FATIGUE STUDIES ON STAINLESS STEEL PIPING MATERIALS AND COMPONENTS: INDIAN AHWR

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ABSTRACT

As a part of component integrity test program at Bhabha Atomic Research Centre, fatigue tests on full scale pipe and pipe welds were conducted in addition to CT and TPB specimens. In this paper the outcome of this program is discussed. Specimen testing was conducted to determine the basic cyclic stress strain curve, LCF and FCGR properties. FCGR tests were conducted on CT and TPB specimens to understand the effect of different conditions: Specimen level tests result show that, for the present grade of material, the FCGR is not significantly affected by specimen type (CT and TPB), specimen thickness and notch orientation. FCGR resistance of the hot wire GTAW is superior compared to that of conventional SMAW. The effects of stress ratio are mildly significant at lower R-values for base metal but are significant for weld metal.

Component tests were conducted to understand the effect of the following variables: (a) Component type and size: pipe and pipe weld, Pipe diameters 170 mm and 324 mm, (b) Pipe and pipe weld: initial notch in pipe base, and girth welded pipe, (c) Pipe welds: Conventional GTAW/SMAW and hot wire narrow gap GTAW, (d) Environment: Air and water, (e) Type of loading: Constant amplitude cyclic, vibration, Block, overload and underload

Results indicated that the fatigue life of the component is reduced under water environment compared to air environment. Fatigue life of the pipe subjected to block loading (increasing stress ratio followed by decreasing stress ratio), intermittent overloading and underloading is also decreased compared to that of constant amplitude loading. Vibration loading reduces fatigue life significantly. Crack growth in thickness direction is more compared to circumferential direction for all types of loading which is desirable for demonstration of LBB criteria. Fatigue life of the notched component has also been predicted using the Paris constants data from the specimen level tests. Fatigue crack growth and the crack shape of the growing crack have been evaluated for regular interval of loading cycles. The predictions compares well with those of experiments.

INTRODUCTION

Fatigue is one of the mechanisms, considered active in the piping system, which may lead to crack initiation from either the highly stressed regions or the undetected flaws. It is desirable to confirm that crack initiation, due to cyclic loading in service period of the reactor, will not occur. Behavior of initiated cracks under cyclic loading is also of concern for safe operations of the reactor. In addition to this safety considerations also call for satisfaction of Leak-Before-Break (LBB) criteria by demonstrating that the flaw at the end of life will not propagate through-wall [1]. Prediction of fatigue crack growth is based on Low Cycle Fatigue (LCF) and Fatigue Crack Growth Rate (FCGR) properties of the specimens. In order to validate this approach large number of fatigue tests on component and specimen were conducted. The tests were planned to account variabilities such as pipe size, thickness, notch orientation/location, manufacturing process, base/weld metal etc. Further, the aim was to understand the behaviour of crack growth under predominant bending moment. This aspect is important for Level-2 LBB requirements, where it is essential to prove that the crack grows more rapidly in depth (thickness) direction as compared to surface (circumferential) direction. The data of the actual piping component tests and standard specimens will also be useful in the accurate prediction of the remaining life of the component which is of concern to most of the older Nuclear Power Plants.

As a part of component integrity test program at Bhabha Atomic Research Centre, 40 fatigue tests on stainless steel pipes and welds were conducted. In addition, fatigue tests were also conducted on the standard specimens such as CT and TPB. In this paper the outcome of this program is discussed.

Fatigue crack growth based on the Paris Law has been studied extensively using compact tension or three point bend specimens following ASTM E647 [2]. The ASME Boiler and Pressure Vessel Code Section XI also gives the fatigue crack growth rate curve for air environments for austenitic stainless steels [3] based on small specimens. In this paper the curve corresponding to air environment has been referred to for comparison purposes for the material (SS 304LN) under study. The effects of stress ratio on the fatigue crack growth behaviour are widely available for standard specimens [4]. These crack growth data obtained from CT specimens are used conveniently for prediction of crack growth in surface flawed components with assumptions such as surface flaw assumes semi elliptical shape during growth, crack growth rate is independent of direction and stress state etc. Few researchers [5-9] have carried out fatigue crack growth studies on full scale piping components. Shimakawa et al [10] performed studies on surface cracked pipes to establish a method based on non-linear fracture mechanics.

