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STRUCTURAL INTEGRITY OF MAIN HEAT TRANSPORT SYSTEM PIPING OF AHWR

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1 ABSTRACT

This paper addresses the issues related to structural integrity of the Main Heat Transport (MHT) System Piping of Advanced Heavy Water Reactor (AHWR) which are of concern to the long life of the plant. Various factors considered for selection of material for MHT system piping are described. Life limiting material degradation mechanism such as Low Temperature Sensitization (LTS) that will lead to IGSCC and Low Temperature Embrittlement (LTE) leading to reduction in toughness were considered. The advantages and disadvantages of existing welding process such as Gas Tungsten Arc Welding (GTAW) and Shielded Metal Arc Welding (SMAW) along with newer hot wire GTAW have been brought out. The use of narrow gap welding technique and high deposition rate welding leading to lower residual stress is demonstrated. This also helps in reducing the material susceptibility to sensitization because of higher cooling rate. Occurrence of IGSCC in austenitic stainless steel (ASS) piping is deterrent in demonstration of Leak Before Break (LBB) design criteria. In view of the improved material specification and welding process optimization, the chances of IGSCC will reduce significantly and help in demonstrating the LBB criteria. The defect tolerance of the piping was demonstrated by carrying out a component test programme showing compliance with LBB criterion.

2 INTRODUCTION

AHWR is a 920 MWth, 300 MW vertical pressure tube type reactor, with boiling light water as a coolant in a high-pressure main heat transport (MHT) system. The MHT system consists of common circular inlet header from which 408 inlet feeders branch out to the coolant channel core. The outlets of the coolant channels are connected to the tail pipes carrying steam water mixture from the individual channels to the four steam drums. The steam is separated from steam water mixture in the steam drum and is supplied to the turbine. The condensate is heated in moderator heat exchangers and feed heaters and is returned to steam drum by feed pump. For each steam drum, four downcomers are connected to inlet header.

AHWR is a new reactor being designed with a target life of 100 years. Structural integrity of the MHT system piping is of concern considering the life of 100 years for which experience and material data are not available. Failure of ASS piping of boiling water reactors due to Intergranular Stress Corrosion Cracking (IGSCC) has been reported extensively in the available literature. Prevention of IGSCC in the operating plant and new plant is of great challenge to the design and material engineers. In view of this it was planned to address all the issues related to structural integrity of the MHT system piping, which are of concern to the long life of the plant. Issues covered in this article are listed below:

(1) Selection of material, (2) Life limiting material degradation mechanism, (3) Optimisation of welding process and technique and (4) Leak Before Break (LBB) design criteria

3 SELECTION OF MATERIAL

The selection of material is based on the literature survey, discussion with material experts, design codes and standard and the R&D activities carried out under component integrity testing program [1]. Various factors considered in the selection of material for MHT system piping of AHWR are as follows:

1. Operating conditions and plant life
2. Material properties such as mechanical, metallurgical, irradiation and corrosion resistance.
3. Availability of the material and data for design
4. Ease of fabrication
5. International experience
6. Cost

Process fluid (coolant) in the MHT system is two-phase steam water mixture and the chemistry of the fluid would be similar to that of typical boiling water reactor. The operating temperature is 288°C.

Austenitic stainless steel (ASS) is the choice because of its ductility, good weldability, excellent corrosion and erosion resistance properties, adequate strength, availability of material data and above all vast experience in the use of this material in boiling water reactors. The experience indicates that Boiling Water Reactor (BWR) piping systems of AISI type 304 and 316 austenitic stainless steels have been susceptible to intergranular stress corrosion cracking in the heat affected zone of the pipe girth welds [2]. Extensive testing in BWR environment has demonstrated that reduction in carbon content in ASS reduces susceptibility to IGSCC. This is in conformity with plant performance, in which higher carbon material (more than 0.04%) has cracked in service [3]. In order to provide sufficient margin for the resistance to sensitization of ASS for Advanced Boiling Water Reactor (ABWR) the maximum carbon content is specified as 0.02%. For major reactor structures, preferred material is SS316L where lower allowable strength is acceptable. To compensate for lower carbon, strength is maintained by adding nitrogen up to a maximum of 0.12 % [3].

Austenitic stainless steel grades such as SS 304, 316, 304L, 316L, 304LN, 316LN, 321, 347 [4] and their equivalents were considered for the choice of the material. SS 304 and 316 are susceptible to sensitisation and lead to weld decay. Stabilised austenitic stainless steel such as SS 321 and 347 are less susceptible to sensitisation, but may be prone to knife line attack and hot cracking during welding. Although all the low carbon grades of austenitic stainless steels viz. SS 304L, 316 L, 304LN and 316LN will satisfy the general structural integrity concerns such as fatigue, fracture, general corrosion and erosion; it was recognized that in view of the proposed design life of 100 years, aspects such as LTS and LTE will influence the material choice. Resistance to LTS for SS 304LN and 316LN is comparable whereas, resistance to LTE is superior for SS 304LN. This is because SS 316LN contains Molybdenum and the kinetics of LTE is faster in presence of Molybdenum. This implies that SS 316LN will embrittle faster than SS 304LN. Therefore, choice is SS 304LN.

