Development and Deployment of Welding Technologies for the Indian Sodium-Cooled Fast Reactor and Advanced Ultra Super Critical Thermal Power Programmes

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ABSTRACT

Robust manufacturing technology for Sodium-cooled Fast Reactor (SFR) components necessitates development of various research-backed innovative welding technologies. Prior to the start of construction of the 500 MWe Prototype Fast Breeder Reactor, extensive technology development was planned and implemented for development of welding consumables, procedures and technologies for fabrication of components with stringent specifications. With close interaction amongst design, materials and non-destructive evaluation engineers, materials and welding consumable manufactures, and the fabrication industries, it has been possible to overcome the challenges and establish robust manufacturing technologies for fabrication of all the structural components. Extensive welding is involved in the fabrication of reactor vessels, steam generators, fuel sub-assemblies etc. Further, Activated Tungsten Inert Gas (A-TIG) welding process, along with activated flux developed in-house, has been successfully implemented on various SFR-related components. Also, a computational-intelligence based welding system for online monitoring and control during welding has been developed for obtaining near defect-free welded components. Plasma Transferred Arc Welding process has been deployed for deposition of the chosen nickel-base alloy for hardfacing of SFR components, which require improvement in resistance to high temperature wear, especially galling, of mating surfaces in liquid sodium.

To reduce carbon footprint substantially, India has initiated a national mission programme of design, development and establishment of 800 MWe Advanced Ultra Supercritical (AUSC) power plant having steam parameters of 710ºC / 720ºC / 310 bar. Materials and fabrication technologies play decisive roles in the success of such mission project. For this purpose, two important India-specific high-temperature tube materials, 304HCu austenitic stainless steel (304HCu SS) and modified Alloy 617M, as also large cylindrical forgings of Alloy 617M of up to 800 mm diameter for turbine rotors have been indigenously developed. Development of welding consumables and welding procedure has also been established for TIG welding of the tubes, including the 304HCu SS/Alloy 617M dissimilar joint. Based on the tensile and creep tests properties, welding consumables for the tubes and their dissimilar joint have been finalized. Technology for dissimilar metal welding between Alloy 617M and 10Cr-steel forgings for turbine rotors has also been developed. Using narrow-gap TIG welding process, the dissimilar metal weld between 200 mm Alloy 617M and 10Cr-steel have been produced by directly welding the two forgings using Alloy 617 filler wire. The weld exhibited no lack-of-penetration defects and passed dye-penetrant, radiographic and ultrasonic examinations. Similarly procedure for NG welding of superheater headers has also been demonstrated.

The details of the Indian efforts towards development and deployment of welding technologies for application to the fabrication to components for the Indian programmes for SFR-based nuclear power and AUSC thermal power plant are presented and discussed.

1.0 WELDING TECHNOLOGIES FOR INDIAN SODIUM-COOLED FAST REACTOR PROGRAM

The main objective of the design and development of 500 MWe Prototype Fast Breeder Reactor (PFBR) **(Fig. 1)**, is to demonstrate the techno-economic viability of sodium-cooled fast reactors for commercial deployment. PFBR will also enable validation of first-of-a-kind design concepts and the experience gained during operation and maintenance of mechanisms, components and sensors in the sodium environment and at reactor operating temperatures (550ºC). This will also lead to standardisation of technologies for the adoption in the series of future sodium-cooled fast reactors. A rigorous technology development phase though proactive interactions with the fabrication industry, backed by wide-spectrum R&D in the science and technology of welding and hardfacing, was essential to ensure that a robust fabrication technology is established for each component. This enabled successful fabrication of all the components by Indian fabrication industries.

Austenitic stainless steel (SS) is the major material of construction. The material for core structural components, viz. fuel cladding tubes and hexagonal wrapper, are made of Alloy D9, a 15Cr-15Ni-2.3Mo Ti-modified austenitic SS. Alloy D9 has an optimised Ti/C ratio of 6 and 20% cold-work for improved void swelling resistance that would enable achieving fuel burn-up of 100 GWd/t. The reactor structural components, whose service temperatures are above 427ºC, are made of 316LN SS containing 0.06-0.08 wt-% nitrogen. The safety vessel, inter-mediate heat exchangers etc., whose service temperatures are below 427°C, are made of 304LN SS. The steam generators are made of modified 9Cr-1Mo steel.

The size and thickness of the major reactor components vary widely. The Safety Vessel, which is the outermost vessel that contains the reactor core, has 13.5 m inner diameter, 12.5 m in height and wall thickness of 20 mm for the cylindrical portion. The Main Vessel is slightly smaller in diameter (12.9 m inner diameter) and larger in height (12.94 m) and is made of 25 mm thick plates for the cylindrical portion. The Grid Plate assembly, in which the fuel subassemblies rest, is made of two large circular plates of more than 6 m diameter and 60 mm thickness. The Roof Slab **(Fig. 2a)** is a massive box-type structure (12.9 m diameter and 1.8 m height), in which the top and bottom plates interconnected by vertical cylindrical shells and radial stiffeners welded to them, is fabricated mostly from 30 mm thick carbon steel plates but also has some components made from plates of much higher thickness. Similarly, the once-through type steam generators (SGs) **(Fig. 2b)** made of modified 9Cr-1Mo (grade-91) steel are 25 m in length, and are made from 12 and 30 mm thick plates for the shells and headers, 150 mm thick forgings for the tubesheet, and of 23 m length and 2.6 mm wall thickness for the tubes (547 tubes per SG).

Development of various research-backed innovative technologies in the areas of welding, were extensively utilised in the fabrication of reactor vessels, steam generators, fuel sub-assemblies etc. Activated Tungsten Inert Gas (A-TIG) welding process, along with activated flux developed in-house, has been successfully implemented on various components. Also, a computational-intelligence based welding system for online monitoring and control during welding is developed for obtaining near defect-free welded components.

