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An Overview of Welding Aspects and Challenges during Manufacture of Intermediate Heat Exchangers for 500mwe Prototype Fast Breeder Reactor

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Abstract

Prototype Fast Breeder Reactor (PFBR) is first of its kind 500MWe pool type, sodium cooled nuclear reactor which is presently in advanced stage of construction at Kalpakkam, India. Intermediate Heat Exchanger (IHX) is a shell and tube type, counter current, sodium to sodium heat exchanger. IHX is a very important, massive, over dimensional (~42 tones in weight, ~2 meters in diameter and ~18 meters in length) and critical component of reactor, as it transfers heat from the radioactive primary circuit sodium to non-radioactive secondary circuit sodium forming the boundary between these two circuits. The principal material of construction of IHX is austenitic stainless steel grade 316LN. Each IHX has 3600 nos. of straight seamless tubes which are rolled and then welded to the either ends of top and bottom tubesheets by autogenous pulsed Gas Tungsten Arc Welding (GTAW) process. The shell welding around the tube bundle is extremely difficult and challenging task due to small gap between the tube bundle and shell inside diameter. Special arrangements were made to avoid arc strike or fusion on the tube during shell welding around the tube bundle.

A mechanical hardfaced seal arrangement at the interface of the IHX outer shell and the inner vessel stand pipe is the chosen design concept to ensure leak tightness in the IHX penetrations. Based on radiation dose rate & shielding considerations during maintenance, handling and decommissioning, nickel based ENiCr-B hard facing alloy (Colmonoy-5) was chosen to replace the traditionally used cobalt based stellite alloys to improve the resistance to high temperature wear, especially galling of mating surfaces in sodium environment. The more versatile Plasma Transferred Arc Welding (PTAW) and Gas Tungsten Arc Welding (GTAW) were used for deposition of Colmonoy-5. The hardfacing on the seal ring is really challenging task, as the diameter is too large and thickness & width is too small and which has hardfacing on all mating surfaces. Extensive varieties of trials were conducted on the mockup to optimize the hardfacing process along with heat treatment cycle to obtain minimum distortion deploying special tools and fixtures.

Intermediate Heat Exchanger involves 10mm and 28mm thick borated stainless steel components around the tube bundle and bottom portion confirming to ASTM 887, Type 304 B4, Grade B classification to reduce the radiation level in secondary sodium system while flowing through the IHX. Various types of welding trials were conducted on the test coupons for welding procedure

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qualification of borated stainless steel components using versatile grades of welding consumables. More than hundred nos. of trial coupons welded using 10 varieties of welding consumables have shown fissures and cracks in weld, as these welding consumables found not having good compatibility with SS 304 B4, Grade B borated steel. Special development work was taken-up for the first time in the country by developing a special grade ~1% borated welding consumable (GRINOX-308BRN electrode) specifically for welding of borated steel components of IHX. This paper highlights on welding aspects and challenges during fabrication of Intermediate Heat Exchangers for 500MWe Prototype Fast Breeder Reactor.

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Keywords: IHX; GTAW; PTAW; Borated Steel; Hardfacing;

1.0 Introduction

Prototype Fast Breeder Reactor (PFBR) is a 500 MWe pool type sodium cooled nuclear reactor, which is presently in advanced stage of construction with physical progress of 96% at the end of December 2013. There are four Intermediate Heat Exchangers (IHXs) in PFBR with equal capacity connected to two secondary loops, each loop containing two IHXs. Intermediate Heat Exchanger is a vertical, counter current, shell and tube type, sodium to sodium heat exchanger (Figure -1). IHX transfers heat from the radioactive primary circuit sodium to non-radioactive secondary circuit sodium forming the boundary between these two circuits. During normal reactor operation, heat from the reactor core is removed by the primary sodium flowing through the core and transported to the shell side of Intermediate Heat Exchangers, where it transfers the heat to the secondary sodium which is flowing in the tube side. The secondary sodium in turn transfers the heat to water in the Steam Generators to generate steam for running the turbine.