4 LIFE LIMITING MATERIAL DEGRADATION MECHANISMS

Identified material degradation mechanism such as LTS and LTE studies were planned to carry out on the base and weld material of the SS 304LN grade. The work carried out and the data available so far and the under our program are described below:

4.1 Low Temperature Sensitization

Carbides nucleated by short exposures in the critical temperature range (500-800°C) without a detrimental degree of chromium depletion, can grow during service well below 500°C causing a severe degree of chromium depletion. This phenomenon is known as *Low Temperature Sensitization (LTS)*.

Extensive research on the LTS in stainless steel suggests SS 304LN and 316LN as alternative materials to combat LTS likely to be encountered in service. This is because time required for the onset of sensitization in stainless steel with low carbon and extra nitrogen is quite high and critical cooling rate below which sensitization takes place is quite low. When carbon is low (<0.03%), very long ageing time at high temperature is required for the nucleation of chromium rich carbide precipitation in sufficient quantities, which may lead to LTS. When nitrogen is also present, the diffusion coefficient of chromium is low and chromium carbide precipitation kinetics becomes sluggish [5].

Low Temperature Sensitization (LTS) studies were carried out to confirm that austenitic stainless steel components (base and weld materials of SS 304LN will not have LTS problem during service of the plant. These studies were performed on materials subjected to accelerated ageing by simulating time and temperature in such a way that the kinetics processes remains unaffected. The ageing durations of 1300 and 8000 hours at temperatures 450°C and 400°C were worked out by considering the activation energy of carbide precipitation ~ 150 kJ/mol. Material is also being subjected to thermal ageing at temperature of 350°C for 50000 hours to verify the kinetics of the sensitisation mechanism close to the operating temperature. These results would be known later. The sensitization was quantified in terms of degree of sensitization (DOS) using double loop electrochemical polarization reactivation (DL-EPR) tests. This was supported by oxalic acid etching according to ASTM 262 practice A and ASTM 262 Practice E tests. The results of the D-EPR and oxalic acid etching tests obtained till now are shown in tables 2 and 3. Typical microstructures of the virgin and aged samples are shown in figure 1.

Table-2: Results of oxalic acid etching and DOS for ageing at 400°C

Aging time(Hrs) at 400˚C	304LN-P1 (168 mm OD)		304LN-P2 (324 mm OD)	
	Etch structure	%DOS Weld HAZ	Etch structure	%DOS Weld HAZ
Virgin	Step	0.009 (Base)	Step	0.0054 (Base)
600 Hrs	Step	0.3104	Step	0.212
3000 Hrs	Step	1.1596	Step	0.368
5000 Hrs	Step	2.17	Dual	0.32
8000 Hrs	Step	1.01	Dual	0.4386

Table-3: Results of oxalic acid etching and DOS for ageing at 450°C

Aging Time(Hrs) at 450˚C	304LN-P1 (168 mm OD)		304LN-P2 (324 mm OD)	
	Etch structure	%DOS Weld HAZ	Etch structure	%DOS Weld HAZ
Virgin	Step	0.009 (Base)	Step	0.0054 (Base)
125 Hrs	Step	0.243	Dual	0.105
500 Hrs	Step	1.00	Dual	0.165
800 Hrs	Step	1.49	Dual	0.289
1300 Hrs	Step	1.504	Dual	0.504

DOS and microstructure (in 10 % oxalic acid solution) is correlated as (a) 0.01-0.1 % DOS corresponds to step structure, (b) 0.1-5 % to Dual structure and (c) more than 5 % as Ditch structure [6]. DOS below 5 % corresponding to dual structure is acceptable. Results in table 2 and table 3 show that DOS of weld HAZ increases with increase in ageing duration at given temperature. There is some scatter in the data because of the inhomogeneity in the chemical composition, which calls for some margins in the various element of the chemical composition. Microstructures of the oxalic acid etch test

given in figure 1, shows carbide precipitations along grain boundaries in aged samples for base and weld HAZ. Results of the tests on base and weld HAZ after accelerated thermal ageing, indicates that carbide precipitation along the grain boundaries is in acceptable limit. Therefore, the study carried out so far indicates that LTS may not be of concern for SS 304LN base and weld material within a time frame of 100 years. Further confidence would be gained after the results of ageing at 350°C for 50000 hours. The tests are also planned under strained and simulated reactor environment, which will be very near to the actual conditions.