EXPERIMENTAL DETAILS

Piping material of austenitic stainless steel of SA312 type 304LN in solution-annealed condition, conforming to the specifications of ASME Section II and Section III of Boiler and Pressure Vessel (B&PV) Code has been used for studies. Pipes of 170 mm and 324 mm outer diameter having 14.2 mm and 25 mm thickness respectively have been considered. Welding of pipes has been carried out as per the procedure given in ASME Section IX of the B&PV code. The Gas Tungsten Arc welding (GTAW) was used for welding of 170 mm outer diameter pipe. GTAW (for root pass and few passes) and Shielded Metal Arc Welding (SMAW) (filling passes) were used for welding of 324 mm outer diameter pipe. Filler wire ER308L has been used for GTAW and electrode E308L for SMAW. Quality assurance and acceptance of the weld joints were as per the requirement of ASME Section III. The tests were carried out in as welded condition. The chemical composition of the pipe and pipe weld materials are given in table (1). The tensile properties of the pipe and pipe weld for each size are given in table (2).

Table (1): Chemical composition of material in weight %

Pipe OD, t (mm)	Material	C	Mn	Si	P	S	Cr	Ni	N	Balance
Stainless steel (304LN)										
324, 27	Base	0.024	1.73	0.55	0.022	0.001	18.8	9.25	0.15	Fe
324, 27	Weld	0.03	1.1	0.56	0.021	0.01	19.8	11.06	0.1	Fe
170, 14	Base	0.013	1.57	0.36	0.025	0.001	18.6	8.46	0.11	Fe
170, 14	Weld	0.03	1.66	0.39	0.017	0.01	19.98	9.97	0.08	Fe

Table (2): Tensile properties of materials

Pipe OD (mm)	Material	σ_y (MPa)	σ_u (MPa)	% El
324	Base	324	660	63
324	Weld	450	593	42
170	Base	318	650	67
170	Weld	400	586	57

Specimen Testing

Specimen testing was conducted to determine the basic cyclic stress strain curve, Low Cycle Fatigue (LCF) and Fatigue Crack Growth Rate (FCGR) properties.

The LCF tests were conducted on standard uniaxial specimens under strain-controlled condition in which strain range (Δε) was varied from 0.4 to 4.0 %. In all 40 specimens were tested. The outcome of these tests was cyclic stress strain and low cycle fatigue curve for base and weld metal.

The FCGR tests were conducted on Compact Tension (CT) and Three Point Bend (TPB) specimens. The outcome of these tests was the material constants of FCGR Law, that is, Paris Law. About 50 specimens were tested at different conditions to understand the effect of following :
   a) Specimen type: CT and TPB (location of the specimens is shown in figure 2)
   b) Base and Weld: Specimens were machined from pipe base and pipe weld.
   c) Welding process: Conventional GTAW/SMAW and Hot wire GTAW,
   d) Welding technique: Conventional V-Groove and Narrow Gap,
   e) Stress ratio (R=Minimum load/Maximum load): 0.1, 0.3 and 0.5.

f)   Notch orientation: Specimens were machined in two orientations namely LC and CL. The notch is in longitudinal direction with respect to the pipe in CL orientation, whereas it is in circumferential direction in LC orientation.

Component Testing

The fatigue crack growth studies were conducted on pipes and elbows with pre-machined notch. In all 17 tests were conducted to cover the effect of the following variables:

a)   Component type and size: pipe and pipe weld, Pipe diameters 170 mm and 324 mm,
b)   Pipe and pipe weld: initial notch in pipe base, and girth welded pipe,
c)   Pipe welds: Conventional GTAW/SMAW and hot wire narrow gap GTAW,
d)   Environment: Air and water,
e)   Type of loading: Constant amplitude cyclic, vibration, Block, overload and underload .
f)   Notch size or notch aspect ratio: Notch length (2C), Notch depth (a) and aspect ratio. Actual size of notch and aspect ratios.