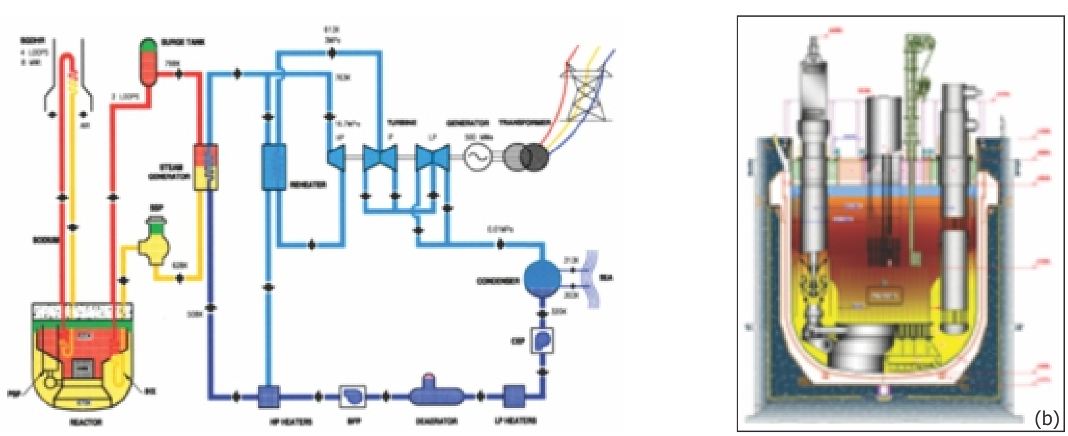


Fig. 1: (a) Schematic of heat transport flow sheet of PFBR; (b) Reactor assembly – major components

(a)

(b)

Fig. 2 : (a) Roof slab of PFBR; (b) Steam generators of PFBR

1.1 Welding of Austenitic Stainless Steels

Various codes for fabrication, such as RCC-MR and ASME Section III, provide for hot cracking tendency of austenitic SS during welding by either specifying limits on ferrite content in weld metal or by weldability tests. RCC-MR specifications for welding filler materials make a distinction for ferrite content based on service temperature. As per RS 3334, 5-15% ferrite is specified for components operating below 375 C. For components operating above 375 C, these limits do not apply and the user must specify ferrite limits. Weld ferrite content is determined by either Schaeffler/DeLong diagram or by magnetic saturation method. When ferrite content of the deposited weld is below 5%, RS 2536 stipulates a groove cracking test for qualification of welding consumables as per RS I 900 or 930. Filler materials or electrodes must ensure freedom from cracking, including crater cracking. ASME Section III NB-2433.2 does not make a distinction based on service temperature but accounts for hot cracking tendency by specifying a minimum ferrite level as per WRC-92 ferrite diagram. Delta-ferrite is restricted in weld metals intended for elevated temperature service because it results in poor creep properties due to its microstructural instability under service conditions.

The current code stipulations rely on conservative tests and additional requirements such as ferrite level specification to provide for resistance to cracking susceptibility. However, the codes do not address adequately the necessary tests for hot cracking behaviour of weld metals intended for high temperature service. The possibility of heat-affected zone (HAZ) cracking in base metal and multipass weld metal are not taken into account in the codes. There was, therefore, need for detailed weldability evaluation to obtain clear quantitative guidelines for excluding possibility of cracking while at the same time avoiding excessive conservatism.

1.1.1 Development of special-purpose welding electrodes

The specifications for welding consumables were drawn up to ensure good resistance to cracking, and also included nitrogen level (0.06-0.10%) comparable to that of the base metal to ensure creep properties comparable to that of the base material. This necessitated developing special welding consumables. For TIG welding, which is used mainly in root pass and in thin section piping, ER16-8-2 wire in accordance with AWS/ASME specification was chosen mainly based on the experience during construction of the Fast Breeder Test Reactor. This filler was developed indigenously and used for TIG welding in fabrication of all components and piping of 304LN SS and 316LN SS. However, weld metal composition for shielded metal arc welding (SMAW) electrodes is significantly different from the corresponding AWS/ASME specification (**Table 1**). Carbon and nitrogen levels are chosen to ensure (C+N)min is 0.105% to ensure weld creep rupture strength at least equal to base metal. Also, Ti+Ta+Nb contents are limited to ensure good weldability. These modified E316-15 electrodes meeting the specifications were developed and manufactured in collaboration with Indian electrode manufacturers [2]. This developmental experience has shown that the identification of critical problems in production and their resolution through collaborative efforts, wherever necessary, have contributed to the success.

Table 1 : Composition of welding consumable for PFBR E316-15M & ASME SFA 5.4 E316L-15 specifications

Element	C	Cr	Ni	Mo	N	Mn	Si	P	S	Ti+Nb +Ta	Cu	Co	B	FN
ASME	0.04 max	17-20	11-14	2-3	NS	0.5-2.5	0.9 max	0.04 max	0.03 max	NS	0.75 max	NS	NS	3-10
PFBR	0.045-0.055	18-19	11-12	1.9-2.2	0.06-0.10	1.2-1.8	0.4-0.7	0.025	0.02	0.1	0.5	0.2	0.002	3-7
Weld metal	0.05	18.5	11.1	1.9	0.1	1.4	0.46	0.006	0.025	<0.1	<0.05	<0.05	0.001	3-3.9

Table 2 : Mechanical properties of E316-15M electrodes of PFBR

Properties	YS (MPa)	UTS (MPa)	Elongation	Charpy U-notch (Toughness (daj/cm^2))	
				As Swlded	750°C/ 100h aged
Specified	350 min.	550 min.	35 min.	7.0 min.	3.0 min
Achieved	504	621	40	8.2	4

The most challenging part of this development was to achieve the toughness specified after the 750°C/100h ageing heat treatment **(Table 2)**. This requirement was included to assess the susceptibility of the weld metal to embrittlement by sigma-phase formed during high-temperature exposure by transformation of the delta-ferrite. It was found that the Mo content has to be carefully controlled in the lower limit of the specification to ensure this. Another challenge was to improve the slag detachability of the deposited weld metal. Poor slag detachability of the weld metal often necessitates extensive grinding and rework. Many trials batches were made to optimize both the composition of the weld metal and flux to meet these demanding requirements. All the welding of various reactor components made of 316LN SS has been carried out by the electrodes supplied by the Indian electrode manufacturers who have successfully developed this electrode.

1.1.2 Weldability evaluation

Detailed weldability assessment of 316LN SS, E316-15M weld metal and 316L SS (for comparison) was carried out by application of strain during welding and assessing the deposited weld for cracking using the Varestraint test in which the criteria used included Total Crack Length (TCL), Maximum Crack Length (MCL) or Brittleness Temperature Range (BTR). In stainless steels, the BTR, the temperature range over which weld metal is prone to cracking during solidification due to presence of low-melting eutectics, and solidification cracking are strong functions of the solidification mode given by WRC Cr_{eq}/Ni_{eq} ratio. The BTR values are low for high Cr_{eq}/Ni_{eq}, i.e., above a value of 1.3, which corresponds to a ferritic solidification mode. Stainless steel base and weld metals solidifying in the FA (ferritic/austenitic) mode of solidification have BTR of 30°C or lower and are resistant to solidification cracking. The cracking tendency increases with decreasing Cr_{eq}/Ni_{eq} ratio, i.e., decreasing ferrite content, while the solidification mode changes to AF (austenitic/ferritic) and to A (fully austenitic). The E316-15M weld metal is in the safe regime with FA solidification mode **(Fig. 3a)**.

