Abstract

Welding is inevitable to make permanent and leak-proof joints to specifically establish power plant structures. However, welding introduces inherent heterogeneity in microstructures, mechanical properties and residual stresses across the weldment, which appears to be the source of many premature failures. Hence, it is critical to systematically examine the weld microstructure heterogeneity and its influence on their eventual behaviour during service conditions. On the other hand, post-weld heat treatments (PWHTs) such as post-weld direct tempering (PWDT) and post-weld normalizing and tempering (PWNT) are being developed to overcome the problem of weld heterogeneity. However, the temperature and time of PWHTs are critical to achieve a better combination of homogeneous microstructures and mechanical properties. Considering this, the current research focused on a careful examination of various PWHTs and their subsequent effect on the weld microstructure heterogeneity.

Further, microstructural degradation during high-temperature exposure (HTE) has been studied to understand the material behaviour and possibly prevent premature failures. A lab-scale welding setup with preheating and uniform rotation speed has been designed and developed to achieve defect-free smooth weld beads. Using the setup, welding was performed considering firstly similar materials (i.e., T91 grade steel with T91) and secondly, considering dissimilar material (T91 steel with Super304H) welds.

The impact of PWDT on microstructure evolution, mechanical properties and residual stress was first investigated, considering the effects of Mn + Ni content on lower critical temperature (Ac_1). The welded tubes were heat-treated (PWDT) at three temperatures (720 ºC, 760 ºC and 775 ºC), chosen below their Ac_1 (~ 791 ± 5 ºC), for varied times. The results demonstrate that PWDT temperatures closer to the Ac_1 temperature (i.e., 760 ºC and 775 ºC) significantly impact hardness, tensile strength and % elongation.

Further, investigations reveal that the tempering at 775 ºC – 30 minutes results in achieving optimum mechanical properties (attributed to fine $M_{23}C_6$ type precipitate size) with minimum residual stresses. Additionally, longer tempering time (~ 120 minutes) at 760 ºC and 775 ºC coarsen the $M_{23}C_6$ types of precipitates that initiate de-cohesion at the weak precipitate/matrix interface.

Even after PWDT, microstructure heterogeneity (such as variation in grain size and precipitates size and their distribution) remains across weldment (WM: weld metal, CGHAZ: coarse grain heat affected zone and FGHAZ: fine grain heat affected zone). This indicates that the individual weld zones may exhibit distinct behaviour during service. To simulate in-service conditions (as experienced by power plant weld materials/components) on the weldment microstructural degradation, the PWDT (760 ºC for 120 minutes) heat-treated weld was exposed to HTE at 775 ºC for varied times (5, 100, 500 and 1000 h). Among the weld zones, FGHAZ specifically demonstrated peculiar behaviour. Significant coarsening of $M_{23}C_6$ precipitates and abnormal grain growth have been noticed, possibly due to the enhanced diffusion through the higher grain boundary areas resulting from the finest grain size in this welded zone.

Additionally, the grain growth may have also been accompanied by the recovery of substructures of laths/packets/blocks and unpinning of prior austenite grain boundaries (PAGBs) from the coarse precipitate. Due to this, after HTE, FGHAZ's hardness deterioration was the highest of all the zones. Moreover, the tensile strength and toughness of the weldment after 1000 h of HTE were reduced by 39 % and 57 %, respectively, compared to the PWDT condition and failure that occurred at FGHAZ. Hence, these results suggest that the selective microstructure degradation in FGHAZ, even below the Ac_1 temperature, could be the cause of T91 steel welds premature failure during service. In contrast, after PWNT, the weld microstructure appears stable, where the selective grain growth or precipitate coarsening in

FGHAZ is inhibited even under the same HTE condition. This is attributed to the increase in the grain size, in the FGHAZ region, from 5 ± 2 μm to 13 ± 4 μm, with an enhancement in martensitic morphology (laths, blocks and packets). The microstructure changes after PWNT had also been demonstrated through their creep performance, where the impression creep rate was substantially lower (i.e., ~ 0.5×10^{-8}/sec) for PWNT as compared to the creep rate (~ 5.3×10^{-8}/sec) for PWDT. Similarly, the impression creep rate for PWNT with 1000 h HTE condition is ~ 8.3×10^{-8}/sec compared to the creep rate observed (i.e., ~ 21×10^{-8}/sec) for PWDT with 1000 h HTE condition. Hence, for T91 welds, PWNT outperforms PWDT; further, it was examined to be established for dissimilar metal welds (DMWs).

DMW of T91 and Super304H material induces an extremely heterogeneous weldment. The studies found failures either from FGHAZ on the T91 side due to rapid microstructure deterioration or Super304H side due to sensitization/intergranular corrosion (IGC). To mitigate the heterogeneity across welds, PWNT was employed to homogenize the microstructure in both the materials and compared with PWDT. It was found that after PWDT, there was no impact on grain size across the weldment. Additionally, it resulted in a sensitization phenomenon on the Super304H side. On the other hand, PWNT heat treatment eliminated the critical FGHAZ of T91 side and as well reduced the sensitization on the Super304H side. Furthermore, the microstructural analysis revealed that PWNT heat treatment reduced grain size heterogeneity and decreased the precipitates' size on both sides of the WM. Moreover, the optimal combination of mechanical properties (0.2 % proof stress, tensile strength, % elongation and toughness were 384 MPa, 691 MPa, 22 % and 132 MJ/m^3, respectively) was found in the case of PWNT heat treatment, which is attributed to uniform grain size and fine precipitates. Furthermore, DMW resulted in higher tensile residual stresses on the T91 side, while the Super304H side exhibited compressive residual stress. PWDT and PWNT could reduce residual stresses, although PWNT is more effective due to complete austenitizing.