Typical Experimental Procedure for Component Tests

Schematic loading condition and actual test set up for pipe tests are shown in figures 1. Actual test set up consists of a servo hydraulic loading system, a support for the specimen and various instruments for measurement of data. The support system consists of two pedestals with two rollers, which provides four-point bending. This type of loading ensures that the mid section of the specimen, where the notch is located, is subjected to pure bending.
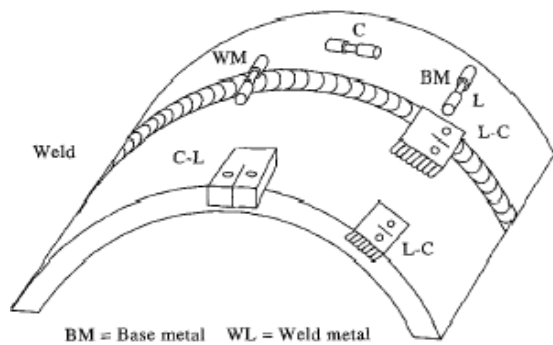

Fig 1: Location of Round Tensile and CT Specimen

Fig 2: Tests set up for fatigue test on pipe

SPECIMEN TEST RESULTS

Low Cycle Fatigue

Low Cycle Fatigue (LCF) tests were carried out on specimens machined from the actual pipe welds. The location of
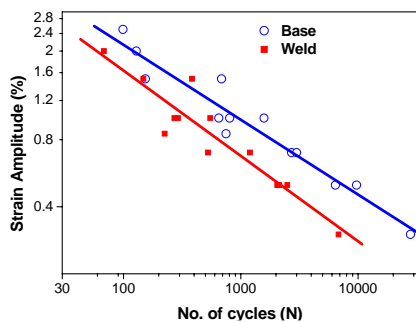

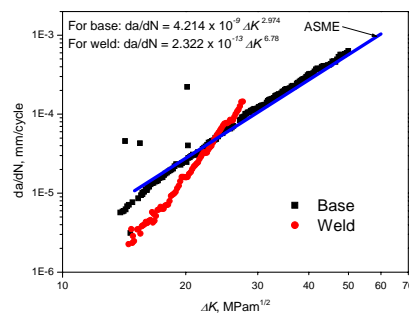Fig 4: Low cycle fatigue curve for base and weld

Fig 5: Fatigue crack growth rate for base and weld

specimen with respect to pipe weld is shown in figure 8. Result (shown in figure 9) shows that low cycle fatigue life of the weld joint (SMAW) is lower compared to that of base metal.

Fatigue Crack Growth Rate

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 2.Tests (on compact tension specimen) show higher FCGR for weld joints (SMAW) as shown in figure 5. FCGR has also been compared with that given in ASME Section XI [2] and is shown in figure 5.
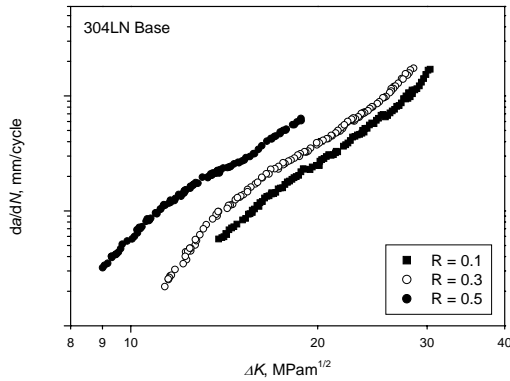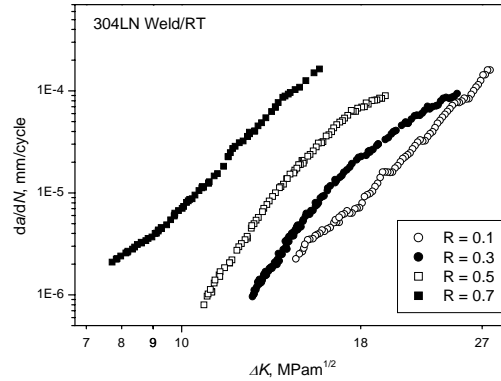

Fig 6: Variation in FCGR with stress ratio for base   Fig 7: Variation in FCGR with stress ratio for weld