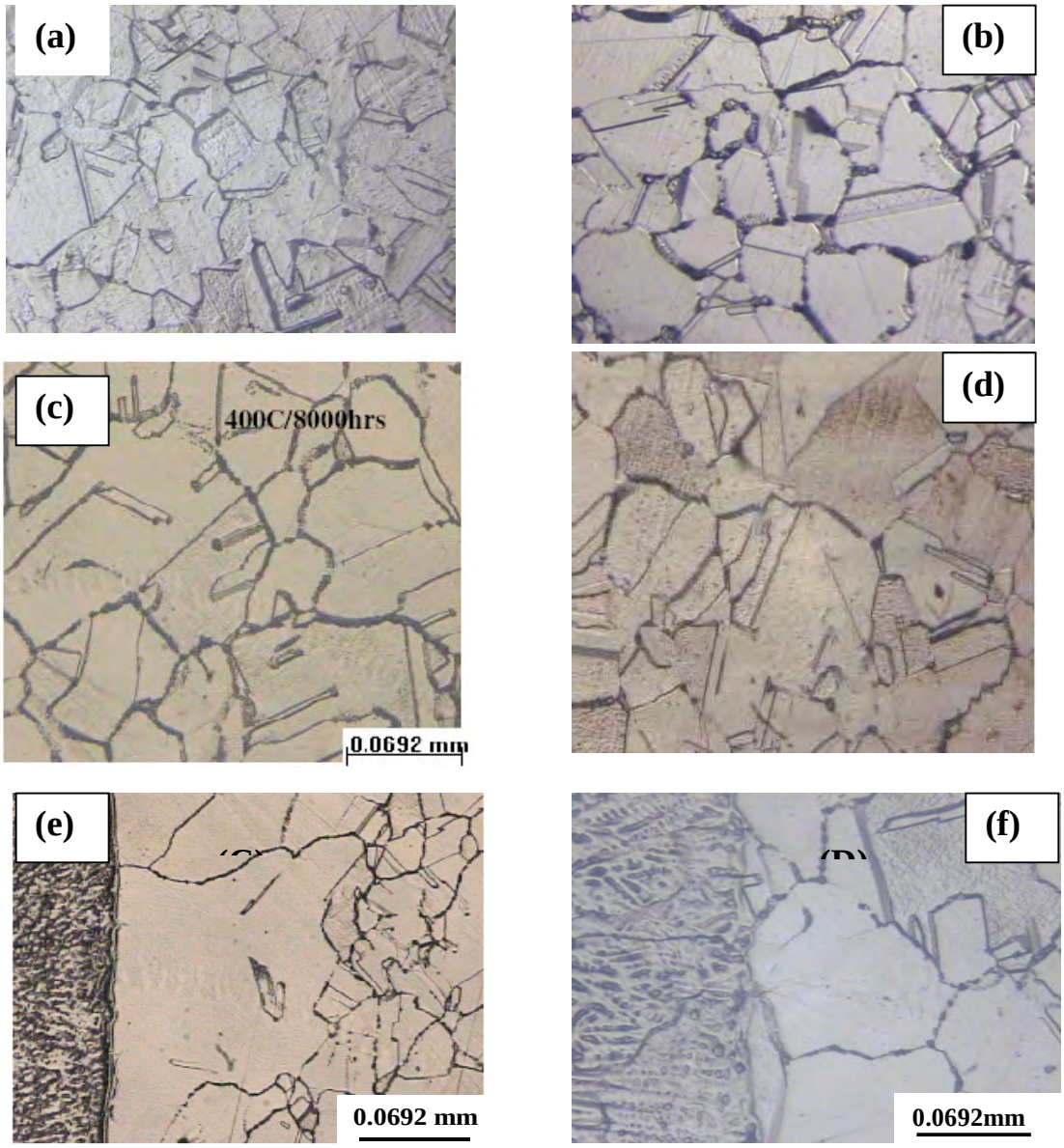

Fig 1: Microstructure of oxalic acid etching test (a) As received (b) Sensitized at 675°C (c) Base, ageing at 400°C for 8000 Hours (d) Base, ageing at 450°C for 1300 Hours (e) Weld HAZ ageing at 400°C for 8000 Hours (f) Weld HAZ ageing at 450°C for 1300 Hours

4.2 LOW TEMPERATURE EMBRITTLEMENT

Hot cracking or solidification cracking [7] is of concern in ASS welds. The solidification cracking results from the segregation of low melting point liquid along the grain boundaries during last stage of solidification. If sufficient stresses are generated before the final solidification, boundaries may separate to form a crack. Presence of retained ferrite in the ASS weld effectively prevents hot cracking. The higher solubility of impurities in ferrite than austenite results in less segregation of low melting impurities, which helps in preventing hot cracking. Delta ferrite has lower thermal coefficient of expansion (α), which helps in reduction of thermal stresses. ASME Boiler and Pressure vessel code calls for minimum of 5% δ-ferrite (or 5 FN) in ASS weld to prevent solidification cracking. Transformation of this δ-ferrite into a brittle phase due to prolonged exposure to temperature of about 300 deg C can cause Low Temperature Embrittlement. The kinetics of low temperature embrittlement is faster in presence of Molybdenum [8].

