

This chapter presents a detailed review of the past work done on various aspects of Creep strength enhanced ferritic (CSEF) and Austenitic stainless steel (ASS) weld joint. It concludes with a summary of the past work, identified research gaps, research objectives of present work, and the work plan opted to meet these objectives.

2.1 Problems associated with the welding of creep strength enhanced ferritic Steel and austenitic stainless steel

Despite the fact that dissimilar welding has been used for numerous high-temperature tubular applications, these welds have reportedly failed before the predicted service life (Laha et al., 2012). A significant difference in thermo-physical characteristics, mechanical properties, microstructure, and chemical composition is introduced during the dissimilar metal welding. According to reports, weld fusion zone with varying mechanical and metallurgical properties shortens the service life of dissimilar weld joints (DWJs). In comparison to their parent metal counterparts, a poor stress rupture properties was reported for DWJ of P91/P92 steels with austenitic grade steels (Laha et al., 2012). The DWJ of austenitic grade steel and ferritic steel have been subjected to one or more of the following challenges: (i) mismatch in coefficients of thermal expansion (CTE) ($13.2 \times 10^{-6}/K$ for ferritic steel and $18 \times 10^{-6}/K$ for austenitic grade steel), (ii) carbon migration from ferritic to austenitic steel, (iii) variation in creep properties of steels, (iv) oxide notch formation on ferritic steel side, and (v) soft heat-affected zone (HAZ) formation in ferritic steel (Huang and Wang, 1998). The residual stresses accumulate at the interface of weld metal and ferritic steel due to the CTE mismatch. Ferritic steel with low CTE attempt to prevent the stainless steel weld from expanding that causes a significant localized tensile stresses at interface which leads to the failure of the joint (Williams, 1984). The carbon migration from ferritic to austenitic steel causes formation of a soft zone and hard zone close to the weld interface. The integrity of DWJ can certainly suffer from the presence of such soft and hard zone. (Ranjbar et al., 2018) investigated the carbon migration phenomenon in dissimilar Inconel 617 and A387 steel combinations. They reported that the use of nickel-based filler reduces the carbon migration from low chromium base metal toward high chromium weld metal due to higher nickel content in nickel-based filler. The nickel acts as a diffusion barrier, and thus, no carbon deduced zone (CDZ)/soft zone is formed at low chromium content base metal. (Kulkarni et al., 2019) in their study of dissimilar P91 and SS 316L welding reported that the carbon migration could be reduced to a certain extent with the help of Incoloy 800 and with Inconel 600 interlayer.

Table 1.1: Physical properties of P92 and 304L steel (Jin et al., 2010)

	P92	304L
Crystal structure	BCC	FCC
Density	7700 kg/m ³	8000 kg/m ³
Melting temperature	1450-1510 °C	1400-1450 °C
Co-efficient of thermal expansion	13.2 $\mu\text{m/m/}^\circ\text{C}$	18 $\mu\text{m/m/}^\circ\text{C}$
Thermal conductivity	25 W/m.k	16.2 W/m.k

2.2 Literature review related to the welding process, groove geometry and filler metals

The power plants have various integrated components, and these high-temperature components are mainly joined by the welding process. There is various welding process such as shielded metal arc welding process (SMAW), submerged arc welding process (SAW), gas tungsten arc welding (GTAW) process, laser beam welding process (LBW), and electron beam welding process (EBW), which are used by various researchers to join CSEF steel and ASS (Mirshekari et al., 2014; Ni et al., 2018; Shanmugarajan et al., 2016; Unnikrishnan et al., 2014). Although the GTAW process is still one of the most widely used methods for joining of these materials due to their excellent productivity, the sound quality of weld produced, and consistency in producing good quality of weld during multi-pass welding. The successful DWJs can be obtained by selecting the appropriate filler metal.