Effects of stress ratio on fatigue crack growth rate are shown in figures 6 and 7 for base and weld metal. Figures indicate that the there is marginal effect of stress ratio in case of base metal but fatigue crack growth rate increases significantly with increase in stress ratio at given crack driving force in case of weld.
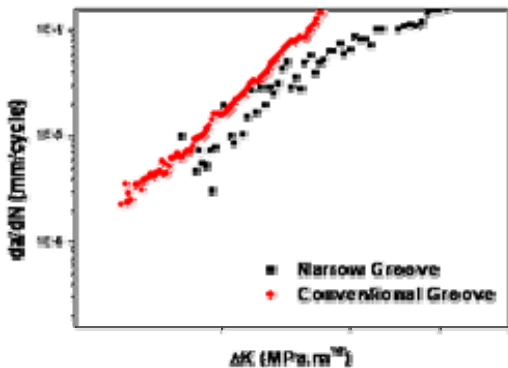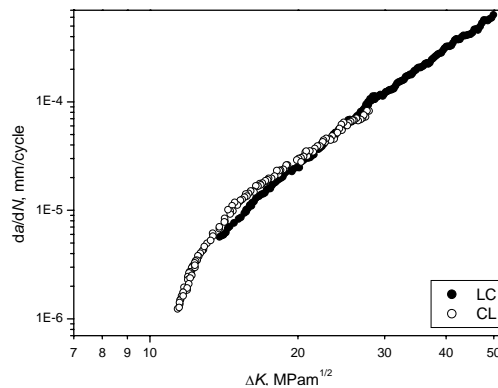

Fig 8: Variation in FCGR with groove size

Fig 9: Variation in FCGR with notch orientation

Effect of narrow gap (12 mm gap at outer diameter) and conventional V-groove (25 mm gap at outer diameter) on FCGR are shown in figure 8. Figure shows marginally superior crack growth resistance in case of narrow groove compared to that of conventional groove. This resistance increases with increase in ΔK. This might be due to the reduced residual stresses in case of narrow groove. Effect of notch orientation (notch plane in circumferential-LC and notch plane in circumferential-CL) of FCGR is shown in figure 9. Figure shows no difference in FCGR. This is due to the equiaxed grain size along both directions.

COMPONENT TEST RESULTS

The basic aim of carrying out the fatigue tests on components (that is, pipe and welds) was to understand the effect on FCGR constants vis-à-vis values determined using specimen, and the behaviour of crack growth under more realistic stress field. A brief detail of the fatigue tests on pipes and pipe welds was discussed in previous section of experimental details. In all the tests the initial notch was machined using a milling cutter. In these tests, the pipe and pipe welds containing machined part through notch were subjected to cyclic loading. Numbers of

cycles to crack initiation and the evolution of crack shape during crack growth were monitored. The test conditions and the results are given in table 3.

Effect of Environment:

Crack length and number of cycles to reach through wall of the pipe has been shown in figure 10 for stainless steel (SS 304LN) in air and water environment. Results indicate that crack growth life has been reduced by 2.5 times in water environment in comparison to air environment. Fatigue life curve generated by various researchers [5] for various steel materials under reactor water environment has shown reduction in fatigue life compared to that of air.
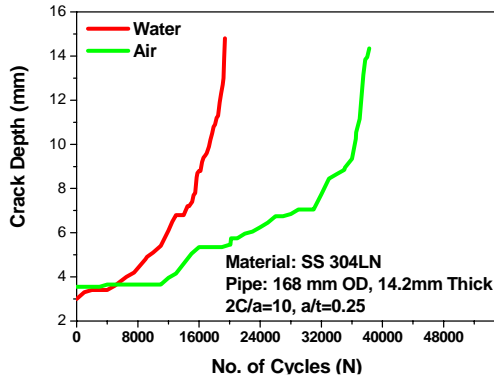

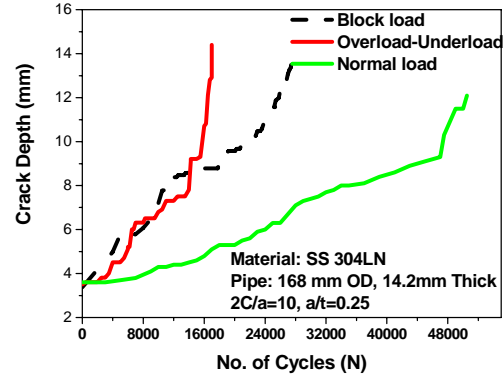Fig 10: Effect of water environment on FCGR