Solidification cracking is a function of the level of impurity elements, S and P, and minor elements such as Ti and Si. Although direct correlation between composition, impurity levels and cracking was not available, the diagram of Kujanpaa et al, viz. Hammar-Svensson (H-S) Cr_{eq}/Ni_{eq} vs. P+S content was used [3]. In this diagram (**Fig. 3b**; BTR values at 4% strain in parentheses), susceptible compositions lie in the region of $Cr_{eq}/Ni_{eq} < 1.5$ and P+S > 0.015%. Much higher impurity levels can be tolerated for higher Cr_{eq}/Ni_{eq} ratios and such compositions were not susceptible to cracking. The unstabilised stainless steels fit reasonably well into the diagram, with low-BTR compositions finding a place in the less susceptible regions and high-BTR compositions are placed in the "highly susceptible" portion.

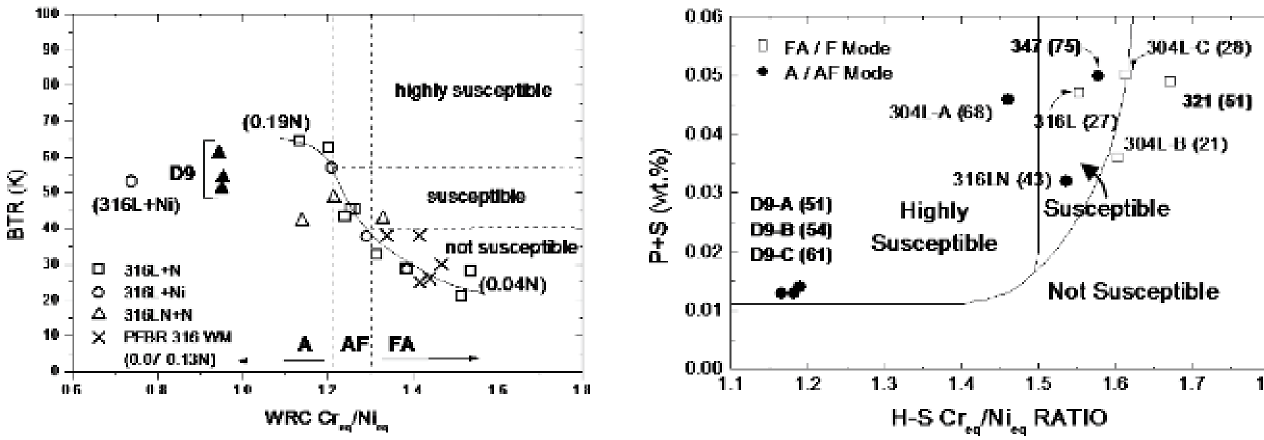


Fig. 3 : (a) Solidification cracking in 316LN and E316-15M weld; (b) Modified Suutala diagram for hot cracking

Extensive studies were carried out on the effect of N on fusion zone and HAZ cracking in these materials [4]. The essential observations from these studies are that N has no detrimental effect on cracking if Cr_{eq}/Ni_{eq} is maintained to obtain a favourable solidification mode in the weld metal. N could be detrimental if ferrite is absent or solidification mode becomes austenitic (A) and when S > 0.01%. This situation is possible during autogenous welding of base metal or when HAZ cracking is envisaged. During structural welding of components, risk of cracking during autogenous welding is small due to stringent specifications, particularly for impurity elements. HAZ cracking is a strong function of ferrite content or ferrite potential of underlying material, but is likely only in extremely high restraint situations. Both these factors are therefore not a serious concern during structural welding.

Application of Varestraint test criteria such as crack lengths and BTR to practical welding situations is complicated as in the actual case, strain, strain rate and stress are difficult to quantify as a function of weld geometry. Investigations showed that the TCL parameter is subject to variations because of weld bead geometry, while BTR is not influenced by these factors that are related to fluid flow effects in the weld pool. For the E316-15M weld metal with limits of ferrite content of 3-7 FN is located in the FA mode of solidification and would essentially be free from hot cracking in the weld metal and HAZ.

1.2 Welding of Modified 9Cr-1Mo Steel

The major technological issues in weldability of modified 9Cr-Mo (grade-91) steel are the determination of the critical preheat-temperature to avoid hydrogen assisted cracking (HAC) and achievement of adequate toughness in the weld metal. Though Section IX of ASME code stipulates post-weld PWHT at a minimum of 700°C for 1 to 2 hours for grade-91 steel, it does not address the issue of preheat temperature. On the other hand, developers of this alloy recommended a mandatory minimum preheat temperature of 200°C. The job thickness, hydrogen content of the electrode, carbon equivalent, and weld heat input need to be considered together to determine the preheat temperature required to prevent cold cracking. International experience shows that the critical preheat temperature is a sensitive function of composition, but the results of various studies are not conclusive.

Achieving good toughness in the weld metal, especially in those produced by processes that involve fluxes (like SMAW, SAW and FCAW) has been an uphill task ever since the development of grade-91 steels. The high impact energy of TIG welds even in as-welded condition could be attributed to the clean TIG process, low oxygen content (< 20 ppm) in the TIG weld metal compared to the MMA weld (400 ppm) and use of higher number of passes than SMAW. During initial stages of development, it was found that achieving good toughness in weld metal with composition optimized for plate or pipe materials is difficult. Systematic studies on effect of various alloying elements on weld metal toughness revealed that Ni is beneficial while Nb and Si have deleterious effect on toughness. As this material is meant for high temperature application, many standards for these consumables do not specify toughness for the weld metal. Accordingly, Ni was added to the welding consumables, and Nb and Si were reduced. Hence, when SMAW process was considered as one of the welding processes for fabrication of steam generators, a separate specification was drafted for welding electrodes so that the weld metal meets the desired toughness and RTNDT requirements. Accordingly, it was specified that for production of electrodes core wire with composition similar to that of the base metal shall be used (non-synthetic electrodes). Also, an upper limit of 1.5% for Ni+Mn was specified so that PWHT temperature would be lower than the transformation temperature for this steel, and impurity elements of S and P were kept at lower limits while composition range for major alloying elements were kept in a narrow range.

For steels with Cr > 9%, microstructure of weld can contain a small volume fraction of delta ferrite in both the HAZ and the weld metal. Toughness of both HAZ and weld metal is found to decrease with increase in volume fraction of delta-ferrite. Delta-ferrite decreases the creep properties of grade-91 weld metal. Accordingly, compositions of both base metal and welding consumables are optimized to have no delta ferrite in the weld metal or HAZ.