LTE studies were carried out to confirm that austenitic stainless steel (SS 304LN) welded by E308L/ER308L would not have problem of loss in toughness during service of the plant. The ferrite content in the weld metal was in the range of 5-8 FN. These studies were performed on materials subjected to accelerated ageing by simulating time and temperature in such a way that the kinetics processes remains unaffected. The ageing durations planned are of 5000, 10000, 20000 and 50000 Hours at temperatures 400°C, 350 and 300°C. Loss in toughness has been quantified by carrying out the impact test. At present, work has been completed for 5000 hours of ageing. The result indicates no reduction in toughness for the ageing duration of 5000 hours at various temperatures.

5 WELDING PROCESS OPTIMIZATION

Optimizing the welding process and technique, due to reduction in heat input and residual stress would reduce IGSCC. The propensity to sensitization can also be reduced by high deposition welding process and narrow gap welding. Existing welding process used in welding of pipes is by GTAW for root pass and filling passes by SMAW as per ASME Section IX [9]. Although fracture toughness properties of the GTAW is comparable to that of base metal (good for LBB) but GTAW is a low deposition process leading to high heat input which is detrimental for resistance to sensitization. Fracture toughness of the SMAW is inferior compared to that of base metal, although deposition rate is higher compared to that of GTAW. Welding process suitable for welding of pipes should have high deposition rate, comparable fracture toughness and superior resistance to sensitisation. These can be obtained by use of hot wire GTAW Process (high deposition rate) with Narrow Gap Technique is suitable for welding of pipes of ASS. The results of welding process and technique optimisation is described below:

5.1 RESIDUAL STRESS EVALUATION

In order to demonstrate the benefits of narrow gap welding, residual stress was measured on a pipe weld joints of 300 mm outer diameter and 25 mm thickness welded (manually) using most widely and versatile welding process, GTAW as root pass (few initial passes) and SMAW as filling passes. The weld joints were having different groove angle. *Manual SMAW with various groove angles* (324 mm outer diameter pipe) shown in Fig. 2 as (a) Conventional groove with 75^{0} included angle, (b) Narrow groove with 0^{0} (width 16mm), (c) Narrow groove with 0^{0} (width 13mm) and extra cap pass. These welds and *Manual GTAW with conventional groove* (168 mm outer diameter pipe) was used for residual stress

evaluation. Residual stress was measured using blind hole drilling method at weld root and top. Fig. 3 shows the significant reduction in the residual stress resulting from narrow gap welding.

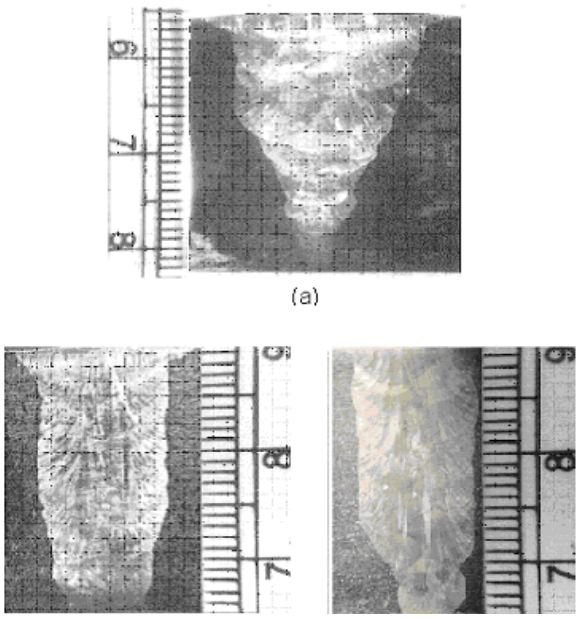

Fig. 2 Cross section of weld joints with different gap or groove width

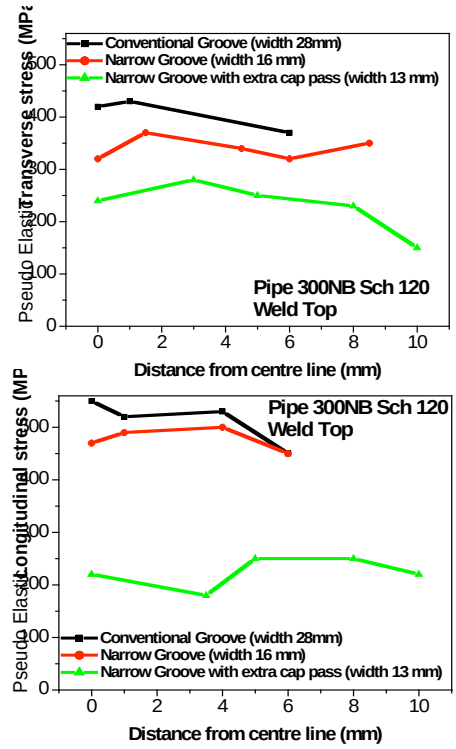

Fig. 3 Residual stress distribution

Mechanized hot wire GTAW with narrow gap technique and *conventional manual GTAW* were compared for residual stress and axial shrinkage (shown in figures 4 and 5). Mechanized hot wire GTAW is a high deposition rate (three times that of conventional GTAW) welding process. Total heat input to the welding is also reduced due to high deposition rate leading to reduction in propensity of weld HAZ to sensitization.