Fig 11: Effect of block, overload and underload on FCGR

Effect of Variable Amplitude, Over Load and Underload

Crack length and number of cycles to reach through wall of the pipe has been shown in figures 11 for stainless steel (SS 304LN) in air environment under variable amplitude (block loading), underload and overload and their combination. The results indicate reduction in fatigue crack growth life for variable amplitude loading compared to constant amplitude loading. Here variable amplitude loading has been applied in terms of block loading of the varying load ration keeping maximum load constant (table 3). In other words we can say that there is variation in the mean load. The observation is in consistent with the data available in the literature. Here reduction in life is approximately half to that of constant amplitude loading. Effect of under load and overload on fatigue life is more deleterious compared to that of block loading. Here overloading was applied by increasing the maximum load by 50% and under load by decreasing the minimum load by 50 % (table 3).

Table 3 Details of fatigue test results on full scale pipe and pipe welds

Test No.	Load (kN)		Stress range (MPa)		Number of Cycles		Test condition
	Maximum	Minimum	Maximum	Minimum	Initiation at depth	Through wall	
SSP B6-1	-258	-25.8	254.989	25.499	4000 (0.10 mm)*	38750	Normal loading
SSP B6-7	-258	25.8	255.730	25.573	1000 (0.30 mm)	19500	Water Environment
SSP B6-10	-258	-129	258.312	129.156	6000 (0.10 mm)	72600	Water Environment
SSP B6-14	-258	-25.8	263.763	26.376	500 (0.01 mm)	19400	Normal loading
	-387	-258	395.645	263.763			Over loading
	-258	+129	263.763	131.882			Under loading
SSP B6-	-278	-27.8	285.237	28.524	2000 (0.8 mm)	27600	Block load 1
	-278	-139	285.237	142.618			Block load 2

15	-278	-222.4	285.237	228.189			Block load 3
	-278	-139	285.237	142.618			Block load 4
	-278	-27.8	285.237	28.524			Block load 5
SSP B6-16	-55	-5.5	56.344	5.634	No crack initiation observed		Vibration loadig
	-258	-25.8	264.306	26.431	1000 (0.30 mm)	14150	Normal loading
SSP B6-17	-55	-5.5	57.581	5.758	No crack initiation observed		Vibration loading
	-258	-25.8	270.107	27.011	1002000 (0.30 mm)	1013400	Normal loading

Effect of Vibration Loading

Vibration loading was simulated by application of low amplitude (constant) loading and frequency of the order of 5-10 Hz. The load applied during the tests was 10 % of the load carrying capacity or 20 % of the yield strength of the material. The low amplitude loading was applied for 10 lac cycles with a frequency of 10 Hz on one pipe (SSPB6-17) and 5 Hz on another pipe (SSPB6-16). There was no crack initiation form the notch. Thereafter constant amplitude loading with higher load was applied. The comparison of crack length Vs number of cycles for the pipe with vibration loading followed by normal loading and without vibration loading (only normal loading) is shown in figure 12. Results indicate that there is no effect of frequency but the fatigue life of the pipe subjected to vibration loading has reduced to one third of the normal loading only.
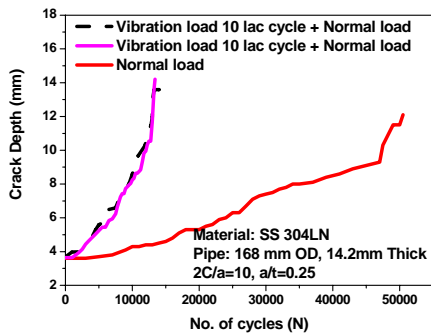

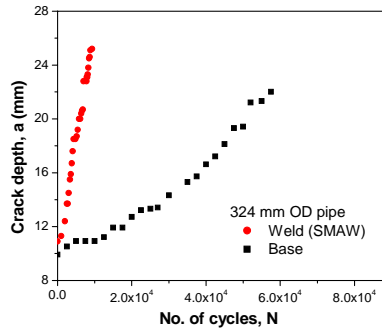Fig. 12: Comparison of fatigue crack growth under vibration+normal and normal loading