The selection of appropriate filler material in dissimilar welding is one of the most critical task. The essential requirement of filler material is that it should have high creep rupture property and high toughness property as the dissimilar ferritic and austenitic weld is supposed to operate at elevated temperature and pressure. The filler metal having intermediate physical and thermal properties of both the parent metal is generally selected for the dissimilar metal joining using GTAW process. Also, the filler metal having chemical composition compatible with the both the base metal is generally selected for the dissimilar material joining. The sound quality of the weld is essential to ensure the structural integrity of the component operating in power plants and industries (Samal et al., 2011). The appropriate filler metal will develop the weld free from defects. The nickel-based filler is most commonly used to achieve defect-free dissimilar joint of CSEF steel and ASS due to their superior mechanical and microstructural properties in severe conditions compared to the others (Kepic et al., 2014; M. Kim et al., 2014). In past years, austenitic filler metal was used to join ferritic and austenitic dissimilar metals. However, the DWJs prepared with austenitic filler result in the premature failure of the components under service due to the carbon migration and formation of the sigma phases (Karthick et al., 2018). Also, due to the carbon diffusion from ferritic steel towards the austenitic stainless steel, the formation of soft carbon depleted zone (also called white bands) occurs at the ferritic/austenitic weld interface (Sirohi et al., 2022). This deteriorates the creep strength of the weld joints (Falat et al., 2014). However, premature failure in service has been reported for these bimetallic metal joints prepared with the iron-based filler metal within 1/3rd of the designed service life. The use of the austenitic filler metal is never recommended for joining of the CSEF steel and ASS, as well as for the weld joint operating at elevated temperature service due to their poor performance at high temperature environment (Bhaduri et al., 1994). The nickel-based filler improves the service life of the weld joint by reducing the carbon diffusion and minimizing the residual stresses at interface. The most commonly used nickel-based filler for joining of dissimilar metal is Inconel 82 (ERNiCr-3), Inconel 625 (ERNiCrMo-3), Inconel 617 (ERNiCrCoMo-1), and Inconel 718 (ERNiFeCr-2) (Liang et al., 2018; Pavan et al., 2015; Shin et al., 2018; Siefert and David, 2014; Yaghi et al., 2013). Based on previous work, the Thermanit MTS 616 filler was found to be suitable for CSEF steel and ASS metal joining (Ren et al., 2019). Use of nickel-based filler rather of austenitic filler can reduce failure tendency caused by carbon diffusion and CTE mismatch. The life of the weld fusion zone get extended by using the filler with intermediate CTE between two base metals (Lee et al., 2007). The nickel-based filler improves the service life of the weld joint by reducing the carbon diffusion and minimizing the residual stresses at interface. The selection of the appropriate filler material for DWJs is essential to achieve desired service life at high temperatures and acceptable mechanical and microstructural properties. The nickel-based filler has been of interest to many researchers to make the dissimilar weldments of CSEF P91/P92 steel and austenitic grade SS304H/304L steel because of its excellent compatibility with both CSEF and austenitic grade steel. The welded joint produced using the nickel-based filler shows enhanced creep strength, high-temperature corrosion, and oxidation resistance. However, the welded joint formed using nickel-based filler shows the degradation in corrosion resistance, toughness, and % elongation mainly because of

the macrosegregation of the alloying elements in inter-dendritic areas (Mortezaie and Shamanian, 2014; Shah Hosseini et al., 2011).

Also, from the various literature reviewed, it was found that groove geometry plays a significant role in DWJs. The narrow groove geometry for the GTAW welding method is one of the most economical methods to join dissimilar metals due to fewer passes required to fill the gap and less filler metal deposition required compared to the conventional groove geometry. The narrow groove geometry requires low heat input, and also use of this design results in less distortion and thermal stresses in weld joints than the conventional groove geometry (Xu et al., 2015). Giri et al. (Giri et al., 2017) investigated the effect of conventional and narrow groove geometry on the residual stress distribution for 25 mm thick 304LN pipes. They observed a 10-15 % reduction in the residual stress magnitude with the narrow groove geometry. The defects such as lack of fusion may frequently occur during the narrow groove welding due to the narrow root gap, if proper attention is not given by the welder (Feng et al., 2017).

