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Monotonic and Cyclic *J*-integral Estimation for Through-Wall Cracked Straight Pipes

Rohit, S. Vishnuvardhan, P. Gandhi and Nagesh R. Iyer

Abstract**—**The evaluation of energy release rate and centre Crack Opening Displacement (COD) for circumferential Through-Wall Cracked (TWC) pipes is an important issue in the assessment of critical crack length for unstable fracture. The ability to predict crack growth continues to be an important component of research for several structural materials. Crack growth predictions can aid the understanding of the useful life of a structural component and the determination of inspection intervals and criteria. In this context, studies were carried out at CSIR-SERC on Nuclear Power Plant (NPP) piping components subjected to monotonic as well as cyclic loading to assess the damage for crack growth due to low-cycle fatigue in circumferentially TWC pipes.

Keywords**—**304LN stainless steel, cyclic *J*-integral, Elastic-Plastic Fracture Mechanics, *J*-integral, Through-wall crack

I. INTRODUCTION

THE use of fracture mechanics in fatigue propagation life prediction has become widespread since it was first applied. The basic assumption made in fracture mechanics is that crack growth starts from a very small size defect, which can even be an inherent flaw in the material. Hence, by this approach towards fatigue life evaluation, major portion of fatigue life is expended in crack propagation. The parameter that describes the stress field around the advancing crack tip is an important component in the fracture mechanics approach (LEFM). The stress intensity factor, *K*, is used in Linear Elastic Fracture Mechanics. When plasticity effects are considered, various parameters such as Crack Tip Opening Displacement (CTOD) and *J*-integral are most commonly used in Elastic Plastic Fracture Mechanics (EPFM). For small-scale plasticity conditions, the *K* approach, corrected for the effect of small plastic zone effect, is advantageous. However, in highly ductile materials and where the crack tip plastic zone is large, EPFM is more appropriate. The *J*-integral has enjoyed great success as a fracture characterizing parameter for nonlinear materials.

Rice [1] identified a parameter used to characterize dissipative material behaviour ahead of a crack that is far from any edges. By idealizing elastic-plastic deformation as non-linear elastic, Rice provided the basis for extending fracture mechanics methodology well beyond the validity limits of LEFM. He showed that a non-linear energy release rate could be quantified by using a line integral, which he called the *J*-integral, evaluated along an arbitrary contour surrounding the crack tip. Rice proved the path independence of *J*-integral for linear as well as non-linear elastic materials using the deformation theory of plasticity which excludes consideration of unloading. The analyses showed that the *J*-integral can be viewed as a non-linear stress intensity parameter as well as an energy release rate. Path independence permitted the calculation of the *J*-integral from a path that is away from the crack tip for which stresses and strains may not be known. Dowling and Begley [2] made an attempt to apply the *J*-integral concept as an elastic-plastic criterion for fatigue crack growth. The tests employed Compact Tension [C(T)] specimens made of material A533B pressure vessel steel. The cyclic *J* values were determined by the following expression:

$$J = \frac{2}{Bb}\int_0^{\delta_0} P d\delta \tag{1}$$

Hutchinson and Paris [3] carried out analysis and showed that outside of a core of non-proportional loading the deformation is nearly proportional. Provided the region of non-proportional loading is well contained within the region dominated by the *J*-singularity, there will exist an annular region where the Hutchinson-Rice-Rosengren (HRR) field holds. If a specimen’s uncracked ligament is sufficiently large compared with the inner core of non-proportional loading and the *J*-stress field dominates the crack extension, the crack growth will be controlled by the *J*-integral. Zahoor and Kanninen [4] proposed a method of evaluating the *J*-integral for a circumferentially cracked pipe in bending which made possible the evaluation of a *J-R* curve directly from the load-displacement record obtained in a pipe fracture experiment. It also permitted an analysis for fracture instability in a circumferential crack growth using a *J-R* curve and the tearing modulus parameter. However, in order to make reasonable predictions of stable crack growth and instability, the proper *J-R* curve satisfying the constraint at the crack tip had to be used. Works were also carried by Rahman and Brust [5] in which a methodology was proposed to predict the *J*-integral and COD of TWC ductile pipe weldments subjected to remote bending loads. Closed form solutions were obtained in terms of elementary functions for approximate evaluation of energy release rate and center COD. Cho et al. [6] described enhanced *J*-integral estimation schemes for pipes with circumferential semi-elliptical cracks subjected to tensile loading, global bending and internal pressure. The schemes which were given in two different forms to cover the wide ranges of geometries and material parameters; the modified GE/EPRI method and the modified reference stress method were validated against corresponding detailed elastic-plastic FE analyses by using actual material data of typical stainless steels.