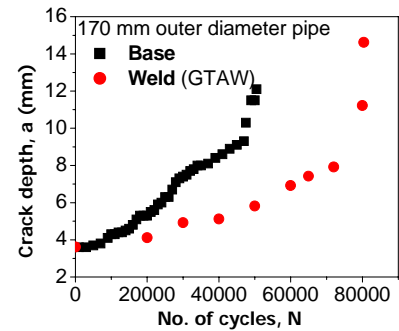Fig. 13: Comparison of fatigue crack growth for pipe (base) and pipe weld (SMAW)

Fig. 14: Comparison of fatigue crack growth for pipe (base) and pipe weld (conventional GTAW)

FCGR in Pipe (base) and pipe weld

Figure 13 and 14 shows the fatigue crack growth rate in pipe (base) and pipe weld. In one case, part through notch has been machined in the circumferential direction of pipe and other case in pipe weld keeping test conditions same. It has been found that crack growth in case of SMAW is significantly higher compared to that of base (figure 13) where as conventional GTAW shows marginally higher crack growth. Hot wire GTAW has been shown to be much superior to SMAW and marginally superior to conventional GTAW. This is shown in figure 15. Superiority of the hot wire GTAW can be explained in terms of heat input required during welding. Heat input in case of conventional GATW is significantly higher to that of the hot wire GTAW which results in higher residual stresses and leads to reduction in fatigue crack growth life for same condition of loading.
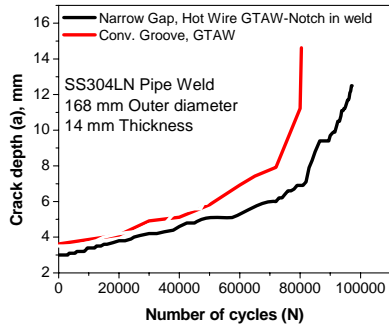
Fig. 15: Comparison of fatigue crack growth in pipe weld (conventional GTAW and hot wire GTAW)
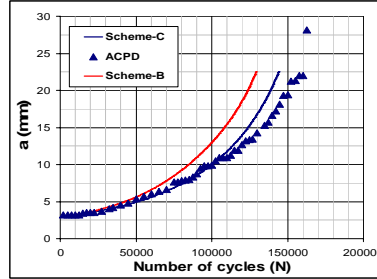

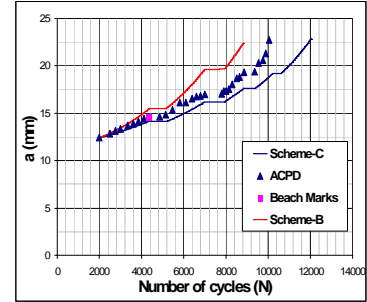Fig. 16: Comparison of fatigue crack growth in pipe (experimental and analytical)

Fig. 17: Comparison of fatigue crack growth in pipe weld, SMAW (experimental and analytical)

Analytical Study for prediction of crack growth

The Paris law has been used for the prediction of fatigue crack growth life. To carry out the analysis, Paris constants determined for pipe (base) and pipe weld materials using Compact Tension (CT) specimens machined from the actual pipe/ pipe weld have been used.. Analyses have been carried out to predict the fatigue crack growth life of the austenitic stainless steel pipes/ pipes welds having part through cracks on the outer surface. In the analyses, Stress Intensity Factors (K) has been evaluated through two different schemes. The first scheme considers the 'K' evaluations at two points of the crack front i.e. maximum crack depth and crack tip at the outer surface. The second scheme accounts for the area averaged root mean square stress intensity factor (K_{RMS}) at deepest and surface points [11]. The experimental and analytical results for the crack growth using both schemes are shown in figures 16 and 17 for pipe (base) and pipe weld respectively. In these figure ACPD indicates experimental crack growth measured using alternating current potential difference technique. It has been found that the crack growth prediction using K_{RMS} approach is closer to experiment. Crack growth analysis has also been performed using Paris constants given in ASME Sec XI [2] and result is shown in figure 18. The figure indicates significantly higher crack growth compared to experiment. Crack growth and the crack shape with loading cycles have also been evaluated using the second scheme and compared with experimental results (figure 19). The crack growth in depth direction has shown to be higher compared to the length direction in experiment as well as analysis (figure 20).
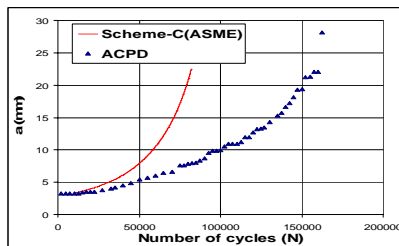

