Fracture behaviour of Dissimilar Metallic Welds: Specimens and Pipe Weld with Crack

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ABSTRACT

Aim of the paper is to understand the fracture resistance behaviour of the DMW joints between low alloy steel and austenitic stainless steel used in the light water power reactors. These materials significantly differ in chemical composition, thermal coefficient of expansion and thermal conductivity. Nickel based alloy has been used as consumables to minimise the gradient of the above mentioned properties. Fracture experiments have been carried out on compact Tension (CT) specimens and full scale pipe weld with crack. Fracture tests on full-scale pipe weld with through-wall crack at weld centre has been carried out under monotonically increasing load. In this paper, design of experiments, experimental results, and evaluation of fracture resistance curve for full scale pipe weld with crack have been discussed. Finally, fracture resistance of the specimen and full scale pipe weld with crack has been compared. Transferability of the fracture resistance from specimen level to component level has also been discussed.

INTRODUCTION

Dissimilar Metal Weld (DMW) joint in this paper is between low alloy steel and the austenitic stainless steel. These welds are used in primary system of the boiling water reactor (BWR) and the pressurized water reactors (PWR) at several locations such as, weld joint at hot leg and cold leg between reactor pressure vessel and steam generator in PWRs and stainless steel piping to reactor pressure vessel in BWRs. In Indian Advance Heavy Water Reactor (AHWR), DMW joints would be used for joining steam drum nozzles (low alloy steel) with downcomer piping (austenitic stainless steel). Schematic of theses joints is shown in figure1. These welds are not easy to prepare and its characterisation of mechanical and fracture properties are difficult. The base metals such as low alloys steel and austenitic stainless steel have different thermal conductivity and the coefficient of thermal expansion apart from chemical compositions and strength. Because of differences in coefficient of thermal expansions, residual stresses would also get generated and remain in the weld. Experimental data available for these types of weld joints are also limited. Recent international surveys of such welded joints have shown that there are several cracking problems, due to ageing or corrosion [Brust (2000), USNRC (2000), Miteva (2006), Taylor (2006), Brust (2007)]. More than 1000 DMW joints were inspected in French PWR plants in 1997 for atmospheric corrosion, among that 50 were reported to be having intergranular degradation at the outer surface few millimetre deep in buttering region close to the ferritic to stainless steel interface [Miteva (2006)]. The degradation mechanisms that can cause pipe weld failures are generally low cycle thermal fatigue, thermal aging primary water stress corrosion cracking (PWSCC) of DMW joints, boric acid corrosion that degrades low alloy ferritic steel components and the atmospheric corrosion on DMW joints.

Since these joints are present in primary component of nuclear reactors, the structural integrity assessment of these joints are very important. Structural integrity assessment of DMW is not straight forward due to different materials across the joint. Therefore, it is desirable to develop fracture assessment methodologies for these joints, and to validate them experimentally. Under this objective, a detailed experimental and analytical programme is was planned.

As a part of the above programme, this paper details, tests carried out to understand the fracture resistance behaviour of the full scale pipe weld with crack, its results, and evaluation of fracture resistance curve for the dissimilar metal pipe weld with through-wall crack at centre cracked.
Finally, fracture resistance of the specimen and full scale pipe weld with crack has been compared. Transferability of the fracture resistance from specimen level to component level has also been discussed.

MATERIAL AND WELDING

Forged pipe (same condition as steam drum nozzle) of ferritic material (SA508 Grade 3 Class1) in quenched and tempered condition and downcomer piping of austenitic stainless steel (SA312 Type 304 LN) in solution annealed condition have been used for specimen and fracture testing of pipe welds. The joint between these two materials is actual representation of joint between LAS steam drum nozzle with austenitic stainless steel downcomer piping. Inconel-182 (ENiCrFe-3) flux coated electrodes is used for buttering of LAS pipe. Nickel-based Inconel-82 (ERNiCr-3) bare wire has been used for welding of root passes and Inconel-182 (ENiCrFe-3) flux coated electrodes for subsequent filling of V-Groove. The nominal chemical composition of base materials and filler metals are shown in Table1.