1.2.1 Development of welding electrodes

Electrodes based on the stringent specifications (AWS classification E9016-B9 of ASME section II-C SFA-5.5 with modified/additional requirements) **(Table 3)**, were developed with Indian electrode manufacturers. The weld metal of one of the synthetic electrodes, made from mild steel core wire, met the specification. Only the electrodes that are developed as per the composition requirements of the specifications possess minimum requirement of 45 J at 20°C after PWHT at 760°C for 3 hours. Results of impact tests on the weld metals produced from these electrodes **(Fig. 4)** showed that most of the commercially available electrodes do not meet the toughness requirement as per PFBR specification.

For the weld metals that met the composition requirements of PFBR specifications, RTNDT was determined from a combination of drop weight test (ASTM E 208) and impact test. For the weld metals of non-synthetic electrodes developed, this value was found to in range of –3 and –5°C. The recommended temperature for hydro-testing of the components is 33°C above the RTNDT determined for the material of construction for the component. This means, hydro-testing of the components fabricated using these consumable (in this case SGs) can be conducted at ambient temperature (~30°C). It is interesting to note that the weld metal of a synthetic electrode had RTNDT much above the room temperature and hydro-testing of a component made using such welding consumable would require use of hot water.

Table 3 : Chemical composition of weld metals from SMAW electrodes

Elements	PFBR	SMAW weld metals						
		E1	E2	E3	E4	E5	E6	E7
C	0.08 - 0.12	0.09	0.06	0.062	0.1	0.085	0.10	0.1
Cr	8.0 - 9.5	9.00	9.8	9.0	8.64	8.30	9.00	9.0
Mo	0.85 - 1.05	1.0	0.8	1.1	0.94	1.0	1.00	1.0
Mn	0.5 - 1.20	0.55	0.6	1.5	0.7	0.7	0.70	0.75
Si	0.15 - 0.30	0.20	0.35	0.3	0.25	0.28	0.24	0.32
S	0.01 max	0.007	0.015	0.01	0.01	0.015	0.012	0.008
P	0.01 max	0.015	0.015	<0.007	0.006	0.015	0.009	0.01
Ni	0.4 - 1.0	0.6	0.1	0.9	0.6	0.5	0.70	0.52
Nb	0.04 - 0.07	0.06	-	0.03	0.05	0.069	0.06	0.065
V	0.15 - 0.22	0.07	0.012	0.012	0.19	0.004	0.17	0.21
N	0.03 - 0.07	0.033	0.025	0.03	0.046	0.025	0.055	0.06
O	NS	0.07	0.05	0.04	--	--	0.068	0.08
Cu	0.25 max	0.05	0.05	< 0.05	0.03	0.05	<0.050	
Al	0.04 max	0.034	0.034	-	0.003	-	<0.01	

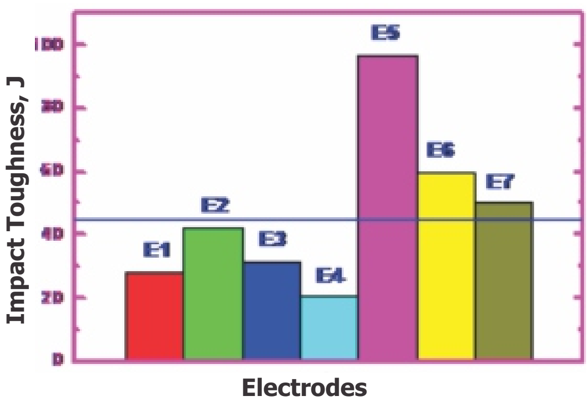


Fig. 4 : Impact toughness of different grade-91 welding electrodes

1.2.2 Fabrication of steam generators

Steam generators (SG) **(Fig. 5)** is one of the most critical components of PFBR because in this component high temperature sodium flows in the shell side and water/steam in the tube side and the boundary separating them is the tube wall of thickness of 2.3 mm. Any leak in the tube or in the tube-to-tubesheet joint can result in direct sodium-water reaction with dangerous consequences. As SGs are made of grade-91 steel, this necessitates a dissimilar joint between stainless steel piping headers of grade-91 steel. Unlike austenitic SS, PWHT after welding is mandatory for welds of this steel and this is another challenge that needs to be overcome during fabrication of SGs. As the steam generators to be subjected to hydro-testing, minimum toughness requirement has been specified for both the weld metal and base metal. Hence choice of welding process and consumable that would ensure good toughness for the weld metal was also a challenge to be overcome for SG fabrication.

Even though the natural choice of welding procedure for thick section welding of the SG shell, tubesheet and headers would have been a combination of TIG (for root pass) and SMAW (for remaining pass), the all TIG process using hot-wire Narrow Gap TIG (NG-TIG) process was chosen for the SGs of PFBR. This eliminated the uncertainty over toughness of the weld metal and the requirement of subzero RTNDT could be easily met. The impact toughness obtained for the all GTA weld metal was ~75 J in contrast to ~43 J obtained for weld metal produced by TIG+SMAW process, which also had high scatter. In addition, the risk of cold cracking could also be reduced considerably by adopting the NG-TIG process. This is also important considering the considerably time gap that would exist between the welding and PWHT during fabrication of such huge components and difficulty in conducting localized PWHT around the welds. In fact, the hot-wire NG-TIG process was employed first time in India for fabrication of PFBR steam generators.

Dissimilar metal welds (DMWs) between austenitic stainless steel and modified 9Cr-1Mo steel have long been recognised to pose a potential problem, because of large thermal stresses generated due to difference in thermal expansion characteristics of the two steels. Thermal cycling during power plant operation plays a major role in premature service failure of this joint. Although similar failures are reported in creep-rupture tests, there is general agreement that in operating plants, stresses responsible for failure of this DMW are due to thermal cycling that occurs during plant start-ups and shut-downs. Laboratory test results and service experience have shown that a significant improvement in service life of this DMW can be achieved by using Ni-base welds instead of austenitic SS welds. However, service failures of DMWs with Ni-base welds have also been reported. Indeed, Ni-base welds only buy more time, but eventually fail before the plant's design life. Among various approaches attempted for development of improved DMWs, one approach is a trimetallic DMW with transition piece having coefficient of thermal expansion (CTE) intermediate to the ferritic and austenitic steels for obtaining a more gradual change in CTE and consequent decrease in magnitude of stresses from thermal cycling. Alloy 800, the most attractive choice for the transition piece, reduces hoop stress near the root of the ferritic steel by 37%, besides providing excellent resistance to oxidation and creep at elevated temperatures.