2.3 Literature review related to the post weld heat treatment

The mechanical and microstructural properties of the P92 steel change during the welding because of the welding induced heat. Thus, post weld heat treatment (PWHT) is performed after welding to obtain the desired mechanical and microstructural properties. The PWHT also minimizes the welding-induced residual stresses. The temperature control is one of the key parameters in all the heat treatment processes. The parameters such as lower Critical temperature (A_{c1}) play important role in the desired outcome of the PWHT. The PWHT known as tempering is performed below the lower critical transformation temperature. Below A_{c1} , the austenite phase is generally stable. Heating above A_{c1} will result in the formation of austenite. This austenite will transform into the untempered, brittle martensite (if the cooling rate is high enough) or soft ferrite (if the cooling rate is slow) during cooling. This untempered martensite deteriorates the creep properties of the material at low temperatures (Chalk et al., 2011; Shin et al., 2018). The PWHT known as tempering (760 °C for 2h, followed by air cooling) is usually performed for P92 steel to stabilize the metallurgical and mechanical inhomogeneity (Barbadikar et al., 2014). (Shuo et al., 2018) studied the effect of the PWHT on DWJ of P92 steel and super 304H DWJ. PWHT was conducted in a temperature range of 730-760 °C for 2 h to stabilize the austenitic phase and to relieve residual stresses. The improved mechanical properties and relieved residuals stress were observed as a result of heat treatment. The investigation on the effect of PWHT on DWJ of martensitic F6NM and austenitic AISI 347 has been carried out by (Sun and Han, 1994). The PWHT has observed a significant effect on the mechanical properties, and it also reduces the stress corrosion cracking tendency. (Awale et al., 2020) investigated the effect of PWHT on DWJ of P91 and 316LN steel. PWHT has observed a significant impact on the microstructure and mechanical properties of the HAZ formed towards the P91 side, and the substantial change in microstructure was found in terms of the size and distribution of Cr-enriched $M_{23}C_6$ precipitates. PWHT resulted in a reduction in strength gradient across the P91 side. (Maddi et al., 2020) found that PWHT (tempering) at 760 °C gives good microstructure stability and high creep rupture time for the P92 steel operating at a temperature of 600 °C. According to the ASME code, PWHT temperature should not be less than 730 °C. The PWHT at a very low temperature will result in low toughness due to insufficient tempering, while the PWHT at a very high temperature will result in a reduction in the creep strength due to the over-tempering (Wang et al., 2018). Thus, the optimized PWHT parameter of 760 °C, 2h is most commonly used. In this study, PWHT, known as tempering, was performed at 760 °C, 2h followed by air cooling.

2.4 Literature review related to the welding induced residual stresses

The welding process does not only change the microstructure of the material, but it also generates residual stresses. The generation of the residual welding stresses of various magnitude and different nature (like tensile, compressive) may lead to the catastrophic failure of the welded joint. Thus, investigation of the residual welding stress becomes essential for the

safety of the power plant. The average value of CTE of P92 steel is $13.2 \times 10^{-6} /K$, while for austenitic steel, it is $18 \times 10^{-6} /K$ (Akram et al., 2017). This difference in the CTE value between the two materials to be joined result in the high welding residual stresses at the weld interface. The use of nickel-based filler wire having the intermediate CTE value of two materials to be joined (like ERNiCrMo-3, CTE of $14.4 \times 10^{-6} /K$) for the welding helps in gradual variation in the CTE value. Thus, it reduces the overall welding residual stresses at the weld interface. Also, the non-uniform heating and cooling of the various regions at the same time lead to the formation of residual welding stresses of various magnitude and nature. It has been reported that by increasing the number of weld passes and by decreasing the overall heat input, welding residual stresses can be minimized (Zhao et al., 2014). Also, the PWHT reduces the residual welding stresses to some extent. However, PWHT can't completely mitigate the residual welding stresses (Skouras et al., 2014). The tensile residual stresses reduce the fatigue life of the component, promote brittle fracture, buckling, and stress corrosion cracking. The residual stress is induced in DWJ due to non-uniform cooling and heating at the same time, shrinkage due to variable cooling rate at different locations of the joint, and strains developed due to metallurgical phase transformation. The strains are generated due to the solid-state phase transformation and solidification. The residual stresses influence the brittle fracture, fatigue failure, and stress corrosion cracking performance of the welded structures in different aspects. Thus, the precise investigation on residual stresses before and after the PWHT is required for safe service of welded structures (De and DebRoy, 2011).