Rohit is with CSIR-Structural Engineering Research Center, Tamil Nadu, Chennai 600113 (e-mail: rohit@serc.res.in).

S. Vishnuvardhan is with CSIR-Structural Engineering Research Center, Tamil Nadu, Chennai 600113 (e-mail: svvardhan@serc.res.in).

Tami P. Gandhi is with CSIR-Structural Engineering Research Center, Tamil Nadu, Chennai 600113 (e-mail: pgandhi@serc.res.in).

Nagesh R. Iyer is with CSIR-Structural Engineering Research Center, Tamil Nadu, Chennai 600113 (e-mail: nriyer@serc.res.in).

Monotonic and cyclic fracture studies have been carried out on 324 mm outer diameter straight pipes at the Fatigue and Fracture Laboratory of CSIR-SERC [7]. In the present studies, monotonic and cyclic *J*-integral values were estimated for these circumferentially TWC straight pipes made of Type 304LN stainless steel used in Primary Heat Transport (PHT) system of NPPs. This paper presents the details of the experiments carried out and estimation of *J*-integral.

II. EXPERIMENTAL STUDIES

A. Material Properties

The pipe specimens were made of Type 304LN stainless steel conforming to ASTM A 312/ A 312 M-09 standard [8]. Actual composition of the material and the specified values as per ASTM A 312/ A 312 M -09 standard are given in Table 1. The yield strength and ultimate tensile strength of the material are 345 MPa and 521 MPa respectively. The percentage elongation is 65 and the Young's modulus is 195GPa.

TABLE I
CHEMICAL COMPOSITION OF TYPE 304LN STAINLESS STEEL

Element	% weight	ASTM A312/A 312M-09 (Max.)
C	0.03	0.03
Mn	1.78	2.00
P	0.024	0.045
S	0.007	0.03
Si	0.38	1.00
Ni	9.11	8-12
Cr	18.26	18-20
N	0.06	0.10-0.16

B. Specimen Details

The dimensional details of the pipe specimens are given in Table 2. The pipe specimens had circumferential through-wall notch in the weld. Fig. 1 shows the schematic of a typical straight pipe with circumferential through-wall notch.

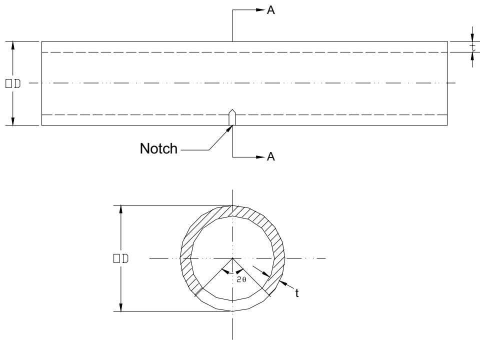

Fig. 1 Details of a straight pipe with circumferential through-wall notch

TABLE II
DETAILS OF THE PIPE SPECIMEN

		Specimen No.	
		SSPW12-27	QCSP-12-60-TWC-NGWP-L2
Diameter of pipe (mm)		325	324
Thickness of pipe (mm)		25.7	26.1
Length of pipe (mm)		4960	5090
Location of notch		Weld	Weld
Notch Dimension	a	TW	TW
	2C (mm)	170	168
	R (mm)	0.1	0.1
	W (mm)	3.0	3.0
	2θ (°)	59.8	59.4
Type of test		Monotonic fracture	Cyclic fracture

a = Notch depth, 2C = Notch length, R = Tip radius, W = notch width, 2θ = Initial notch angle, TW = Through-wall

C. Fatigue pre-cracking

Since the fracture mechanics theory applies to cracks that are infinitely sharp prior to loading, all the specimens were fatigue pre-cracked before carrying out the fracture experiments. The fatigue pre-cracking was carried out under four point bending using a ±1000 kN capacity servo-hydraulic actuator applying sinusoidal constant amplitude cyclic loading. The minimum and maximum load values were 16 kN and 160 kN respectively. The maximum load was kept within 20% of the Theoretical Plastic Collapse Load (TPCL) of the pipe.