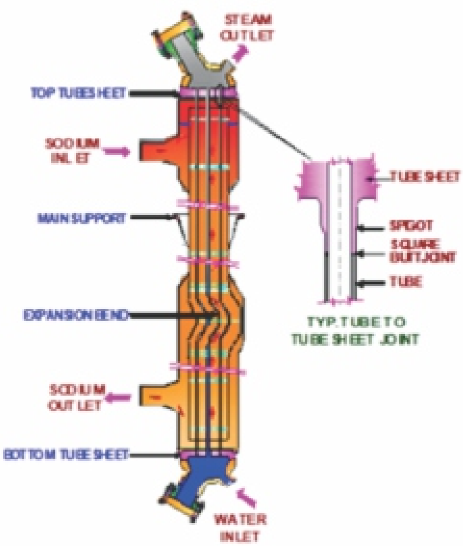


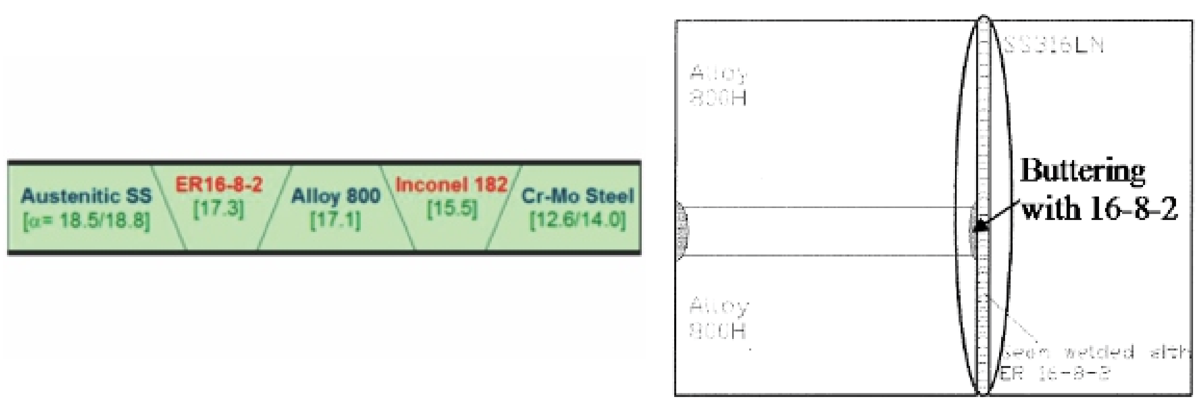
Fig. 5 : Schematic of steam generator of PFBR and its tube-to-tubesheet joint configuration

Numerous reports available on premature failures of these DMWs in fossil power plants worldwide encouraged us to carry out a detailed systematic study on the performance of the DMW between 316LN SS and grade-91 steel much before actual SG fabrication was taken up. A new trimetallic DMW configuration, which would last for entire life of the plant, was developed using a transition piece of Alloy 800. Comprehensive work was carried out on choice of welding consumables, evaluation of hot cracking susceptibility, high temperature stability of weld interface, and service performance using thermal cycling tests [5]. Based on these investigations, the trimetallic DMW joint configuration was evolved for joining SG header with SS piping **(Fig. 6a)**, in which Inconel 82/182 is used for the grade-91/Alloy 800 joint and ER16-8-2 for welding the Alloy 800/316LN SS joint. Performance evaluation by thermal cycling tests indicated a four-fold increase in the life of this joint with the trimetallic configuration as compared to bimetallic configuration. Accordingly, for PFBR, the trimetallic joint configuration has been adopted.

In spite of extensive studies conducted and experienced gained on this trimetallic joint, this dissimilar weld did give some surprises during actual fabrication of SG. The intermediate pipe piece of Alloy 800 was produced by rolling Alloy 800 plate and L-seam welding it with Inconel 82 into a pipe. However, during C-seam welding of 316LN SS and Alloy 800 pipes using ER16-8-2 welding consumable, hot cracks developed at the L-seam/C-seam junction. Consequently, the welding procedure for this location was modified to include buttering of the Inconel weld area with 16-8-2 weld metal prior to C-seam welding **(Fig. 6b)**.

1.3 Activated Tungsten Inert Gas (A-TIG) Welding

In 1960, the Paton Electric Welding Institute Ukraine, developed an effective improvement to the TIG welding process, designated as active tungsten inert gas welding (A-TIG). Before welding, a thin layer of an inorganic powder, known as activating flux, is coated on the surface to be welded. This results in increase in the depth of penetration by a factor of 1.5 to 3 when compared to single pass manual TIG welding. The advantages offered by this process include (a) ensuring good penetration in welding of thin sections welding of materials like austenitic stainless steels which are known for poor depth of penetration, (b) avoiding edge preparation for thickness up to 10 mm, (c) reduction in both time and cost for edge preparation and (d) avoiding the use of filler wire. The A-TIG welding process with a new flux has been successfully developed for joining both 304 and 316 grades of austenitic SS [6]. The innovation in flux formulation has resulted in improvement in creep rupture properties and toughness [7]. **Fig. 7(a)** and **Fig**. **7(b)** compare the weld penetration in normal TIG and A-TIG welding processes. The A-TIG process, along with activated flux developed, has been successfully used in fabrication of fuel subassemblies (FSA) required for testing, and the hexagonal wrapper of FSA being welded using A-TIG process is shown in **Fig. 7(c)**. The wall thickness of the sheath is 3 mm and the procedure considered earlier involved edge preparation, filler addition and two pass welding. All this could be avoided and welding could be completed with more speed (70% more than SMAW). Subsequently, this process has been used for fabrication of many other components. **Fig. 7(d)** shows the welding of a shell structure of 304L SS of 3 mm



(a) (b)

Fig. 6 : (a) Schematic of configuration of the trimetallic transition joint adopted in PFBR (number below each material denotes mean CTE, in m/m/C, upto 600°C); (b) Modified procedure adopted to avoid hot cracking at the L-seam/C-seam junction