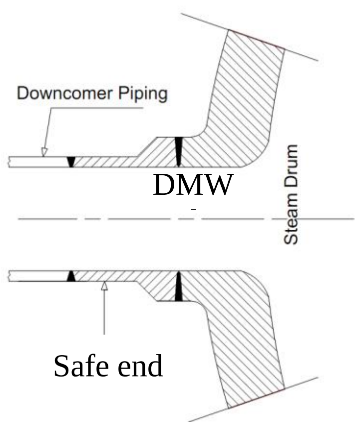

Figure1. Schematic of steam drum nozzle welded to downcomer piping

Table 1: Chemical composition (weight %) of base and filler wire

Element in (Weight %)	C	S	P	Mn	Si	Cr	Ni	Mo	Cu	Al	Nb	Ti	Fe
SA508Cl1	0.19	0.002	0.018	1.3	0.23	0.17	0.7	0.44	0.13	0.02	---	---	96.8
SS304LN	0.023	0.001	0.024	0.82	0.46	18.13	8.17	0.26	1.07	0.027	---	---	71.015
ERNiCr-3 (Inconel-82)	0.092	0.008	0.006	4.0	0.05	17.24	64.3	0.47	0.09	0.063	---	---	11.21
ENiCrFe- 3 (Inconel-182)	0.09	0.015	0.014	6.75	0.87	16.59	66	0.80	0.08	0.062	2.10	0.029	6.24

Welding Details

The welding processes adopted for experimental joints were Gas Tungsten Arc Welding (GTAW) for root pass and Shielded Metal Arc Welding (SMAW) for filling passes. One end of each pipe has been machined to a half groove angle of 37.5°. Welding has been performed in three stages. These are as follows:

(a) In first stage, buttering on LAS pipe face is carried out by SMAW process.
(b) In second stage, root pass and 1st two passes after root pass are carried out by GTAW process.
(c) In third stage, subsequent filling passes were carried out using SMAW process.

Buttering layer is deposited by SMAW process on low alloy steel pipe cross section using Inconel filler wire (ENiCrFe-3). The pipe is preheated to 150°C before start of buttering. Stress reliving heat treatment of buttered LAS pipe was carried out in electrical furnace. It was heated to 610°C and kept at this temperature for soaking for 90 minutes. Heating and cooling rate is maintained 50°C/Hr starting from 300°C. After the stress reliving, the buttering face of LAS are assembled with austenitic SS pipe and tacked together with insert ring of Inconel filler wire. Low alloy steel was preheated to 150°C before start the root welding. Subsequent filling of groove was carried out by manual Shielded Metal Arc Welding (SMAW) using Inconel-182(ENiCrFe-3) flux coated electrode. All the welding parameters meet the recommendations given in ASME Sec IX (2001). Weld quality assurance was based on acceptance requirements of ASME Section III NB of Boiler and Pressure Vessel (B&PV) Code (2001).

DISSIMILAR METAL PIPE WELD FRACTURE TEST

Specimen's details and test procedure

Details of the full scale pipe weld fracture test experiment is shown in Table 2. Pipe weld with 60° and 90° through wall weld centre crack has been used for fracture testing. 60° and 90° through wall weld centre crack specimens are named as QMSP-2-60TWC-CW and QMSP-3-90TWC-CW. DMW pipe specimens were fabricated by joining the 2000 mm long 324 mm outer diameter pipe of SA312 Tye304LN and SA508 Cl3Gr1 material using Inconel 182 electrode by SMAW welding procedure. Notch was produced in centre of weld by electro-discharge machining along circumferential direction. The notch tips are of V-shape at both ends with tip radius of 0.1mm and width of 3 mm.