The details of fatigue pre-cracking of the specimens are given in Table 3 and Table 4 gives the crack length measurements obtained during fatigue pre-cracking.

TABLE III
DETAILS OF FATIGUE PRE-CRACKING

		Specimen No.	
		SSPW12-27	QCSP-12-60-TWC-NGWP-L2
Span (mm)	Outer	4000	4000
	Inner	1200	1200
Frequency (Hz)		0.6	0.9
Cyclic load (kN)	Min	16	16
	Max	160	160

TABLE IV
FATIGUE PRE-CRACKING TEST RESULTS

		Specimen No.	
		SSPW12-27	QCSP-12-60-TWC-NGWP-L2
No. of cycles		18000	18000
Fatigue pre-crack (mm)	Tip A	3.5	3.5
	Tip B	2.15	2.50

D. Fracture experiments

Subsequent to fatigue pre-cracking, fracture experiments were conducted using a ±2000 KN capacity servo-hydraulic actuator. The pipes were supported on pedestals over a hinge support on one side and a roller support on the other. The upward movement was prevented at the ends by placing a stiffened plate over the pipe and holding it down using high strength steel tie rods. A rigid steel distribution beam supported on steel curved blocks was fixed to the actuator to apply two-point loading. To ensure proper application of reverse cyclic loading the pipe was held to the load distribution beam using rigid plates at the top and bottom connected by means of high strength tie rods. Figs. 2 and 3 show close-up view of monotonic and cyclic fracture experiment on a straight pipe, respectively.

Fig. 2 Close-up view of monotonic fracture experiment

Fig. 3 Close-up view of cyclic fracture experiment

During the fracture experiment, the pipe specimen was instrumented to obtain applied load, load-line displacement (LLD), Crack Mouth Opening Displacement (CMOD), crack extension and deflection of pipe. The load-line displacement was measured by the in-built LVDT of the actuator. CMOD was measured using specially fabricated clip gauges. Image Processing Technique (IPT) consisting of three CCD cameras interfaced to a computer system with image acquiring software was used for online monitoring of surface crack growth. These images were later on processed to get the crack growth data at various loads. Table 5 shows details of cyclic fracture experiment. Figs. 4 and 5 show load vs. LLD plots obtained during monotonic and cyclic fracture experiments respectively.

TABLE V
DETAILS OF CYCLIC FRACTURE TEST

		Specimen No.	
		SSPW12-27	QCSP-12-60-TWC-NGWP-L2
Mode of control		Displacement	Load
Span (mm)	Outer	4000	4000
	Inner	1300	1300
No. of cycles		Monotonic	1-21
Frequency (Hz)		--	0.0417
Cyclic load (kN)	Min	--	-650
	Max	--	+650
Rate of loading		0.04 mm/sec	4 min/cycle

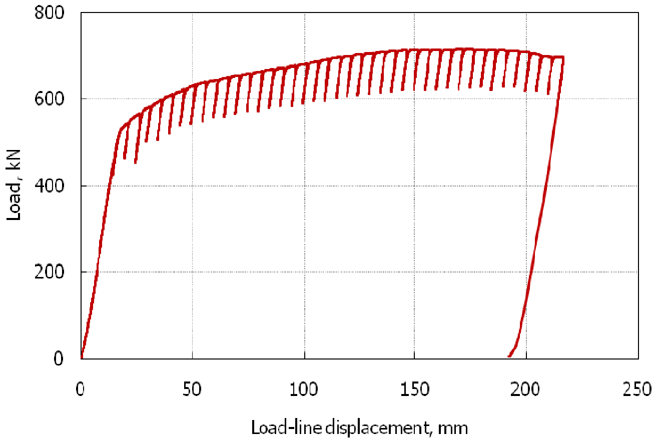

Fig. 4 Load vs. load-line displacement curve during fracture experiment on specimen SSPW12-27