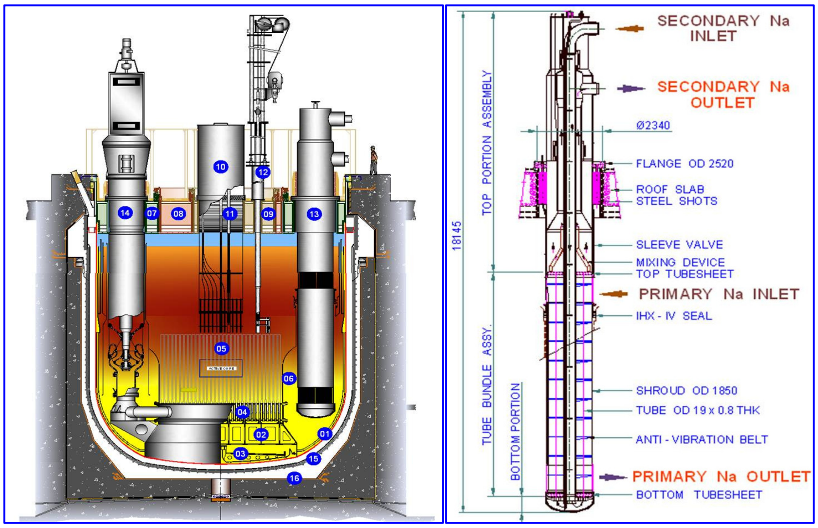

Figure 1: Primary reactor assembly and Intermediate Heat Exchanger of PFBR

The sodium temperature in the primary cold pool during normal reactor operation is 397^0C while the hot pool sodium temperature is 547^0C. The minimum and maximum sodium temperatures in the secondary circuit are 355^0C and 525^0C respectively. The hot primary sodium flows through the shell side of the IHX due to the difference in levels of sodium in the hot and cold pools. Primary sodium from the hot pool enters the shell through the windows at the top of the tube bundle region and exits to the cold pool through the windows at the bottom of the tube bundle. The secondary sodium enters the IHX through the downcomer pipe, flows downwards and then rises up through the tubes gaining heat from the primary sodium.

Each IHX consists of tube bundle having 3600 nos. of straight seamless tubes of 19 mm OD X 0.8mm wall thickness each of 8050 mm length in austenitic stainless steel, rolled and welded to the top and bottom tubesheets.

The tubes are arranged in radial pitch of 25mm and circumferential pitch of 26.2mm around an inner shell of size OD 579mmX16mm thickness. The secondary sodium inlet pipe of size OD 497mmX 8mm thickness passes inside this inner shell and is welded only to the bottom tubesheet. There is a vertical outer shell around the tube bundle. There are inlet and outlet windows for primary sodium flow provided in this shell. Hot sodium flows through the inlet window and transfers the heat to the tube bundle and come out from the outlet window as cold sodium. Secondary sodium enters the IHX at the top, flows from top towards downwards and then flows upwards through tubes of the tube bundle and is discharges through outlet pipe. A flow distribution device is provided at the inlet to the tube bundle for proportioning of secondary sodium flow to the tube bundle. A flow mixing device is provided at the secondary outlet header just above the top tubesheet for mixing the sodium coming out from the outer row and inner row tubes. The IHX is supported on the roof slab and penetrates at the bottom portion through a vertical shell (stand pipe) of the inner vessel. The hot sodium pool and cold sodium pool of the reactor at IHX penetration is separated by a mechanical seal called Inner Vessel seals (IV seals) which reduces the bypassing of hot primary sodium to the cold pool and maximum of 1% leak is permitted through IV seals as per the design.

The major material of construction is austenitic stainless steel grade 316LN (Cr: 17-18%, Ni: 12-12.5%, Mo: 2.3-2.7%, Mn: 1.6-2.0%, C: 0.024-0.03, N: 0.06-0.08%). This is a low carbon stainless steel chosen to ensure freedom from sensitization during welding and Intergranular corrosion of the components. In addition, this steel also possesses excellent mechanical and creep properties. SS316LN materials were procured in solution annealed, pickled and passivated condition. During material procurement, specimens of the plates were subjected to chemical examination, metallographic examination, test for delta ferrite, inclusion content test, Intergranular corrosion test as per ASTM A262, Practice E. During material procurement, plates were subjected to thorough Visual Examination/Liquid Penetrant Examination (LPE) and 100% Ultrasonic Examination (UE) with minimum 10% overlap of previous scan to ensure soundness of the plate. Grain size and chemical composition of plate material has been precisely specified with upper & lower values to optimize the mechanical & creep properties. During plate procurement, high temperature tensile test is also carried out in addition to tensile test at ambient temperature on specimens to evaluate & ascertain the properties for service conditions.

2.0 Tube Bundle Welding and Fabrication

Tubes, tubesheets and tube to tubesheet joints are the most critical parts in IHX, as these separates radioactive primary sodium & non-radioactive secondary sodium and hence a high degree of reliability against failure is must. The tubes are seamless and both tubes & tubesheets are produced by electric arc melting with tight control on inclusion content to achieve sound weld during autogenous welding process between the tubesheet and tube. Ultrasonic test is done on the entire length of each tube in accordance with ASME Sec.III Class I. Each tube is subjected to hydro testing as per PFBR specification to ensure the integrity. Tube bundle activities of IHX were done in separate nuclear clean hall conditions as per the class-1 component requirements of PFBR. Each tube is supported with anti-vibration belts at 11 locations to minimize the flow induced vibration during reactor operation. There are 49700 nos. of ferrule supports required to be welded on anti-vibration belt for each IHX maintaining the pitch with very tight tolerances, which is a one of challenging task.