Table 2: Details of the DMW pipe weld specimens with notch for fracture test:

Sr. No.	Experiment Name	Outer Diameter (mm)	Thickness (t) (mm)	Crack Size	Type	Total Length (mm)
1	QMSP-2-60TWC-CW	325	28.17	$2\theta= 61.44^{o}$	TWC	4000
2	QMSP-3-90TWC-CW	325	26.08	$2\theta= 89.69^{o}$	TWC	4000

Tests were carried out under four point bend loading, so that pipe weld notch section (inner span or the loading points) is subjected to uniform load. Schematic of the test set up showing, outer and inner spans and loading points are shown in figure 2. Actual test setup used for monotonic fracture tests is shown in figure 3. The servo-hydraulic actuator was fixed to a steel reaction frame, which was connected to the strong floor of the laboratory. The actuator system consists of an in-built LVDT and a load cell for measurement of the displacement and the applied load. The deflections along the length of the pipe weld specimen were measured using ±100 mm range LVDTs (LVDT1 to LVDT5) installed along the different locations as shown in figure 2.

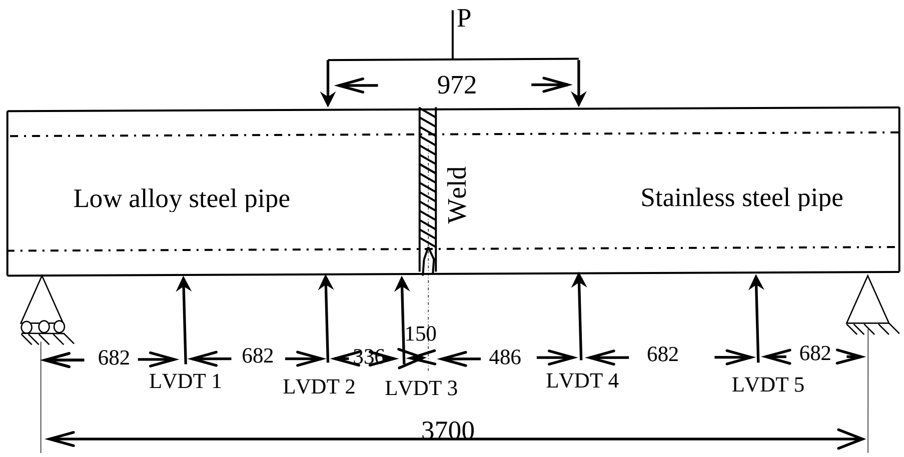

Figure 2. Details loading scheme and LVDT locations for deflection measurements during the fracture test on the specimen. **Note**: All dimensions are in mm

Figure 3: A view of fracture test set-up for a DMW pipe weld

Fracture test results and discussion

Table 3. Key results of all the fracture tests on DMW pipe weld with crack

Experiment Name	Span (mm)		P_{max} (kN)	Load-line Displacement at maximum load (mm)	Displacement (mm) at the end of the test				Crack initiation load (kN)	
	Inner span	Outer span			LVDT1	LVDT2	LVDT4	LVDT5	Tip A	Tip B
QMSP-2-60TWC-CW	972	3700	804.97	96.24	79.9	137	148.95	87.35	582.73	492.61
QMSP-3-90TWC-CW	972	3700	562.62	58.68	85.4	128.5	136	92.3	457.46	457.46