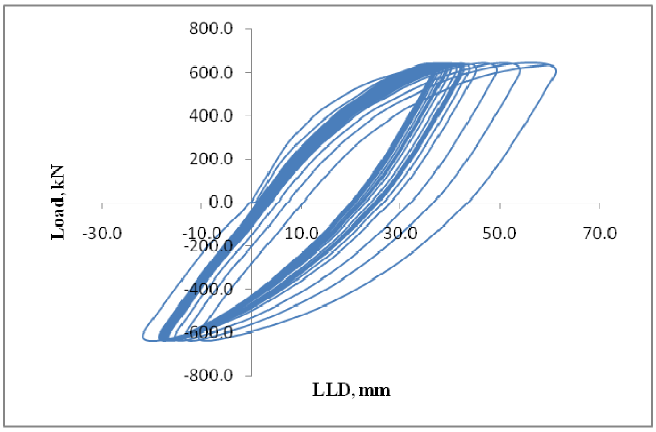

Fig. 5 Load vs. load-line displacement curve during fracture experiment on specimen QCSP-12-60-TWC-NGWP-L2

III. ESTIMATION OF *J*-INTEGRAL

A. J-integral under monotonic loading

The calculation of monotonic J for a TWC pipe experiment where the load and load-line displacement are known is done using an analysis given by Zahoor and Kanninen [4], an approach similar to η-factor analysis.

1. Basis of approach

In plastic fracture mechanics, experimental as well as theoretical methods have been developed to compute *J* for through-thickness cracks in planar specimens. For a non-linear elastic material, the energy release rate, J, is given as:

$$J = -\frac{d\Pi}{dA} \tag{2}$$

where Π is the potential energy and *A* is the crack area. The potential energy is given by:

$$\Pi = U - F \tag{3}$$

where *U* is the strain energy stored in the body and *F* is the work done by external forces. For a load controlled test, Π is given by:

$$\Pi = U - P\delta = -U^* \tag{4}$$

where δ is the load-point displacement and U^* is the complimentary strain energy, defined as:

$$U^* = \int_0^P \delta dP \tag{5}$$

Thus for a load controlled test, *J* is given by:

$$J = \left(\frac{dU^*}{dA}\right)_P \tag{6}$$

If the crack advances at a fixed displacement, *F* = 0, and *J* is given by:

$$J = -\left(\frac{dU}{dA}\right)_\delta \tag{7}$$

By invoking the definitions for *U* and *U**, *J* in terms of load and displacement is expressed as:

$$J = \int_0^\delta \left[-\frac{\partial P}{\partial A}\right]_\delta d\delta \tag{8}$$

$$J = \int_0^P \left[-\frac{\partial \delta}{\partial A}\right]_P dP \tag{9}$$

The load-point displacement δ is the relative displacement between the load points and the supports and can be split into its elastic and plastic parts as:

$$\delta = \delta_{el} + \delta_{pl} \tag{10}$$

Substituting (10) in (9) and noting that crack area (*A*) = $Rtd\varphi$, where φ is the angle subtended by the crack, *R* is the mean pipe radius and *t* is the wall thickness, gives:

$$J = \frac{1}{Rt}\int_0^P \left(\frac{\partial \delta_{el}}{\partial \varphi}\right)_P dP + \frac{1}{Rt}\int_0^P \left(\frac{\partial \delta_{pl}}{\partial \varphi}\right)_P dP \tag{11}$$

where,

$$J_{el} = \frac{1}{Rt}\int_0^P \left(\frac{\partial \delta_{el}}{\partial \varphi}\right)_P dP \tag{12}$$

and

$$J_{pl} = \frac{1}{Rt}\int_0^P \left(\frac{\partial \delta_{pl}}{\partial \varphi}\right)_P dP \tag{13}$$

where, J_{el} and J_{pl} are the elastic and plastic components of *J*-integral.

2. Analysis for crack initiation

Assuming that all plasticity is confined to the cracked cross section, an expression for δ_{pl} needed to evaluate J_{pl} can be obtained from dimensional analysis which will be independent of material's stress-strain behavior. The functional form of bending deflection of the pipe due to plasticity can be written as follows:

$$\delta_{pl} = f[P/h(\varphi)] \tag{14}$$

Thus, from (14) we get

$$\left(\frac{\partial \delta_{pl}}{\partial \varphi}\right)_P = -\frac{P}{h(\varphi)} h'(\varphi) \left(\frac{\partial \delta_{pl}}{\partial P}\right)_\varphi \tag{15}$$

This when substituted in equation (13), leads to

$$J_{pl} = \beta \int_0^{\delta_{pl}} P d\delta_{pl} \tag{16}$$

where $\beta = -h'(\varphi)/Rth(\varphi)$, *R* and *t* are the mean radius and thickness of the pipe and $h(\varphi) = [cos(\varphi/4) - 1/2\sin(\varphi/2)]$