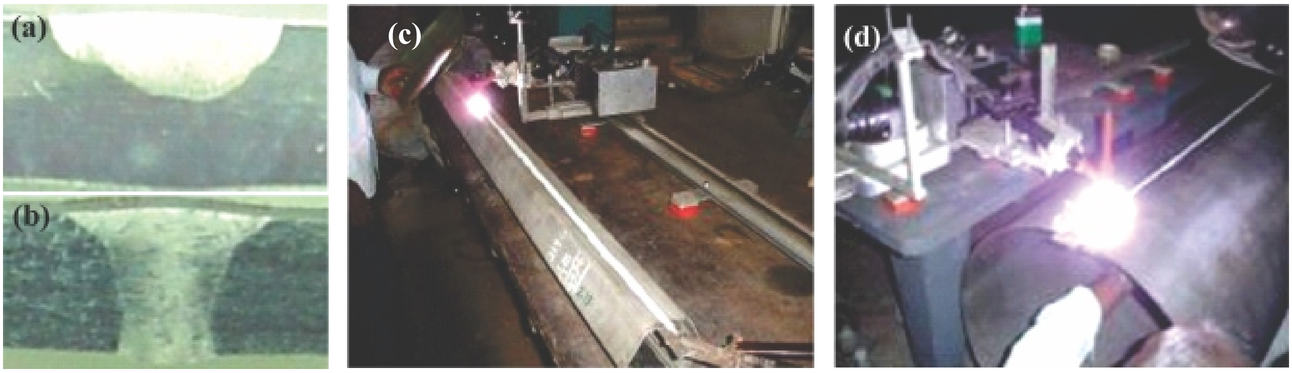
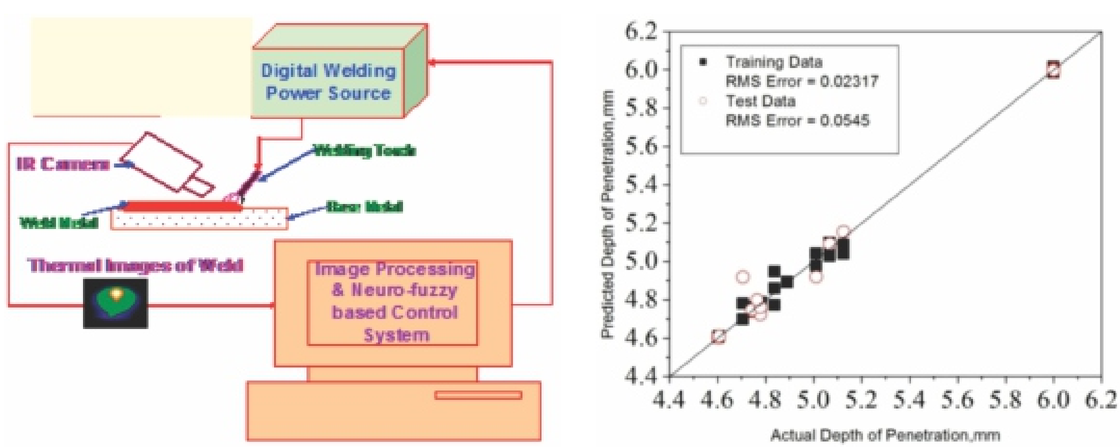


Fig. 7 : (a) Shallow penetration in conventional TIG welding; (b) deeper penetration in A-TIG welding; (c) A-TIG welding of hexagonal sheath of fuel subassemblies; snd (d) A-TIG welding of cylindrical shell for a water storage tank

thickness meant for water storage tank. The A-TIG based welding procedure has also been developed for welding of the 316LN SS foot to the Alloy D9 hexagonal wrapper for the FSA of PFBR. A maximum thickness of 12 mm of austenitic stainless steel has been welded so far employing the A-TIG process using the activated flux developed, which is patented [8].

1.4 Computational Intelligence based Welding for Online Monitoring and Control

Real-time monitoring and control of weld processes is gaining importance due to the requirement of remote welding process technologies. Hence, it is essential to develop computational methodologies based on hybrid intelligent techniques for predicting and controlling the depth of penetration and weld bead width. Welding being a thermal processing method, infrared (IR) sensing using IR sensors are most extensively used technique for sensing, monitoring and control of the welding process **(Fig. 8a)**. The basis for using IR imaging lies in the fact that an ideal welding condition would produce surface temperature distribution that show a regular and repeatable pattern. Any variation or perturbation should result in discernible change in the thermal profiles. IR images have been recorded in real-time during A-TIG welding of 6 mm thick 316LN SS weld joints. Various current values were used to produce different depths of penetration in 6 mm thick weld joints. From the acquired IR images, image features were extracted using Cellular Automata image processing algorithm. The current and the extracted features from the IR thermal images are used as inputs while the measured depth of penetration and weld bead width are chosen as the output of the respective hybrid intelligent technique based models. **Fig. 8(b)** shows the comparison between the model predicted depth of penetration and the measured depth of penetration values. A good correlation between the measured and



(a) (b)

Fig. 8 : (a) Schematic of a computational inteligence based welding system, and (b) comparison between the model predicted and measured depth of penetration values.

predicted values of weld bead width and depth of penetration were observed in the developed models [7]. These developed models can find application during the real time control of the welding process.

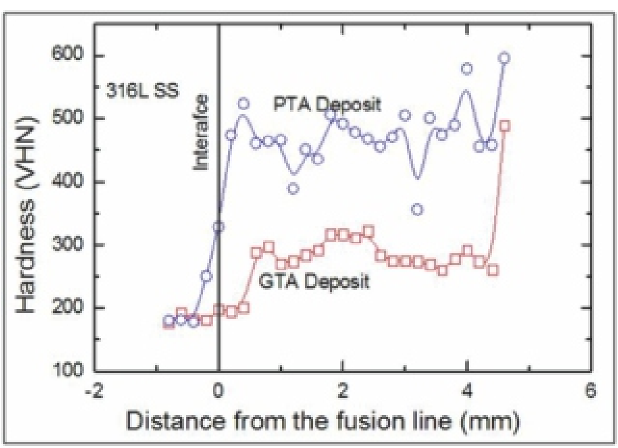
1.5 Hardfacing with Nickel-Base Alloy

Metallurgical studies revealed that the hardness and microstructure of the TIG deposit of the nickel-base hardfacing alloy is significantly affected by dilution from the base metal with the width of the softer dilution zone (of up to 2 mm) often exceeding the recommended final hardface deposit thickness [9]. Also, certain components, like Grid Plate sleeves of about 80 mm inner diameter, which required hardfacing deep inside the inner surface of the sleeve, were not amenable for hardfacing by conventional processes like TIG unless major design concessions were permitted. Hence, the more versatile plasma transferred arc welding (PTAW) process was chosen to ensure that the width of the dilution zone could be controlled to as low as 0.2 mm **(Fig. 9a)** by optimising the deposition parameters [10]. An Indian fabricator designed and developed a suitable miniature PTAW torch **(Fig. 9b)** for hardfacing the inner surface of Grid Plate sleeves. The PTAW process was qualified and has being used for hardfacing of all the necessary components of PFBR.

1.5.1 Hardfacing of Grid Plate Assembly

The Grid Plate assembly of PFBR is a massive structure consisting of a two plates (top and bottom) about 6.5 m in diameter and comprises large number of sleeves in which the foot of fuel sub assemblies rest. The Grid Plate rests on the Core Support Structure that also acts as boundary between the cold and hot sodium in the reactor. Both the Grid Plate and the Core Support Structure are made of 316LN SS and are immersed in flowing sodium and remain in contact throughout the reactor life (at least 40 years). Hence, there should not be any self-welding between these components at their contact locations. Therefore, the design requires hardfacing on two annular grooves machined on the bottom plate of the Grid Plate. These grooves are located near the periphery of the bottom plate and hence, the diameters of these grooves are similar to that of the Grid Plate itself, with the total circumferential length of each hardfaced deposit being about 21 m. These components are designed to ensure that area of contact between Grid Plate and the Core Support Structure is confined to these hardfaced grooves on the bottom plate.