Applied loads and the displacements of the load point for the 60° and 90° through wall cracked DMW pipe joints have been shown in figure 4. The maximum experimental load of the 60° and 90° cracked pipe weld was 804.97 kN and 562.62 kN respectively. The key results of tests under monotonic loading. are summarized in Table. 3. The initiation of crack growth in pipe weld with through-wall crack 60° crack pipe has been observed at load 582.73 kN at Tip-A and at 492.61 kN at Tip-B. Similarly, initiation of crack growth in case of 90° crack was around 475.46 kN at the both tips. Initiation of crack growth has been assumed when crack has grown by 0.2 mm. A close-up views crack growth after fracture tests at both the tips for 90 ° cracked pipe weld is shown in figure 5. Almost symmetric crack growth was observed at both tips. A Stable crack growth initiated prior to 18-38 % of maximum load in both the tests. It indicates that ductile crack growth is the failure mode in case of a crack lying in the Inconel 182 weld using shielded metal arc welding (SMAW) process. The maximum deflections of the cracked DMW pipe joint at the end of the tests at different distances from the crack plane along the axial length have been given in Table 3. Deflection of load point at SS side (LVDT-4) is approximately 9% higher than the load point at LAS side (LVDT-2) in case of 60° crack pipe whereas, it is 6% in case of 90° crack pipe weld. The deflection of middle of outer span in SS side (LVDT-5) is approximately 10 % higher than that of LAS side (LVDT-1) in case of 60° crack pipe whereas, it is 8 % in case of 90° cracked pipe weld. It shows that, deformation across crack plane in SS side is marginally higher than LAS side. However, it is expected to have large deformation in SS side compared to LAS side. Relative lower fracture toughness of Inconel 182 weld may be the region of less difference in deformation across notch plane. Total deflection/deformation in notched pipe weld is sum of deflection due to un-cracked pipe plus deflection due to crack only. Because of faster crack growth in weld, deflection due to crack only will be large than un-cracked pipe. Hence, hence LAS and SS side is having almost comparable deflection at symmetric location with respect to notch plane.

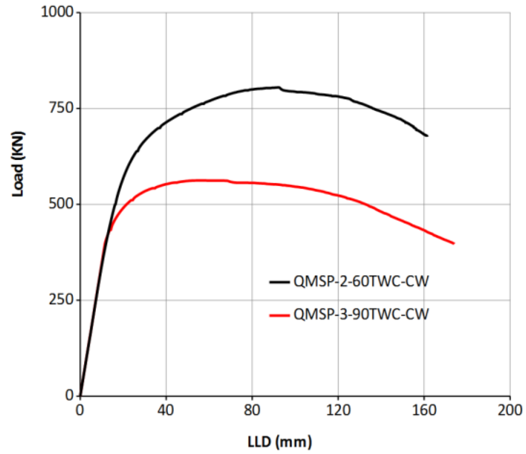

Figure 4. Load vs. LLD for pipe with through-wall crack in centre of weld

Figure 5. Close-up views of crack location after the fracture for QMSP-3-90TWC-CW

Fracture Resistance (J–R) Curve of Cracked Pipe Weld

The cracked pipe weld J-R curve have been constructed using experimental load versus load-point displacement data and load versus crack growth curve according to the expression given by Zahoor (1989). The detail of the evaluation procedure for J-R curve is given below,

$$J=J_e+J_p \tag{1}$$

Where, J_e is elastic component and J_p is plastic component that will be evaluated by,

$$J_e = \frac{F_2\, M^2}{(R^2\, t^2\, E)} \tag{2}$$

$$J_P = J_{PO} + \int_{\theta_0}^{\theta} \gamma\, J_{PO}\, d\theta \tag{3}$$

$$J_{Po} = \int_0^{\Delta_P} \beta\ P\ \ d\Delta_p \tag{4}$$

Here, M is bending moment. R, t, θ and E is the pipe mean radius, wall thickness, crack half angle, and elastic modulus. Expression for F_2, β, and ϒ can be found in Zahoor hand book. dθ is the crack growth at each crack tip. θ_o and θ are the initial and instantaneous half crack angle respectively. The J_{PO}, β, and ϒ are evaluated with current value of θ, P (load), and plastic component of load point displacement Δ_P due to crack. Plastic component of load point displacement due to crack only can be evaluated from total load point displacement using,

$$\Delta = \Delta_P + \Delta_{ec} + \Delta_{nc} + \Delta_m \qquad (5)$$

Where,

Δ_P-Plastic component of the load-point displacement due to crack, Δ_{nc}-Load-point displacement of the unflawed pipe including both the elastic and plastic components of the displacement (without crack), Δ_m - P C_m , P-load, C_m- Compliance of testing machine, Δ_{ec}-Elastic component of the load-point displacement due to crack refer, Zahoor (1989). It should be noted that for evaluation of J_p, the multiplying factor β and ϒ given in Zahoor (1989) hand book are valid for pipe of homogenous which may not be applicable for pipe weld. The solutions of β and ϒ for cracked dissimilar metal pipe weld are not available in open literature. In present analysis, solutions of β and ϒ derived for pipe of homogeneous material has been used for pipe weld with crack.