3. Analysis for stable crack growth

The analysis for stable crack growth was carried out based on the following expression:

$$J_{pl} = \beta \int_0^{\delta_{pl}} P d\delta_{pl} + \int_{\varphi_0}^{\varphi} \gamma J_{pl} d\varphi \tag{17}$$

where δ_{pl} = plastic part of load-line displacement
φ_0 = crack angle at crack growth initiation
φ = crack angle considering stable growth
$\gamma = h''(\varphi)/h'(\varphi)$

For stable crack growth, the first term in (17) is calculated using the area under the *P*-δ_{pl} curve to obtain an approximate value of J_{pl}. This is substituted in the second term to obtain a correction to J_{pl}. Accepted convergence can normally be achieved in a single iteration if the correction is made with small increments in crack growth.

It should be noted that the data from no more than a single load-displacement record is needed to generate the *J*-resistance curve. However, for stable crack growth, a simultaneous measurement of crack growth and load during the test is needed.

The elastic solution for a circumferential TWC in a pipe subjected to four point-point bending is given as [4]

$$K_I = \sigma\sqrt{\pi a}F(x) \tag{18}$$

where K_I = opening mode stress intensity factor
$[F(x)]^2 = [0.7631 - 1.7602x + 1.3511x^2 - 0.3822x^3] / (1 - x)^3$
x = cracked area/cross-sectional area of the pipe

$2a$ = circumferential crack length
σ = outer fiber tensile bending stress (= *Mc/I*)
The elastic contribution to *J* is then

$$J_{el} = \alpha \frac{K_I^2}{E} \tag{19}$$

where α takes the value of 1 for plane stress and $(1-\nu^2)$ for plane strain where ν is the Poisson's ratio.

The total *J* is calculated as follows:

$$J = J_{el} + J_{pl} \tag{20}$$

B. J-integral under Cyclic Loading

The results from the experiments carried out at CSIR-SERC clearly show that the pipe fracture evaluation criteria which consider a flaw stable if it can tolerate just one time applied loading, leads to a catastrophic failure. The analysis of cyclic crack growth classically involves the use of the linear-elastic stress-intensity factor, K. In the presence of plasticity at crack tip, Dowling and Begley [2] used the J-integral parameter. The cyclic J, ΔJ, is calculated by integrating the load-displacement test record on a cycle-by-cycle basis as illustrated in Fig. 6.

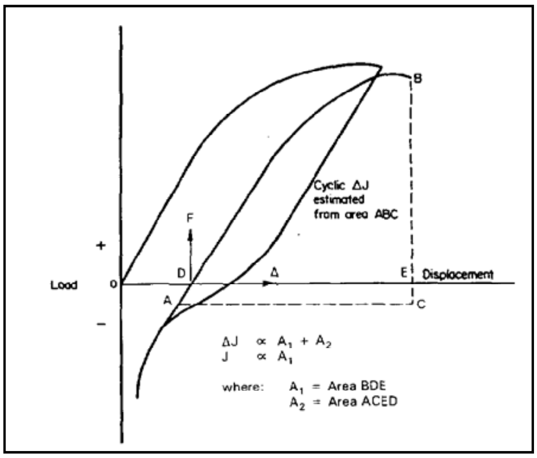

Fig. 6 Schematic of Dowling analysis of area used in *J* calculations for crack growth in the presence of plasticity

For fully reversed cyclic loading, it has been suggested that a negative load level corresponding to crack closure should be used. The rationale for such an argument is that once the crack is fully open, the energy spent in further opening it directly contributes to crack tip processes responsible for crack extension. The crack closure load can be determined from the experimental test record.

A TWC pipe subjected to large amplitude fully reversed bending is considered. The actuator load varies from +*P* to –*P* during a typical load cycle. This is similar to the test performed on the pipe specimen QCSP-12-60-TWC-NGWP-L2 wherein the load amplitude varied from +650 to -650 kN.

Such load cases are encountered in NPPs when the piping system is subjected to a seismic ground motion. The procedure given by Rahman et al. [9] was undertaken to study the crack growth in a TWC pipe subjected to large amplitude fully reversed bending representing low-cycle fatigue phenomena.