The figures 4 and 5 shows that residual stress and shrinkage in weld joints of mechanized hot wire GTAW are less compared to that of conventional GTAW. Variation of residual stress in weld joints produced by mechanized hot-wire GTAW is also less compared to that of manual GTAW.

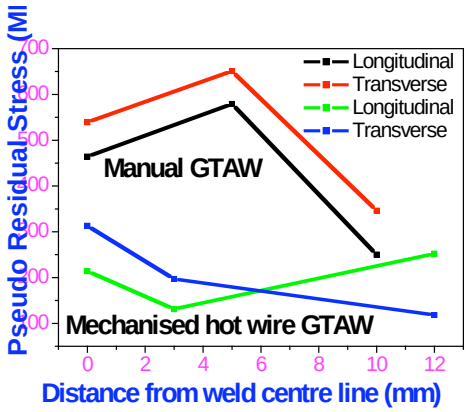

Fig 4: Residual stress in conventional GTAW and hot wire GTAW

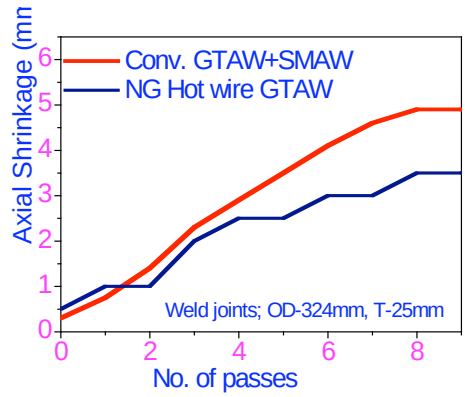

Fig 5: Shrinkage in conventional GTAW and hot wire GTAW

5.2 MINIMIZATION OF SENSITIZATION IN WELD HAZ

Sensitization of ASS material can be reduced by material optimization (detailed in section 2) and weld optimization. Weld HAZ is subjected to temperature range of 500-800°C during heating and cooling. Increasing the cooling rate can reduce the chances of sensitization. Cooling rate (figure 6) of the weld HAZ in case of hot wire GTAW is 3 times faster compared to that of manual GTAW. The temperatures were measured using thermocouples at various distances from the weld center line. This is because of the lower heat input of 0.9 KJ/mm for hot wire GTAW and 1.89 KJ/mm for manual GATW.

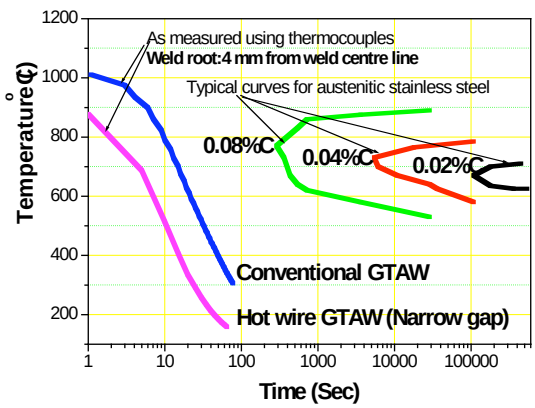

Fig 6: Time-Temperature for material and cooling rate in weld HAZ

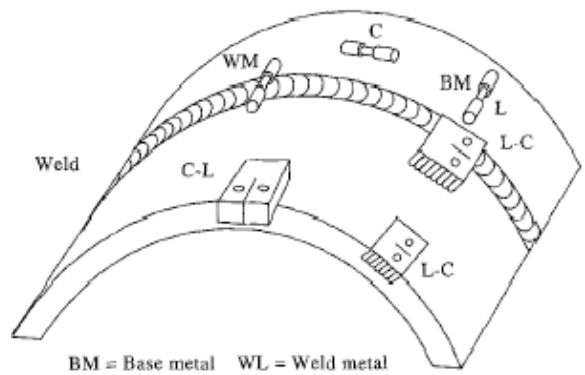

Fig 7: Location of Round LCF and CT Specimen

5.3 FATIGUE AND FRACTURE TOUGHNESS

It is desirable to have comparable fatigue and fracture properties for weld with respect to base to maintain homogeneous characteristics of the material. Fatigue and fracture resistance of the welds were also quantified by carrying out the tests on specimens as per the guidelines of ASTM standard. The details of the results are described below:

Low Cycle Fatigue (LCF) and Fatigue Crack Growth Rate (FCGR) tests were carried out on specimens machined from the actual pipe welds. The location of specimen with respect to pipe weld is shown in figure 7. Result (shown in figure 8) shows that low cycle fatigue life of the weld joint (SMAW) is lower compared to that of base metal. Tests (on compact tension specimen) show higher FCGR for weld joints (SMAW) as shown in figure 9. FCGR has also been compared with that given in ASME Section XI. [10] and is shown in figure 10.