2.5 Literature review related to the creep and high-temperature tensile properties of the creep strength enhanced ferritic and austenitic stainless steel weld joint

To guarantee the long-term safety and reliable operation of thermal power units in high-temperature environments, it becomes imperative to conduct a thorough investigation into the high-temperature tensile properties and creep strength of these DWJ. The failure of such joints due to the degradation of the microstructure before the predicted service life has been reported in literature (Samuel et al., 2013). The creep rupture behaviors of dissimilar weld joints involving ferritic and austenitic steels are primarily influenced by the ferritic steel side, as it exhibits relatively inferior creep strength compared to the austenitic steel. The austenitic steel is comparatively more stable at high temperature than CSEF steel due to the high amount of the nickel (Ni) and chromium (Cr) elements in its chemical composition. The failure of such joints due to the degradation of the microstructure before the predicted service life has been reported in the literature (Samuel et al., 2013). In the case of creep condition, the ruptures typically occur from one of the following locations: the parent metal of the ferritic steel (Cao et al., 2011a), the HAZ of the ferritic steel (Falat et al., 2012), or at the weld fusion zone and the ferritic steel interface (Matsunaga et al., 2017). (Chen et al., 2012) investigated the high-temperature tensile strength of the T92/TP347H DWJ. The authors reported the fracture from the fine grain heat affected zone (FGHAZ) region of the P92 steel and fracture mode as normal plus shear. Based on the high-temperature tensile test data, the creep rupture strength was also numerically predicted using Goldenberg's model. (Akram et al., 2017) studied the creep behavior of the friction welded P91 and 304 DWJ. They concluded that with the help of the nickel-based interlayers, the creep performance of the DWJ can be significantly improved. It is because of the fact that the major creep failure occur due to the large difference in the co-efficient of the thermal expansion. The nickel-based interlayers having intermediate co-efficient of the thermal expansion gradually reduces the tensile residual stress built-up at the weld interface and prevents the premature failure. (M. Y. Kim et al., 2014a) reported the creep failure from the P92 steel during the short-term duration and from the FGHAZ region during the long-term service condition. It is due to the faster degradation of the microstructure properties at high-temperature service condition. (Seo et al., 2021b) concluded that the heterogeneous microstructure formed in the P92 HAZ region is largely responsible for the creep failure from the inter-critical heat affected zone (ICHAZ) and FGHAZ region of the P92 steel.