During technology development of the Grid Plate (using plates of similar dimensions as for the actual PFBR Grid Plate), extensive cracking of the deposit was observed when deposition was carried out as per the procedure finalised initially based on trails carried out on a 1000 mm diameter plate of 80 mm thickness. Subsequently a detailed review of the groove design, welding process, procedure, heat treatment etc. was undertaken. The groove width was reduced from 45 to 20 mm and the groove angle increased from 30 to 60. This enabled to carry out hardfacing in single layer and single pass of deposition. Preheat temperature for deposition was increased from 500 to 650°C, and furnace for preheating and stress-relieving heat treatment was modified to ensure that temperature variation across the component during heating or cooling is reduced considerably. Insulation was also improved to reduce heat losses. It was also decided to carry



(a)

(b)

Fig. 9 : (a) Hardness profiles for Colmonoy hardface deposits made by TIG (GTA) and PTAW processes; and (b) Hardfacing of grid plate sleeve (inner diameter ~80 mm) using indigenously designed PTAW torch.

out hardfacing continuously using four PTAW machines positioned on a circular track, which is concentric to the bottom plate. Machine controls were suitably modified to have smooth deposition between starting and ending locations of the deposits, which were found to be more prone to cracking than the other locations of the deposit. New trials were taken up during technology development for hardfacing of the Grid Plate and cracking of the deposits reduced considerably in these attempts. The process was further refined and it was demonstrated on the Grid Plate for technology development that crack-free hardface deposit meeting all design requirements could be made using this improved procedure.

After successfully demonstrating the procedure on the technology development Grid Plate, hardfacing of the bottom plate of the PFBR Grid Plate was taken up **(Fig. 10)**. Due to the above prior experience, it was possible to achieve much better control over temperature during heating and the heat treatment stages. Deposition was carried out simultaneously using four PTAW machines mounted on the track, 90 apart. After the bottom plate reached preheat-temperature the entire operation of hardfacing the two grooves of about 6.5 m diameter took only a few hours. Neither cracks nor debonding nor surface porosities were observed on the deposits. There was no need to carry out any repair though a procedure for repair had also been finalised. The deposits made on the bottom plate of the PFBR Grid Plate were found to be better than the deposits made during technology development. This was possible only because of the dedicated efforts of designers, engineers, hardfacing agency and the manufacturer of the component.

Fig. 10 : The bottom plate of PFBR Grid Plate mounted on the preheating furnace with hardfacing in progress

2. WELDING TECHNOLOGIES FOR THE INDIAN ADVANCED ULTRA SUPER-CRITICAL THERMAL POWER PROGRAM

Coal fired power plants will continue to contribute a significant part of the supply of electric power for India in the near future. Significant efforts are being made today towards enhancing the plant efficiency and reducing the carbon-dioxide emissions. To achieve higher efficiency, it is necessary that the power plants be operated at higher steam temperatures. Towards this, a mission programme has been initiated in India towards evolving a design for an 800 MWe capacity Advanced Ultra Supercritical (AUSC) plant with steam parameters of 710^{o}C/720^{o}C/ 310 bar to achieve high efficiency. To implement this programme, advanced materials that show good performance and life under such conditions are required. Currently plants worldwide are working with superheater and reheater temperatures of up to about 660^{o}C. However, further significant efficiency increase is being considered with steam temperatures above 700^{o}C. As part of the mission programme, two high-temperature materials, 304HCu austenitic stainless steel (304HCu SS) and modified nickel-base Alloy 617 (Alloy 617M), have been developed for boiler tubes operating at temperatures beyond 530^{o}C.

For development of India-specific 304HCu SS and Alloy 617M, a stage-wise characterization approach was adopted to establish optimised process route, involving vacuum melting, hot forging, hot extrusion, cold pilgering and final solution annealing, for obtaining quality tubes. Detailed characterisation of thermo-physical properties, microstructure, heat treatment response and evaluation of thermo-mechanical processing map enabled necessary understanding of the behaviour of these materials during mechanical working and heat treatment. Chemical compositions of both the materials were controlled more stringently within their specified limits to ensure enhancement of mechanical properties and reduction in scatter of mechanical properties. Elaborate physical and mechanical property studies including various phase formations, thermal conductivity, specific heat, hot tensile, low and high cycle fatigues, long-term creep and fracture toughness have been carried out on the indigenously developed tubes for establishing their worthiness against the internationally developed tubes. Indigenous tubes have mechanical properties comparable / better than those of the internationally developed tubes. Compared with internationally reported data, creep-rupture strength of the India-specific 304HCu SS tube material, based on short-term creep tests, is within the ±20% scatter band and is similar to the VdTÜV and ASME average values [11]. The variation of creep-rupture life of the Alloy 617M tube material with applied stress at different temperatures, based on short-term creep tests, compared with internationally reported data shows very encouraging trends with the India-specific tubes showing better creep properties. Long-term creep tests are in progress [11].

Welding filler wires of matching composition to 304HCu SS and Alloy 617M were manufactured by Indian industries, and used for development of procedures for TIG welding of 304HCu SS and Alloy 617M tubes, including their dissimilar metal tubes welds. Detailed evaluation of mechanical properties, viz. tensile, creep, fatigue, impact, quasi-static fracture, and creep and fatigue crack growth, of the tube materials and their weld joints were carried out to qualify these materials for use in the Indian AUSC power plant boilers [11].

For AUSC turbine rotors, large cylindrical forgings of Alloy 617M of up to 800 mm diameter have been successfully manufactured in India for the first time. The forgings passed all the required quality control checks of ultrasonic and dye-penetrant examinations, as also mechanical properties. Technology for dissimilar metal welding between Alloy 617M and 10Cr-steel forgings for AUSC turbine rotors has been developed. Using hot-wire narrow-gap TIG (NG-TIG) welding process, the dissimilar metal weld between 200 mm Alloy 617M and 10Cr-steel have been produced using Alloy 617 filler wire.