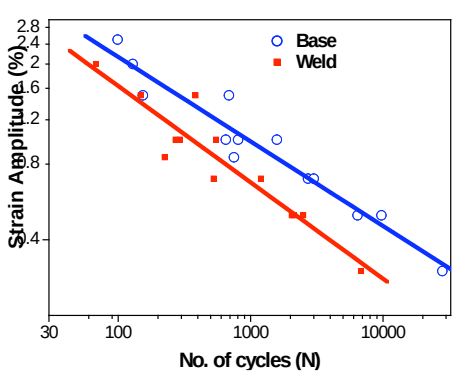

Fig 8: Low cycle fatigue curve

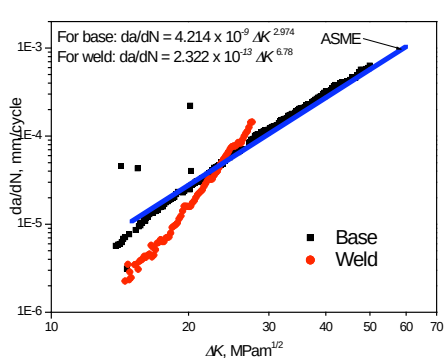

Fig 9: Fatigue crack growth rate curve

Fracture toughness tests require load and crack mouth opening displacement (CMOD) for fracture resistance characterization. Measured load verses CMOD curves for weld of SMAW is shown in figure 10. Figure indicates that in case of weld (SMAW) there is rapid load drop as compared to base. This clearly indicates that there is excessive crack tearing. GTAW has much higher crack tearing resistance as compared to SMAW. This observation is further highlighted in fracture resistance (J-R) curves shown in figure 11. The figure clearly quantifies that fracture resistance of GTAW is significantly higher than that of SMAW. J-R curve of conventional and narrow grove weld joints are same (shown in figure 12).

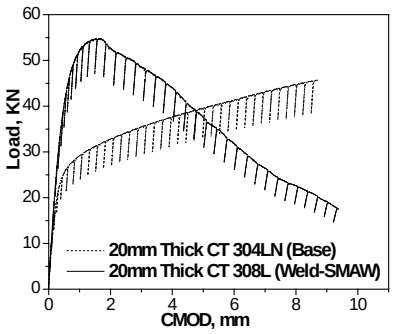

Fig 10: Comparison of base and SMAW weld joint

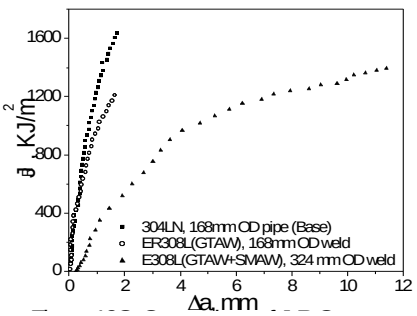

Fig 11: Comparison of J-R curves for SMAW & GTAW

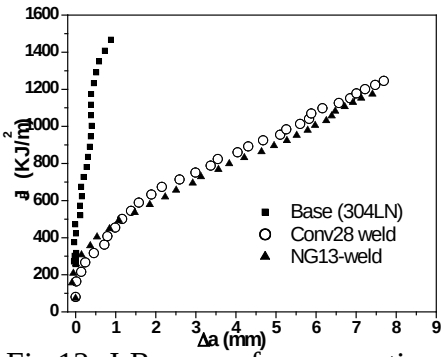

Fig 12: J-R curves for conventional groove and narrow gap SMAW

6 LEAK-BEFORE-BREAK

This concept aims at the application of fracture mechanics principle to demonstrate that pipes are very unlikely to experience sudden catastrophic break without prior indication of leakage. LBB evaluation is divided in three stages: In the **first level**, material specification (as detailed in section 3) and fabrication (as detailed in section 5) were optimized to improve quality of the material and weld to prevent crack initiation, thus avoiding the possibility of crack propagation. In addition to the mechanical properties, fatigue and fracture properties were evaluated. In the **second level**, a crack of certain length and depth that has escaped detection is postulated. But, it can be shown that for the duration of plant life this crack will not grow enough to penetrate the wall, let alone cause catastrophic failure. This has been demonstrated by carrying out tests on actual pipes and pipe welds with postulated part through crack to show that there is not significant crack growth for the anticipated loading cycle during the plant life. This is described in detail in section 5.2. In the **third level**, through thickness crack is postulated and show that the resultant through-wall crack is stable, produces leakage in sufficient quantity to enable detection for timely corrective action. In addition it is shown that if design basis Safe Shutdown Earthquake (SSE) occurs then crack remains stable. This has been demonstrated by carrying out tests on actual pipes and pipe welds with postulated through crack to show that there is no unstable crack growth. This is described in detail in section 6.3