Fracture resistance (J_R) curves of the pipe weld with initial crack in centre of weld (QMSP-2-60TWC-CW and QMSP-3-90TWC-CW) have been shown in figure 6. Fracture resistance curve of centre of weld obtained using standard 1/2 Compact Tension (CT) specimen has also been shown in figure 6. Break black line in figure 6 is extrapolated line of fracture toughness data of the CT specimen. Extrapolation of J-R curve has been done based on power law up to the twice of maximum J value evaluated experimentally.

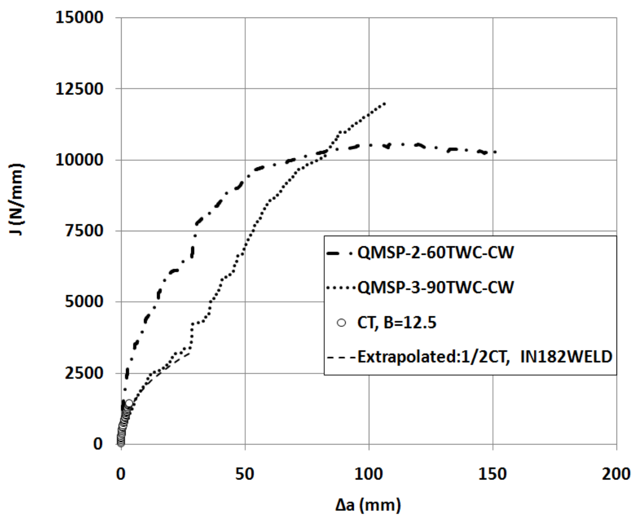

Figure 6. J-R curves of cracked pipe weld (through wall crack in centre of weld) and compact tension specimen.

Fracture resistance (J_R) curves of the pipe weld with initial through wall crack in centre of weld (i.e. QMSP-2-60TWC-CW) with crack half angle 60° increases monotonically with increase in crack extension. In this test, symmetric crack extensions were observed at both crack tips. By and large crack extension was in the weld region with slight crack deviation (5-6 mm) at both crack tips from the initial crack plane. This deviation could be due to the multi-pass nature of the weld. Fracture resistance (J_R) curves of test QMSP-3-90TWC-CW increases monotonically with crack extension. However there is change in the slop of the J-R curve at around 30-40 mm of crack extension. During fracture test, it has been observed that crack extension is symmetric at both crack tips. The crack initiation and thereafter crack extension till 30-40 mm was in the weld region. After crack extension of 30-40 mm both crack tips deviated toward austenitic stainless steel region. Increase in slope of the J-R curve after crack extension of 30-40 mm is due to the crack deviation in austenitic stainless steel region which has higher fracture toughness compared to that of the weld region [Kumar (2016)].

Fracture resistance (J_R) curves of the cracked pipe weld are higher than or equal to the 1/2 CT specimen of weld material. This observation is consistent with that reported in literature [Zhu(2001), Kumar (2000)] that fracture resistance of the CT specimen is lower because of the higher constraints at the crack tip of the CT specimen compared to that of the pipe weld (lower constraints). Among the TWC crack in weld with 90° half crack angle shows lower J-R curve than 60° half crack angle. This again may be attributed to the higher constraint in deep cracked pipe weld compared to 60° half crack angle. Hence, use of the fracture toughness (J-R) of specimen level test for component having DMW weld joint will be conservative.

CONCLUSIONS

- Initiation of the Stable crack growth prior to 18-38 % of maximum load has been observed in both the tests. Ductile crack growth failure has been observed for cracked pipe weld having crack at the Inconel 182 weld centre using shielded metal arc welding (SMAW) process.
- Marginally higher deflection has been observed in stainless steel side of pipe weld joint compared to that of LAS side.
- Fracture resistance (J_R) curves of cracked pipe welds are higher than the CT specimen having initial notch in the centre of weld.

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