The *J* values were computed for pipe specimen no. SSPW12-27 and QCSP-12-60-TWC-NGWP-L2 by [4]. This gives the Deformation *J*. The Deformation *J* is not the same as Dowling definition of *ΔJ*, especially when reverse loading occurs. However the Deformation *J* can be related to Dowling's cyclic *ΔJ* [2] as follows:

$$\Delta J = \psi J \tag{21}$$

where ψ is a suitable multiplier that determines the operational Δ*J* during a load cycle. If the maximum and minimum loads during a cycle are *P* and 0 (i.e. load ratio = 0), Δ*J* becomes equal to *J* (i.e. ψ = 1) for a load *P* in the absence of any crack closure. If the maximum and minimum loads are +*P* and -*P* (i.e. load ratio = -1), which are the conditions in the present case, the value of operational Δ*J* depends on the load point where crack-closure occurs. In this regard the procedure examined by Joyce and Hackett [10] was used to determine the closure load P_c and the multiplier ψ.
The multiplier ψ is given by:

$$\psi = 1 + \left\{\left[\left(\frac{1}{2}\frac{P_c}{P} + 1\right) C_1 P^2 + \left(\frac{1}{2}\left(\frac{P_c}{P}\right)^n + 1\right) C_2 P^{n+1}\right] \frac{P_c}{P}\right\} / \left[\frac{1}{2} C_1 P^2 + \frac{n}{n+1} C_2 P^{n+1}\right] \tag{22}$$

where C_1 and C_2 are coefficients that depend on the pipe dimensions, crack geometry and pipe material properties, *n* is the Ramberg-Osgood hardening parameter and P_c is the closure load. Figure 7 shows crack-closure load vs. number of cycles for specimen QCSP-12-60-TWC-NGWP-L2.

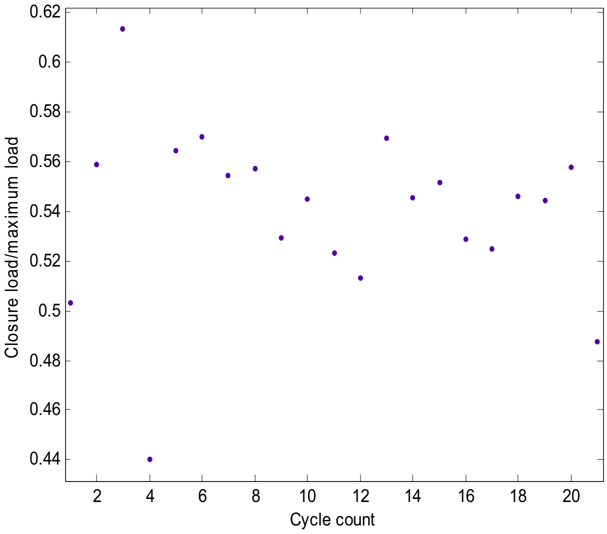

Fig. 7 Crack-closure load vs. number of cycles for specimen QCSP-12-60-TWC-NGWP-L2

IV. RESULTS AND DISCUSSION

Figures 8 and 9 show close-up views of crack location for specimens SSPW12-27 and QCSP-12-60-TWC-NGWP-L2, respectively obtained during fracture experiments. Figure 10 shows monotonic *J-R* curve obtained for specimen SSPW12-27.

A quadratic polynomial was fitted by the method of least squares to the *J-R* curve of the specimen subjected to monotonic loading. The equation obtained is as follows:

$$J = -2.734(\Delta a)^2 + 260.1(\Delta a) - 300.2 \qquad (23)$$

Figures 11 and 12 show cyclic *J-R* and *da/dN* vs. *ΔJ* curves respectively for specimen QCSP-12-60-TWC-NGWP-L2 subjected to cyclic loading. A power law fitted by the method of least squares to the crack growth vs. cyclic *J, ΔJ,* curve gave the following equation:

$$\frac{da}{dN} = 3.684 \times 10^{-8}(\Delta J)^{2.653} \qquad (24)$$

Thus the values of *C'* and *m'* obtained were:
$C' = 3.684 \times 10^{-8}$ and $m' = 2.653$
where *da/dN* is in mm/cycle and *ΔJ* is in kJ/m^2.