6.1 DESCRIPTION OF TESTS

Pipe material was austenitic stainless steel of SA312 type 304LN. Tests were carried out on seamless pipe and pipe weld of nominal outer diameter 324 mm and 168 mm having thickness of 27 mm and 14.3 mm respectively. The pipes were in solution-annealed condition. Gas Tungsten Arc Welding (GTAW) was used for welding of 6”NB pipe. GTAW (for root pass and few passes) and Shielded Metal Arc Welding (SMAW) (filling passes) were used for welding of 12”NB pipe [10]. The tests were conducted in four point bend loading condition (figure 13). Pipes with part through and through-wall notch were

subjected to fatigue loading till the crack has grown through thickness. Thereafter fracture tests were carried out on through-wall cracked pipes. The final through-wall crack size after fatigue test was taken as the initial crack size for the fracture tests.

Fig. 13: Actual experimental set up for pipe test

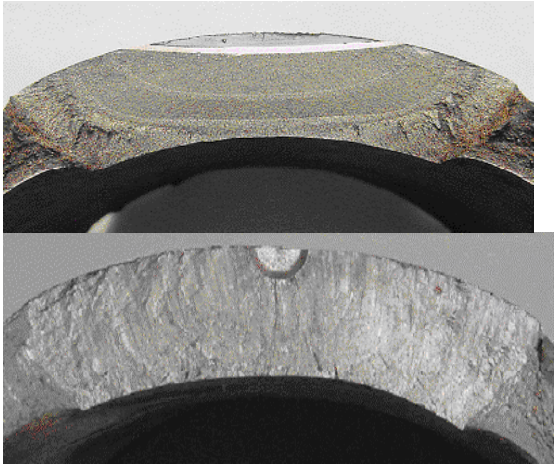

Fig 14: Fracture surface showing crack shape during fatigue crack growth

6.2 FATIGUE TESTS (LEVEL II OF LBB)

In these tests, the pipes containing machined notch were subjected to cyclic loading. Number of cycles to crack initiation and the evolution of crack shape during crack growth was monitored. Fracture surfaces of fatigue-tested pipes are shown in figure 14. The results of these studies on fatigue crack growth resistance behaviour of the ASS pipe and pipe welds can be summarized as:

- For the typical stress range expected in the piping of AHWR, the number of cycles to crack initiation is very large compared to the expected number of cycles (Fig. 15).
- Fatigue crack growth also depends on the aspect ratio. Aspect ratio (2C/a) at the point of through thickness lies in the range of 3 to 4 irrespective of the initial notch aspect ratio (Fig. 16). This provides justification for the usual assumption in LBB that for a reasonable part through crack the length at break out (leakage size crack) is not likely to be more than that is normally assumed. Crack growth in surface direction is more for the aspect ratio greater than 4 compared to thickness direction. Notch of semi circular front (aspect ratio is crack length by crack depth=2) maintains its shape till through thickness (Fig. 14). Number of cycles required for crack to grow through thickness is very large compared to those expected during plant life.
- The use of the fatigue crack growth curve given in ASME Section XI [11] will produce a conservative result (Fig. 17).

6.3 FRACTURE TESTS (LEVEL III OF LBB)

The fatigue test was continued till the crack grew through-wall. The pipe containing through-wall crack was subjected to monotonically increasing load till collapse. Normalized moment and crack extension plot of the pipe and pipe weld are shown in Figs. 18-19. The results of the fracture resistance can be summarized as:

1. Initiation of crack growth occurred at a load lower than the maximum load bearing capacity of the pipe, e.g. the crack extension at maximum bending moment, in pipe and pipe weld (GTAW), are 4.5 and 8.5 mm respectively. This shows that failure is not due to plastic collapse alone and therefore fracture mechanics has a role in prediction of instability condition in pipes.