Figure 2: Tube to tubesheet rolling and welding of Intermediate Heat Exchanger

The tube to tubesheet joints are rolled and subsequently seal welded by autogenous pulsed Gas Tungsten Arc Welding (GTAW) process. Even though conventional heat exchanger tube to tubesheet joints are done first by welding and then rolling, PFBR tube to tubesheet joints are executed first by rolling using mechanical tube expanders and then welding to avoid stresses on the welds during tube expansion step. After completion of tube bundle, IHX tube bundle is subjected to Helium Leak Test (HLT) under vacuum as per PFBR specification during which the global leak rate shall not be more than 10^{-7} Pa-m^3/s.

2.1 Problems Faced During Tube to Tubesheet Welding Trials/Qualification and Discussion

Various trials were conducted before actual procedure qualification for tube to tubesheet rolling and welding. The rolling trials were carried out successfully. However, during tube to tubesheet welding trials some explosions in the weld bead with associated smoke emanations and base material contamination were observed on the tungsten electrode. Few blows/porosities at random locations were observed in the seal weld and the profile of the weld was not smooth.

Investigations revealed that the lubricant which was used during rolling was causing these explosions and porosities in the weld bead. Due to this reason, appearance and profile of the weld seam was not smooth. To overcome the above, it was debated for carrying contact rolling (2-5%) in the region ‘B’ first, then seal welding and then full expansion (7-10%) in the region ‘A’ was proposed. As this proposal may induce stresses in the weld joints and may lead to weld failure during transient reactor operating conditions, this proposal was not taken into consideration. Subsequently, it was explored for full expansion & contact rolling without using lubricants and trials of the same were carried out on the mock up blocks. During the trials, the surface finish and visual examination of sectioned tube after rolling was satisfactory. The rolled tube was free from scratches, cracks, peels etc. Micro examination revealed a smooth transition of the rolled region to the unrolled region. As observations made after above trials after rolling were satisfactory, seal welding was carried out between the tube & tubesheet ends. The earlier experience of explosion during welding and base material contamination on tungsten electrode was not observed. Subsequently, welds have been subjected to visual examination, floroscent LPE, HLT & destructive testing and the same were found satisfactory. The pullout strength measured for the expanded and welded joint was 29 KN to 29.5 KN with an average value of 29.25 KN. It is noted that the above pullout strength is greater than 27.67 KN, which was observed during technology development stage.

The tube to tubesheet rolling and welding (36000 joints) of all 5 IHX’s (4+1 spare) were carried out successfully without any non conformances meeting all the stringent specification requirements.

3.0 Shell Welding and Fabrication Activities

After completion of tube bundle fabrication, SS 316LN shell welding is carried out around the tube bundle by combination of Gas Tungsten Arc Welding (GTAW) and Shielded Metal Arc Welding (SMAW) processes. The welding is carried out using 16-8-2 filler wires and E 316-15 electrodes with controlled heat input to minimize the distortion and dimensional deviations.

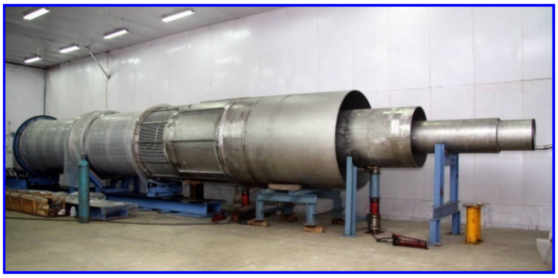

Figure 3: Shell fabrication stage of Intermediate Heat Exchanger

The welding procedure is qualified with various destructive and non-destructive examinations and testing before welding on the actual job. The qualification test coupons were subjected to all the non-destructive examinations applied in fabrication of actual job. During qualification, weld joints were subjected to thorough visual examination, LPE, radiography examination, longitudinal tensile test at room temperature, transverse tensile test at room temperature and high temperature, bend tests, Charpy U notch impact test, delta ferrite content test, IGC and metallographic examination for the complete transverse section of the weld. Root and final pass LPE and 100% radiography examination is done for all the job weld joints. In case radiography for the job weld joint is not possible due to practical limitations, the quality of the weld joint is evaluated by ultrasonic examination.

