stresses caused by the weld thermal cycles.

(ix) Linear relationships to predict the failure of super 304H parent metal and filler added CC-GTAW joint by SCC were derived from the elongation rate and time to failure. It is possible to extrapolate and predict the time to failure from the corrosion elongation curves. SCC was transgranular in nature at all the test conditions, and the SCC mechanism was found to be anodic path cracking.

(x) The pitting resistance of the super 304H stainless steel was found to be deteriorated by GTAW welding. Both potentiodynamic cyclic polarization test and oxalic acid etch test confirmed that HAZ of the GTAW weld joint is highly susceptible region to pitting corrosion.

(xi) The carbide formation was evidenced by the ditches in microstructure of oxalic acid etched specimen, which disturbs the protective passive film and provides sites for pit initiation. The poor quality of the passive film formed during repassivation,
determined from the cyclic polarization test, aggregates the situation for susceptibility to SCC.

9.3 Scope for Further Research

GTAW is considered to be the mostly widely used welding process in fabrication boilers. Hence, in the present investigation, the mechanical and corrosion properties of GTAW joints of super 304H austenitic stainless steel was taken in to consideration.

(i) The work can be further extended to other fusion and solid state welding processes, which can be of relevance to boiler fabrication.

(ii) The hot corrosion and oxidation studies on welded joints of super 304H can be potential area for further research.

(iii) The effect of long term ageing behaviour on microstructural and mechanical properties of the welded joints of super 304H can be done.

(iv) The creep properties of super 304H welded using other fusion and solid state welding processes can be evaluated.

(v) The microstructural development on long term exposure to elevated temperature can be modelled and simulated using finite element analysis.