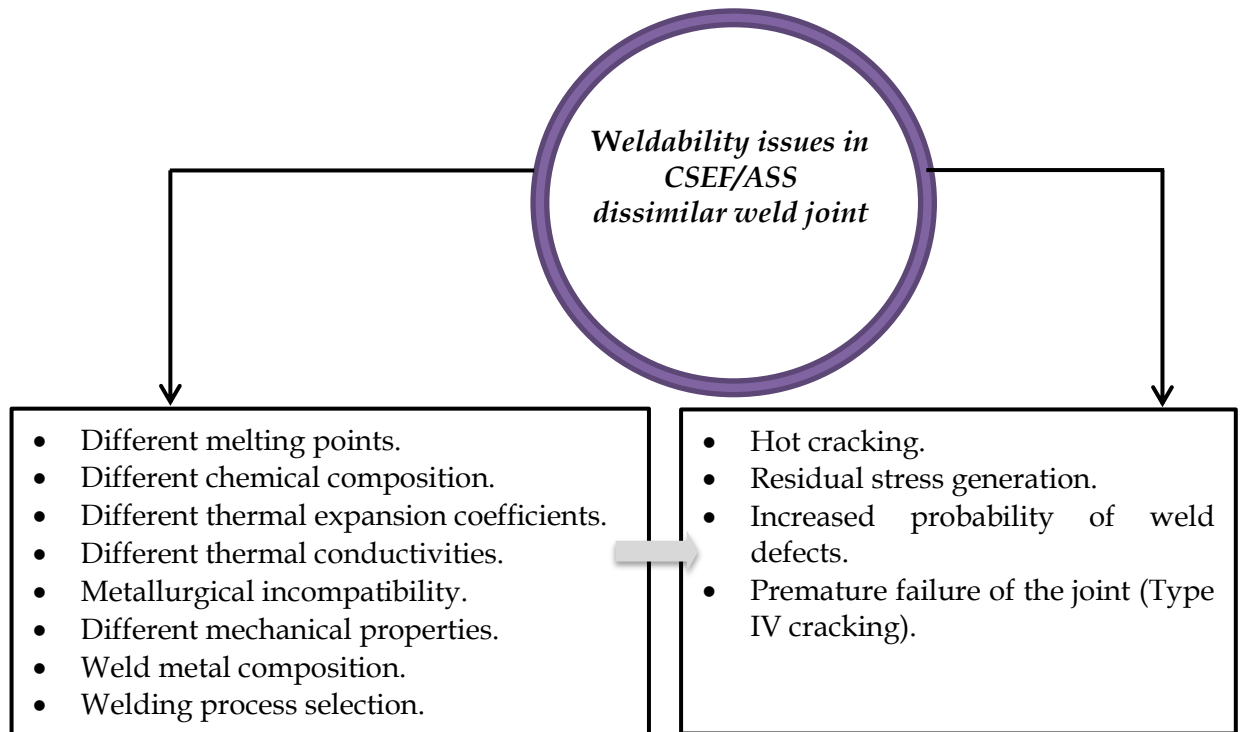
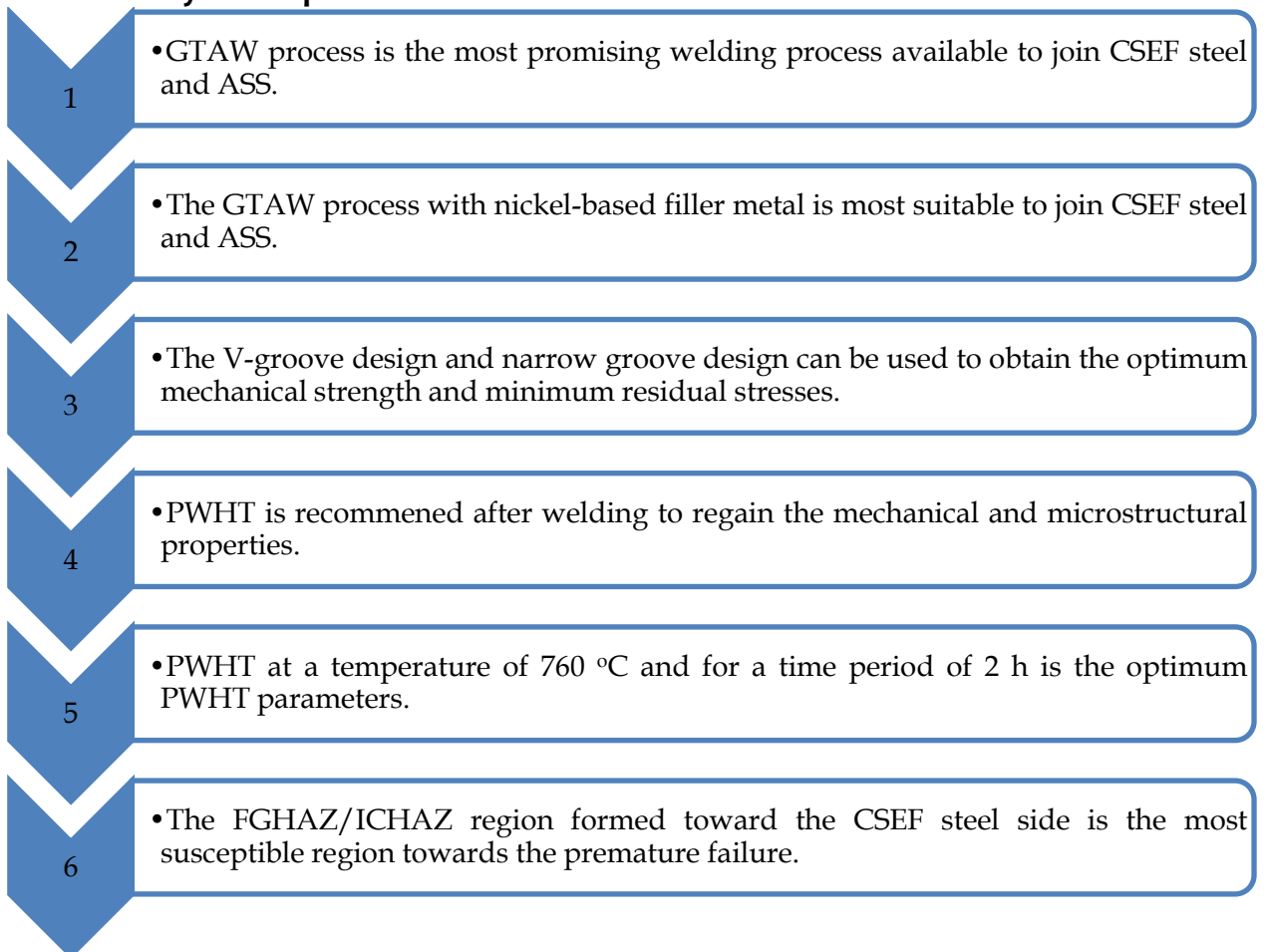