The shell welding around the tube bundle is extremely difficult and challenging task due to small gap existing between the tube bundle and shell inside diameter. Special arrangements were made to avoid arc strike or fusion on the tube during shell welding around the tube bundle.

4.0 Hardfacing of Seal Assembly and Main Considerations

Intermediate Heat Exchanger is supported at the top on the roof slab and penetrates through a vertical shell which is called as stand pipe of the Inner Vessel (IV). The hot sodium and cold sodium is separated by a mechanical seal made of austenitic stainless steel of grade 316LN.

Figure 5 shows the seal assembly arrangements at IHX-IV penetrations. IHX IV seal assembly components consists of a fastened assembly of metallic top, middle and lower seal holder which provides housing for the seal rings. The seal rings are in two halves and are bolted together to form circular rings which are housed inside the seal holders. During reactor operation, seal rings would arrest/minimize the bypass of hot primary sodium into cold primary sodium pool. The seal rings are designed for assembly in a sequential manner in such a way to facilitate its easy maintenance/replacement during service. The seal holders and seal rings are made from SS316LN plates procured as per PFBR specification. As SS316LN material is highly prone to galling and seizing under the sliding contact at high temperature in the presence of sodium, it needs further surface modification. Therefore, hardfacing is carried out with Colmonoy deposition on all mating surfaces of seal rings.

Figure 4: Fabrication of Intermediate Heat Exchanger

ENiCrB hardfacing alloy popularly known as colmonoy–5 or Deloro-50 has been chosen for hardfacing of seal assembly components of IHX. Colmonoy–5 has typical hardness of 45-50 HRC and this alloy is an excellent substitute for cobalt based satellites for minimizing the dose rate to the personnel during handling, maintenance and decommissioning activities. The more versatile Plasma Transferred Arc Welding (PTAW) and Gas Tungsten Arc Welding (GTAW) were used for deposition of Colmonoy-5. But difficulties involved in overlaying this alloy is brittleness and highly prone to cracks (poor weldability), crater shrinkages (almost inevitable) and very reactive with atmospheric oxygen, hence requires high purity argon gas for shielding.

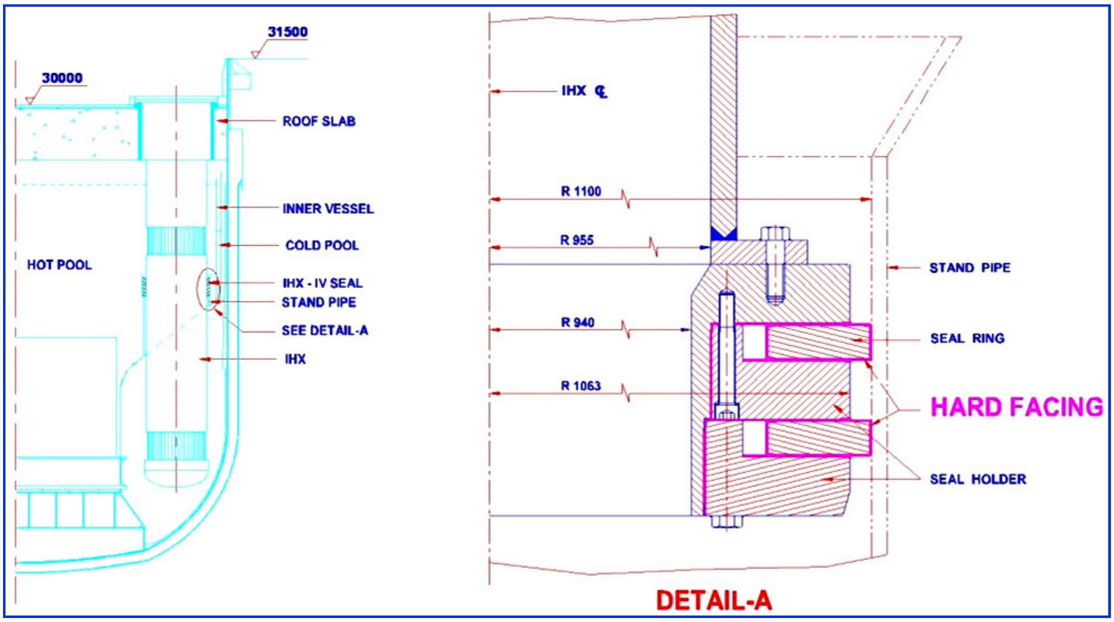

Figure 5 IHX Inner Vessel (IV) seal assembly arrangements

As the differential co-efficient of thermal expansion between Colmonoy and austenitic stainless steel is high when compared to stellites, the overlaying of Colmonoy is difficult and challenging. As a consequence of differential shrinkage of the molten deposit and heated base metal leads to generation of residual stresses because of process-induced thermal gradients and difference in coefficient of thermal expansion between the deposit and base material. The magnitude and distribution of the residual stresses vary depending on the preheat temperature, coating thickness, heat input, deposition process and geometry of the components.