The results of the experiments carried out at CSIR-SERC show that low-cycle fatigue as compared to monotonic load can contribute to significant crack growth and reduction in load carrying capacity in through-wall cracked pipes. If $(dJ/da)_{applied}$ is less than $(dJ/da)_{material}$, crack growth is stable. The value of *J* at the intersection of $(dJ/da)_{applied}$ and $(dJ/da)_{material}$ can be used to find out the amount of crack growth at instability. Also, $(dJ/da)_{material}$ decreases rapidly as *J* increases. Hence, the tendency of unstable crack growth increases as *J* increases, at least if the applied curve continuously increases or is constant.

(a) Tip A

(b) Tip B

Fig. 8 Close-up views of crack location of the specimen SSPW 12-27 after fracture test

(a) Tip A

(b) Tip B

Fig. 9 Close-up views of crack location of the specimen QCSP-12-60-TWC-NGWP-L2 after fracture test

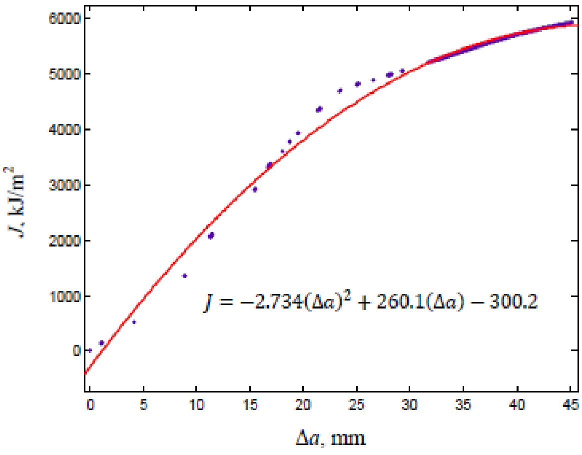

Fig. 10 Monotonic J-R curve for specimen SSPW12-27

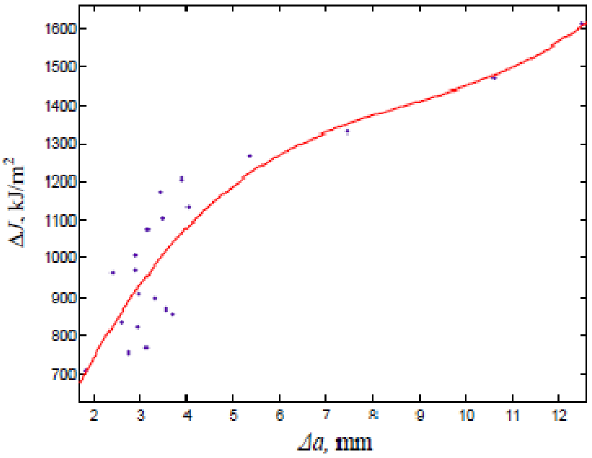

Fig. 11 Cyclic *J-R* curve for specimen QCSP-12-60-TWC- NGWP-L2

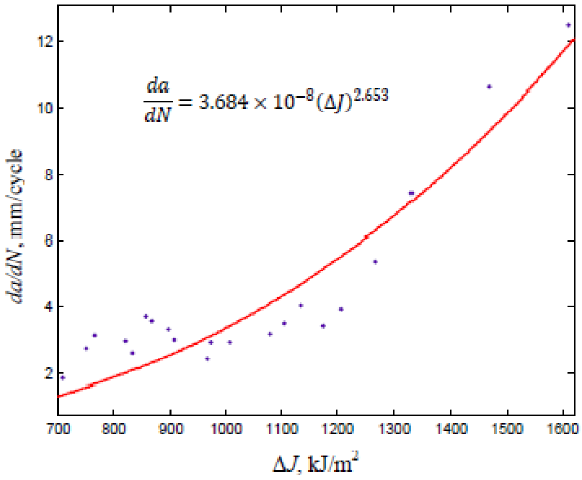

Fig. 12 *da/dN* vs. *ΔJ* curve for specimen QCSP-12-60-TWC-NGWP-L2

V. SUMMARY AND CONCLUSIONS

J-integral was estimated for circumferentially TWC straight pipes subjected to monotonic and cyclic loading. Monotonic *J*-integral was estimated using the approach given by Zahoor and Kanninen, whereas cyclic *J*-integral was estimated using method proposed by Dowling and Begley. Monotonic *J-R* curve was obtained, a quadratic polynomial was fitted to the *J-R* curve and a relation between *J* and *Δa* was obtained. Similarly, cyclic *J-R* and *da/dN* vs. *ΔJ* curves were also obtained. A power law equation was fitted between *da/dN* and *ΔJ*.

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