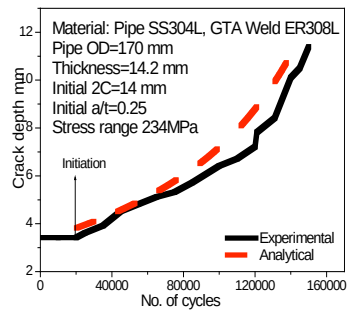

Fig. 15: Crack initiation and growth with no. of cycles

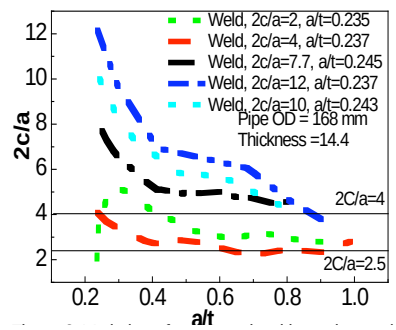

Fig. 16: Variation of aspect ratio with crack growth

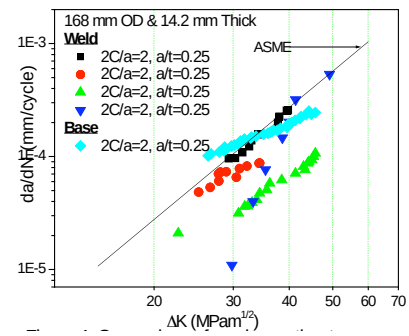

Fig. 17 Crack growth rate curve from pipe tests and ASME

2. Drop in bending moment after maximum moment is faster in weld.
3. In the case GTAW, the crack extension in pipe (base) and the pipe (weld) is comparable (Fig. 18). But in case of GTAW + SMAW, the crack extension is much more than that in base (Fig 19). This indicates that fracture resistance of pipe and SMAW weld differs considerably whereas in case of GTAW weld this difference is not significant. Thus there is a substantial incentive towards employing GTAW for welding of ASS pipes.

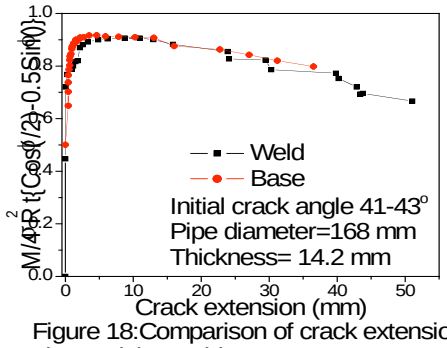

Figure 18:Comparison of crack extension for pipe andpipe weld

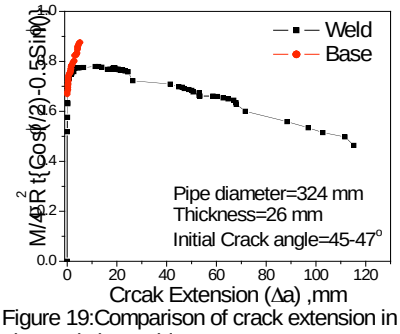

Figure 19:Comparison of crack extension in pipe and pipe welds

7 Prediction of limit load

Limit load analysis is one of the simplest methods to predict the instability of the piping system. This is also known as net section collapse. Analytical limit load (P_o) was calculated based on initial crack angle by expression,

$$P_o = (16\sigma_f R^2 t)/(Z-L)[\cos\{(a/2t)(\theta/2)\} - (a/2t)\sin\theta]$$

Where σ_f is flow stress i.e. average of yield and ultimate tensile strength of material in MPa, R is mean radius of pipe in mm, Z is outer span and L inner span in mm, θ is half the crack angle in degree, t is thickness in mm. The results indicate that the limit load expression requires modification for using it for welds. Based on the results of the several pipe welds, existing expression for limit load evaluation for pipe can be modified by incorporating a multiplication factor for good prediction of limit load in case of pipe welds. The suggested factor is 0.85 for pipes welded using GTAW and 0.7 for pipes welded using GTAW + SMAW. Modified expression can be written as:

$P_o = 0.85\ (16\sigma_f R^2 t)/(Z-L)[\cos\{(a/2t)(\theta/2)\} - (a/2t)\sin\theta]$ for GTAW welds

$P_o = 0.70\ (16\sigma_f R^2 t)/(Z-L)[\cos\{(a/2t)(\theta/2)\} - (a/2t)\sin\theta]$ for GTAW + SMAW welds

8 CONCLUSIONS

Among the various low carbon grades of austenitic stainless steels viz. SS 304L, 316L, 304LN and 316LN, choice of SS 304LN is based on its satisfactory low temperature sensitization behaviour and superior low temperature embrittlement behavior. The IGSCC resistance is further improved by adopting high deposition rate (hot wire GTAW) process and narrow gap technique, which has shown reduced residual stresses compared to conventional welding. Further during welding, the margin on sensitization in terms of time temperature (cooling rate) is higher in case of hot wire GATW. Gas Tungsten Arc Welding gives much better fracture resistance compared to Shielded Metal Arc Welding. A combination of narrow gap technique and hot wire GTAW will provide an added assurance against failure due to IGSCC/fatigue/fracture. Number of cycles for crack initiation in AHWR piping is considerably higher than the number of cycles anticipated during the design life. The use of the fatigue crack growth curve given in ASME Section XI will produce a conservative result where as Paris constants determined for this material using CT specimen gives good prediction. Crack growth in depth direction is more than that in length direction. Aspect ratio (2C/a) at the point of through thickness lies in the range of 3 to 4 irrespective of the initial notch aspect ratio, thus favouring Leak-before-break. The load carrying capacity of a through-wall cracked pipe is higher than the maximum credible loading due to a Safe Shutdown Earthquake. Thus, AHWR piping has been shown to satisfy the Leak-before-break criterion. Suitable multiplication factor has been suggested for prediction of limit load of pipe welds (GTAW and SMAW) based on flow stress of the base material.

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