4.1 Issues on Hardfacing of Seal Rings

As diameter of seal ring is too large, each half ring is made by welding with two SS316LN plate segments before hardfacing process. Hence, hardfacing is inevitable on the plate material as well as local weld area between 2 plate segments. This necessitates material qualification meeting all the destructive & non-destructive examinations and testing for the weld as well as base material for ascertaining & ensuring the properties for service conditions. During material procurement, Intergranular corrosion test as per ASTM A 262, Practice E is carried out on the specimens with material been subjected to sensitization treatment at 725 ± 10^0C for 30 minutes to ascertain the sensitization phenomenon during hardfacing process. In addition, the specimens of plates were subjected to impact test in the solution annealed condition as well as embrittled condition (soaking at 750^0C for 100 hours).

Before hardfacing deposition on the actual job, the complete hardfacing process is qualified in a qualification block simulating the actual job conditions. The base material before hardfacing is subjected to visual examination, dimensional check, liquid penetrant examination and surface hardness measurement. After completion of hardfacing & stress relieving heat treatment, dimensional check, visual examination, LPE, ultrasonic examination, surface finish, measurement for minimum hardfacing deposit thickness, chemical analysis, metallographic examination, line of hardness measurement and surface hardness measurement is done.

Initially, hardfacing on all the faces of seal rings were carried out by PTAW process. Preheating of the job is done at 650^0C before starting hardfacing deposition to reduce the cooling rate and cracking tendency. The preheat temperature is optimized after various trials on the mock up during technology development program for optimum fluidity. As a matter of abundant precaution, fast heating and cooling cycle has been specified at the rate of 110 to 150^0C/h at temperature between 500^0C to 850^0C to avoid the phenomenon of sensitization on the materials, eventhough materials were qualified before starting hardfacing on the actual job.

4.2 Challenges Faced During Hardfacing of Seal Rings

As per specification, minimum 1mm hardfacing deposition is required on all the mating surfaces (entire width) of seal rings i.e. top face, bottom face, outer diameter face, inside diameter face and all the step faces where 2 half rings are getting bolted. The hardfacing of seal rings is carried out in 1G position (Figure-6) in a sequential manner to ensure minimum distortion. Special fixtures and tooling were designed & developed for hardfacing deposition. The hardfacing on the seal rings is extremely difficult, as the diameter is too large (i.e. around 2m diameter) & thickness is too small (i.e. 30mm thick) and has hardfacing deposition on all the mating surfaces. Due to high diameter to thickness ratio, hardfacing process is exceptionally challenging and achieving the final dimensions with close tolerances is tough task.

If ring is clamped at many locations during hardfacing process, there were tendency for hardfacing material to crack, as free expansion of the material is arrested. If the job is clamped at minimum locations during hardfacing, there was distortion tendency at high hardfacing temperature, leading to dimensional deviations. The stress relieving heat treatment at 850^0C is carried out at different stages of hardfacing on the seal rings to relieve the welding stresses and to avoid cracks. As hardfacing deposition is carried out in a sequential manner on various faces of seal ring, the intermittent heat treatment is carried out which helps in avoiding cracks to the extent possible during subsequent hardfacing on balance faces. Hardfacing on the seal ring is done in a motorized welding fixture where job table is rotated in horizontal condition for top/bottom face deposition during which PTA welding torch is stationary. The job is covered with thick insulation to avoid heat dissipation to the atmosphere during hardfacing process. Temperature control is easier during top/bottom face hardfacing on the seal rings, as deposition is done in horizontal condition. However, Inside diameter (ID) and Outer diameter (OD) face deposition of the seal ring is cumbersome task, as job was required to make vertical (by indexing the table to vertical condition) and rotated alongwith its fixtures for deposition (as hardfacing is done in 1g position). As the job is made vertical alongwith fixtures & insulation, it is difficult to control the preheat temperature (as job is rotating in vertical condition during deposition) due to dissipation of heat during vertical rotation.