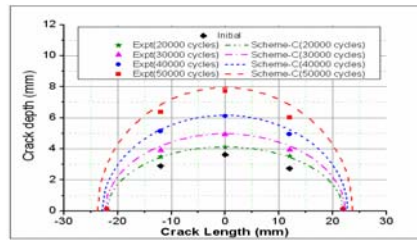Fig. 18: Comparison of fatigue crack growth in pipe (base) using ASME constants

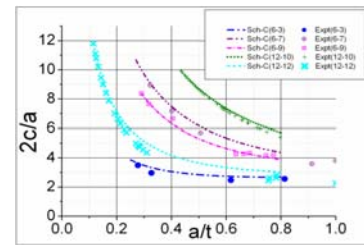Fig. 19: Comparison of crack shape at different loading cycle (Experiment & Analysis)

Fig. 20: Crack growth in depth direction is higher than length direction

Fractographic Examinations

Fracture surfaces of the tested pipes and compact tension specimens have been examined under scanning electron microscope for striation spacing and other features. Typical striation of the fatigue fracture surface is shown in figure 21. It has been found that the striation spacing increases with increase in crack length/depth (figure 22). This validates the crack growth measurement and analytical procedure.
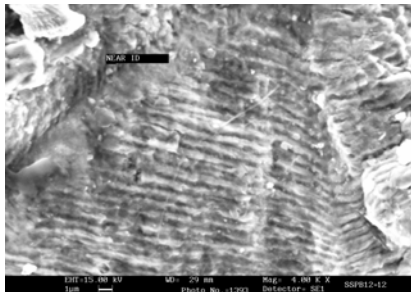
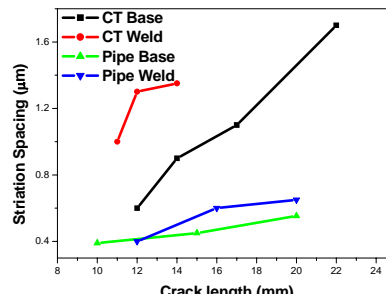Fig 21: Typical striation on the fatigue tested pipe (2000X)

Fig 22: Striation spacing in pipe weld and CT specimen

CONCLUSIONS

The fatigue studies on austenitic stainless steel materials and components for Indian AHWR can be summarized as:

1. Low cycle fatigue properties of the base metal are superior compared to weld (SMAW). Fatigue crack growth rates of pipe (base) and pipe weld (SMAW) differ significantly as brought out from component and specimen tests. FCG in pipe weld (GTAW) is comparable to that of pipe. Pipe welds of hot wire GTAW (narrow gap) has been shown to be superior compared to conventional GTAW.

2. FCGR does not depend on the notch orientation. Stress ratio effect is significant in case of weld joint. FCGR is significantly different for base and weld metal. Hot wire GTAW with narrow groove shows marginally higher resistance to crack growth compared to GTAW with conventional groove.

3. Two schemes based on the evaluations of effective stress intensity factors, result in marginally different fatigue crack growth life predictions. Scheme-C based on K_{RMS} gives comparable results w.r.t. experiments whereas scheme-B based on K at two points gives marginally conservative.

4. Prediction of fatigue crack growth life for notched pipe welds using Paris constants obtained for pipe (base metal) will lead to non-conservative results. Paris constants for actual product can be used for realistic FCG assessment. FCGR given in ASME Section XI is very conservative for pipe (base).

5. The crack growth in depth direction has been shown to be higher than length direction which is desirable demonstration of Leak-Before-Break applicability in pressurized primary components.

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