Fig. 2.1: Challenges in welding CSEF and ASS material

2.6 Summary of the past work



2.7 Identified research gaps

The literature review indicated that the very limited research is available in the public domain on the creep performance of the P92 and 304L DWJ prepared with nickel-based filler and ferritic-martensitic filler. The individual behavior of the P91 steel and P92 steel at elevated temperature and at a different stress range is frequently reported in various literatures. However, the combined behavior of P92 and 304L DWJ prepared using nickel-based filler metal is still not available in public domain. The objective of this study is to provide detailed inside about the creep and high temperature tensile behavior and fracture behavior of P92/304L DWJ at different temperature and stress range. The present work will also be helpful for the researcher and reader to understand the effect of nickel-based filler on mechanical, microstructural, and residual stresses properties of P92/304L DWJ. The effect of narrow groove geometry is also discussed in detail concerning microstructural changes, mechanical properties, and residual stresses. The through thickness residual measurement in the weld fusion zone and HAZ for the P92/304L DWJ using deep hole drilling (DHD) technique is completely novel approach. The identified research gap is as follows:

- 1 •The detailed research related to the application of nickel-based filler like ERNiCrMo-3, ERNiCr-3, and ERNiFeCr-2 for the welding of P92 and 304L is still not available in the public domain.
- 2 •The weldability of such dissimilar welds joint is affected by high residual stress. The research related to study on effect of the nickel-based filler on through thickness residual stresses is not reported yet.
- 3 •The detailed study on effect of the groove geometry and PWHT on residual stresses, microstructure evolution and mechanical performance of P92/304L DWJ is not observed in literature.
- 4 •The detailed research related to creep and high-temperature tensile behavior of P92/304L DWJ prepared with such nickel-based filler metal is still not available in the public domain.
- 5 •The detailed research related to the role of nickel-based filler buttering on the structural integrity of the P92/304L DWJ need to be investigated.

2.8 Research objectives and methodology of the present work

R.O-1: To obtain the defect-free P92/304L dissimilar metal weld joint.	Work Plan • Use of GTAW Apparatus for joining the P92 and 304L metal. • To prepare the groove geometry: V-groove and narrow groove geometry. • To identify the welding process parameters. • Selection of various filler metals. • To ensure the quality of the weld joint using non-destructive testing (NDT) method i.e., X-Ray Radiography analysis, Liquid dye penetrant (LDP) test.
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R.O-2: To investigate the effect of the filler composition (nickel-based and ferritic-martensitic filler) and groove geometry on mechanical behavior and microstructure evolution in P92/304L DWJ.	Work Plan • Improvements of Mechanical and Microstructural properties by PWHT. • Macrostructure characterization using Stereo zoom microscope. • Microstructure characterization using Optical Microscope, Field emission scanning electron microscope (FESEM). • Energy dispersive spectroscopy (EDS) and Electron probe micro analysis (EPMA). • To conduct the tensile test. • To conduct the Vickers Micro-hardness test. • To conduct the Charpy Impact toughness test.
R.O-3: Residual stress measurement of weld joint after welding and PWHT Using DHD technique.	Work Plan • Measurement of residual stress of GTAW welded dissimilar welds joint using hole drilling technique using the data logger and hole drilling set-up. • To examine the welding induced residual stresses in the various regions of the dissimilar weld joint i.e., Weld fusion zone and HAZ. • To investigate the effect of groove geometry and filler composition on welding induced residual stresses. • Analyze the effect of PWHT on residual stresses magnitude. • To develop a relation between microstructure behaviors with residual stress variation.
R.O-4: To investigate the high-temperature tensile strength of the P92/304L DWJ.	Work Plan • Macrostructure characterization using Stereo zoom microscope. • Microstructure characterization using Optical Microscope and FESEM. • Fracture surface analysis.
R.O-5: To investigate the creep performance of the P92/304L DWJ.	Work Plan • Macrostructure characterization using Stereo zoom microscope. • Microstructure characterization using Optical Microscope and FESEM. • Fracture surface analysis.
R.O-6: To investigate the role of nickel-based filler buttering on the structural integrity of the P92/304L DWJ.	Work Plan • Macrostructure characterization using Stereo zoom microscope. • Microstructure characterization using Optical Microscope and FESEM. • Mechanical properties investigation.