Figure 6 Seal ring hardfacing in the shop

4.3 Experience during Hardfacing of Seal Ring on 30mm Thick Region

The hardfacing of seal ring was initially carried out by PTAW process on the top face from Inside Diameter (ID) towards Outside Diameter (OD) for the complete 80mm ring width with 3-4mm overlap for a deposition width of 7-8mm after each run to ensure complete coverage of hardfacing material on the base material. Hardfacing is carried out on each face from ID to OD and OD to ID in a sequential manner for the complete width to control distortion. Hardfacing of bottom face (from ID to OD) is carried out similar to top face during which job would be rotated in the horizontal condition. Subsequently, bed/fixture is indexed to vertical condition during which job would be rotated in vertical condition for OD face deposition. After heat treatment, intermittent dimension check is carried out. During initial trials, it was noted that the seal ring has more distortion i.e. ovality of about 40mm and face out of around 35 mm. As the amount of hardfacing done on the seal ring is too large, the slim ring has distorted heavily after hardfacing on the 3 faces due to high heat input. There were many apprehensions of crack development if shape correction is carried out in as hardfaced condition due to high hardness of the deposition. Therefore, it was decided to carry out stress relieving of the ring at this stage before shape correction. Stress relieving heat treatment is carried out at 850^{0}C with 1 hour soaking time to relieve the welding stresses and also for dimensional stability. Specially designed screw & rod fixtures were used for shape correction in hot condition after heat treatment before ID deposition. The job was heated upto 600^{0}C for shape correction allowing the above hardfaced seal ring to move freely in all the directions. Subsequently, the shape correction is done locally by means of screw rod mechanism which is made of Carbon Steel (CS) with sufficient SS pad to avoid CS and SS contact at high temperature. After completion of ovality correction in hot condition, the seal ring is cooled and then machined on its ID before hardfacing. After completion of ID deposition and minor shape correction, the complete ring is again subjected to stress relieving heat treatment at 850^{0}C to relieve the stresses. The job was then cooled to room temperature and subsequently all the specified NDTs were carried out. However, dimension achieved in the above procedure is not so satisfactory due to the shape and configuration of the seal ring.

Various full size trials of hardfacing were conducted on the seal rings for establishing the process parameters. As diameter of seal ring is too large and thickness & width is too small having hardfacing on all the faces, the distortion control was impossible even after sequential welding (and sequential heat treatment) due to large heat input during hardfacing. Many trials of hardfacing were carried out by providing additional stiffeners on the ID before hardfacing. These trials have not delivered encouraging results. Hardfacing trials were also conducted by keeping the 2 half rings one above the other by stitch welding to avoid distortion in the flatness. However, targeted full success could not be achieved by adapting the above procedures.