2.1 Welding of 304HCu SS and Alloy 617M tubes

Specifications for appropriate filler wires, of both matching and non-matching chemistry were finalised, including for development of 304HCu SS and Alloy 617M filler wires. Matching composition ER304HCu filler wires and two nickel-base alloys filler wires, ER625 (AWS ERNiCrMo-3) and ER617 (AWS ERNiCrCoMo-1) were used for TIG welding of 304HCu SS, while ER617 filler wires were used for TIG welding of Alloy 617M tubes and 304HCu SS/Alloy 617M dissimilar tubes. Welding procedure qualification (WPQ) was carried out using optimised welding parameters. WPQ was also carried out for 304HCu SS joints with matching chemistry ER304HCu filler wires, and with ER617 filler wires for the Alloy 617M joints and the 304HCu SS/Alloy 617M dissimilar joints. All the similar and dissimilar tube weld joints passed the soundness evaluation tests as per ASME Section IX, viz. dye-penetrant and X-ray radiography examinations, the face-bend and root-bend tests. Transverse-weld tensile properties of similar and dissimilar weld joints of 304HCu SS and Alloy 617M are given in **Table 4.**

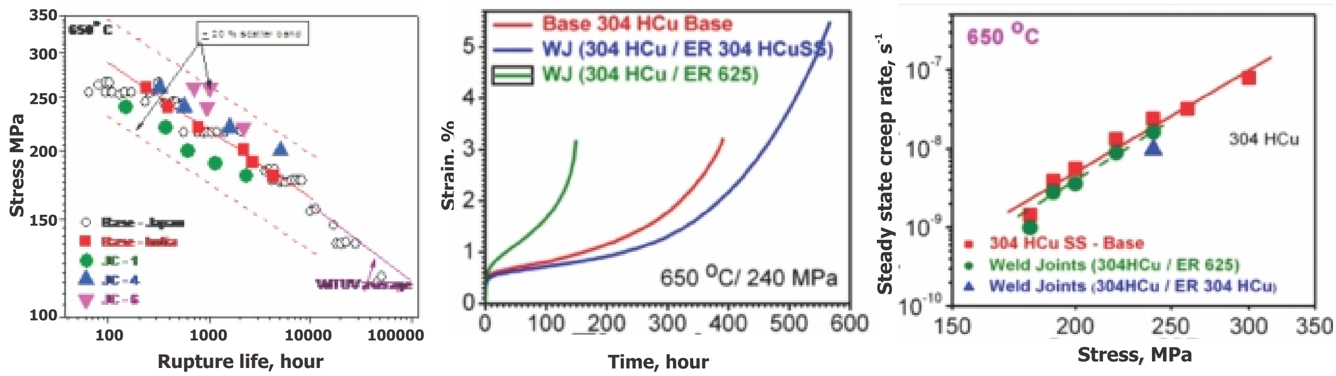
Compared to the creep-rupture life of the base material at 650^{o}C, the 304HCu SS joint welded using ER625 filler wire (JC-4) shows lower creep rupture life and ductility while the one welded with ER304HCu filler wire (JC-1 and JC-6) shows higher creep rupture life and ductility (**Fig. 11a** and **Fig. 11b**) along with lower steady-state creep rate (**Fig. 11c**).

2.2 Welding of 10%Cr steel to Alloy 617M cylindrical forgings

Dissimilar metal welding between 10%Cr to Alloy 617M cylindrical forgings was carried out using Alloy 617 filler (ERNiCrCoMo-1) wire by hot-wire NG-TIG welding process, using specially designed TIG torch on a narrow-groove joint preparation. Welding procedure has been developed for joining 10%Cr steel to Alloy 617M by two methodologies. The first method is direct welding between 10%Cr steel and Alloy 617M using ERNiCrCoMo-1 filler metal followed by post weld heat treatment (PWHT). The second method is by buttering/weld overlaying of 10%Cr steel by ERNiCrCoMo-1

Table 4 : Tensile properties of tube materials and transverse-weld joints of tubes

Tube Material	Filler wire	YS (MPa)	UTS (MPa)	Failure Location
304HCu SS Tube	311	635	-	
304HCu SS	ER625	479	688	Base metal
304HCu SS	ER617	424-436	651-762	Base metal
304HCu SS	ER304HCu	428-457	637-694	Base metal / Weld metal
Alloy 617M Tube	331-339	783-813	-	
Alloy 617M	ER617	418-443	747-798	Base / Weld metal / HAZ
304HCu SS/Alloy617M	ER617	455	706	Base metal



(a) (b) (c)

Fig. 11 : Comparison of creep behaviour at 650ºC of 304HCu SS and its weld joints: (a) creep-rupture life; (b) creep rupture ductility; and (c) steady state creep rate at different stress levels.

filler metal followed by PWHT and subsequent welding of overlay deposit with Alloy 617M part. The PWHT temperature and time is governed by 10%Cr steel which is carried out in the temperature range of 670-720°C. To develop the NG-TIG welding procedure, mock-up welding was carried out using 200 mm diameter hollow cylindrical forgings of 10%Cr steel and Alloy 617M with wall thickness of 50 mm. NG-TIG weld joints of 50 mm thickness produced by two methodologies showed no significant defects in radiography. The direct weld joint between 10%Cr steel and Alloy 617M showed good ductility during side bend test with bend radius of 3T. The cross weld tension test of 10%Cr steel/Alloy 617M direct joint fractured in Alloy 617M base metal and is acceptable as per ASME Section IX [12]. An appropriate ultrasonic examination technique has been developed for examining the dissimilar metal weld between cylindrical forgings of 10%Cr-steel and Alloy 617M.

3. CONCLUDING REMARKS

Right from the early stages of the Indian PFBR, the importance of metal forming and welding was realised and given priority in R&D and validation. Hence, systematic programmes were undertaken to integrate the fabrication aspects in design and selection of materials. This approach enabled overcoming challenges faced during fabrication of the components with stringent specifications. In this paper, only a few examples have been presented of fabrication technologies completed in time and exceeding the specifications in most of the cases. The experience gained in construction of PFBR is vital in the design and construction of future Indian SFRs. It is envisaged that select modifications in the design, material selection, fabrication processes etc. will continue to be achieved to reduce cost of construction, have improved safety and thermal efficiency of the Indian SFRs.

For the Indian AUSC mission program, welding procedures were developed and qualified for welding of 304HCu SS tubes using ER304HCu filler wires, of Alloy 617M tubes using ER617 filler wires, and dissimilar welding of 304HCu SS tubes to Alloy 617M tubes using ER617 filler wires. The results of mechanical properties of the similar and dissimilar weld joints of the India-specific 304HCu SS and Alloy 617M tube materials indicate that their properties are comparable to the internationally reported values as also the codified values in the VdTÜV standard. The dissimilar metal weld of 10%Cr steel to Alloy 617M cylindrical forging using ER617 filler wire required for steam turbine rotor has also been successfully demonstrated using hot-wire NG-TIG welding process.

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