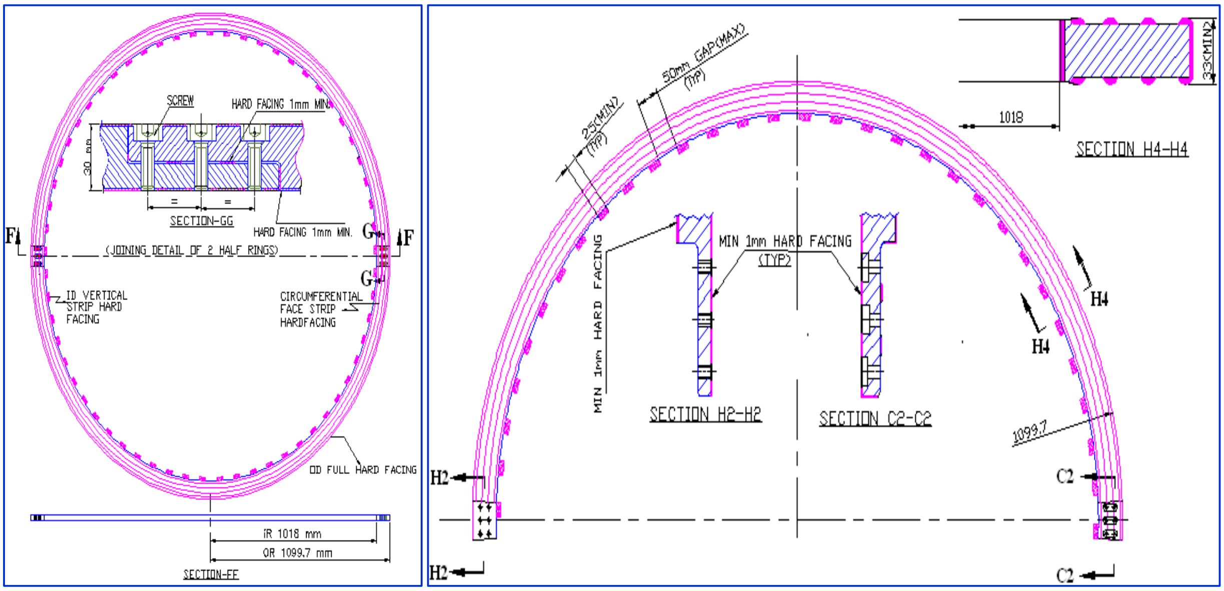

Figure 7 Hardfacing on seal rings after design modifications

Finally, it was decided to reduce the amount of hardfacing on the seal rings to minimize the distortion. It was inevitable to review the design aspects and thus changes were carried out in the design for successful hardfacing on the seal rings (Figure 7). The hardfacing deposition on the ID face was reduced by deposition in the form of vertical strips parallel to the axis (25mm strip width with gap of 50mm in between strips) as probability of bypass flow of hot primary sodium is very less through ID of the seal ring. The vertical strip hardfacing is carried out by manual GTAW process. The circumferential strip hardfacing (10mm width and 12mm gap in between strips) is carried out instead of full hardfacing on the top & bottom face of the seal ring to reduce the amount of hardfacing deposition. The above exercise and design modifications have delivered excellent results with least distortion and dimensional variations in the hardfaced seal rings.

4.4 Experience during Hardfacing on the Stepped Region of Seal Ring

Each half of seal ring has 18mm thick step portion at one end and 12mm thick step portion at other end where two half rings are being joined by means of bolting. There were cases of shape out and cracks on the step portions during hardfacing. The 18mm thick step portion has lower tendency for distortion than 12mm thick step portion. It was analyzed that heavy distortion is because of large amount of deposition in less section thickness area. Detailed investigations revealed that stress concentration at corner at the step region has resulted in crack initiation and propagation towards periphery during hardfacing process. Therefore, it was decided to modify the design by leaving the corner of base material without having hardfaced deposit. In addition, it was decided to reduce the amount of hardfacing deposition on the step regions to the extent possible. The amount of hardfacing is substantially reduced in the 18mm thick step portion (Figure 8) and deposition is completely eliminated in 12mm thick step portion except on the OD face (Figure 9), as there is no concern of wear during reactor operation at these regions. It was clarified that one side hardfacing would suffice, address and avoid the self welding phenomenon in the step locations where 2 half rings are being joined. By the above design modifications, the cracking tendency of hardfaced deposit has reduced drastically and distortion found to be negligible.

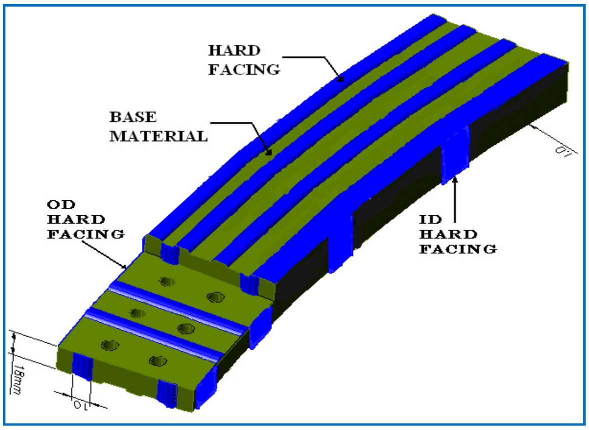

Figure 8 Hardfacing on 18 mm thick side

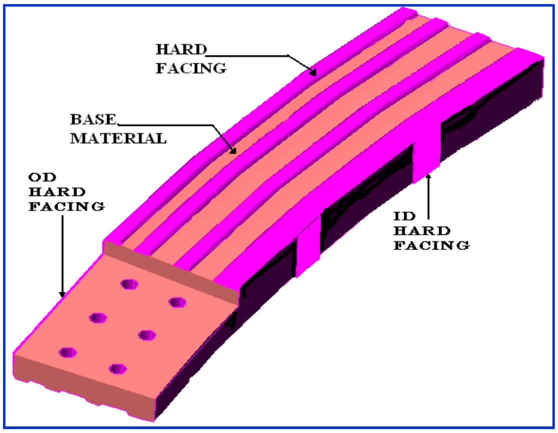

Figure 9 Hardfacing on 12 mm thick side

4.5 Experience During Handling and Machining of Seal Rings

It is mandatory and inevitable in the shop to handle the seal rings with utmost care due to high hardness of the hardfaced deposit. Even minor impact load on the seal ring during handling may cause fine cracks due to complex and intricate geometry of the seal ring. The machining of hardfacing deposition (Figure-10) is another challenging task and time consuming process due to very high hardness. There were incidences of fast tool wear rate, fine cracks on the deposit and tool breakage/failure due to intermediate cut, higher feed rate and depth of cut during machining. Machining was required to be carried out with controlled feed rate and depth of cut to avoid repetition of above incidents.

Figure 10 Seal ring machining in the shop

5.0 Experience during Welding of Borated Stainless Steel Components

Intermediate Heat Exchanger involves 10mm and 28mm thick borated stainless steel components around the tube bundle and bottom portion confirming to ASTM 887, Type 304 B4, Grade B classification to reduce the radiation level in secondary sodium system while flowing through the IHX. Various types of welding trials were conducted on the test coupons for welding procedure qualification of borated stainless steel components using versatile grades of welding consumables. More than hundred nos. of trial coupons welded using 10 varieties of welding consumables have shown fissures and cracks in weld, as these welding consumables found not having good compatibility with SS 304 B4, Grade B borated steel. The observations of welding trials are summarized below.

5.1 Observations and Results of Various Welding Trials Conducted on the Borated Steel

The following paragraphs summarize the observations and results of various welding trials conducted on the borated steel using different types of welding consumables.

a. The ASME classified electrodes such as E316-15 [Mod.], ENiCrFe3, E308 L-15, E316 L-15, E307 L-15, EA 981/15, E310 L-15, E312-16 have revealed longitudinal cracks in the root pass weld during welding trials conducted on the 28mm thick borated steel.
b. When E312L-15 electrodes were employed on the 28mm thick borated steel, no visual cracks were observed during welding, however, radiographic examination after welding revealed cracks in the weld.
c. It is noted that no cracks were observed during welding on 10mm thick borated steel welded using E-309L-15 electrodes. The radiography examination, tensile test and hardness tests were found satisfactory.
d. Initial 2 runs were free from the cracks during welding trials conducted using E-309L-15 electrodes on 28mm thick borated steel, however balance layers revealed fissures. Subsequently fissures were removed and welding is completed. Radiography examination found satisfactory. However, side bend test conducted on 4t & 6t were not ok at 20º-25º angle of bend.
e. The unconventional welding consumables such as E308-17 and E-2209-17 have revealed fissures and cracks during welding trials conducted on the 28mm thick borated steel.
f. Many nos. of welding trials were conducted using E-308-16 (Nearest) electrodes. Visual examination, radiography examination, tensile test and hardness test carried out on the welds produced using E-308-16(Nearest) welding consumable were found near satisfactory than earlier trials, eventhough these trials were not delivered consistent positive results.
g. Finally based on the near satisfactory results after welding many nos. of test coupons, it was decided to develop a special electrode E-308-16(Nearest) containing Boron which is not in line with any classification for welding of 28mm thick borated steel after establishing the repeatability. The welding trials conducted by maintaining zero root gap using this specially developed ~1% borated welding consumable (GRINOX-308BRN electrode) has delivered excellent results meeting all non-destructive examinations and destructive testing requirements of the weld.

6.0 Testing of IHX after Completion of Fabrication

After completion of fabrication of IHX, the secondary side is subjected to pneumatic test at 29 bar gauge pressure for minimum of 30 minutes to check the integrity of the component. No pressure drop is acceptable. All the accessible welds were subjected to soap bubble test. No leak is acceptable during the test. After completion of pneumatic test, IHX secondary side is subjected to Helium leak test under vacuum as per PFBR specification during which the global leak shall not be more than 10^{-7} Pa-m^3/s and local leak shall not be more than 10^{-8} Pa-m^3/s.

7.0 Conclusion

The manufacture of Intermediate Heat Exchangers was a great challenge. Eventhough the Intermediate Heat Exchanger have been manufactured for the first time in the country, design features have been correctly translated into the manufacturing overcoming all the difficulties involved in various phases of raw material procurement, engineering, welding, fabrication, inspection and testing meeting stringent requirements of specification. The hardfacing of Colmonoy-5 is difficult and challenging task. With lot many difficulties and challenges, the hardfacing procedure was established on the seal rings. Exhaustive review is very much essential and full scale technology developmental work is mandatory wherever surface modifications are required on the slim components using any process which involves huge amount of deposition with larger heat input. The hardfacing on the forging material instead of plate material may reduce the amount of distortion and a systematic technology development on forged seal ring is inevitable and can be explored. Alternatively, hardfacing trials can be carried out on the top, bottom and outer diameter faces on as procured plates before cutting into the shape of seal ring which may substantially reduce the distortion. Sound & defect free hardfacing deposition is possible on SS316LN material; if proper control & optimization is made between preheat temperature, heat input, deposition process & its sequence, coating thickness, amount of deposition and geometry of the components. Understanding nature of the material, cause of the problem, a patient analysis to find the ways & means to counter the fabrication difficulties and a positive attitude to face and resolve the technological issues have lead this great success. Full size Intermediate Heat Exchanger is fabricated after rigorous technology development which gave lot of confidence for self reliance in engineering, science and technology. Reliable service is expected from the Intermediate Heat Exchangers for the design service life of 40 years on the basis of high standard quality control and quality assurance during raw material procurement, welding and fabrication.

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