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A Study Of Fracture Mechanics Behaviour Of High Strength-Low Alloy Steel Of A Welded Penstock Structure

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Abstract— A study of fracture mechanics behavior of an under-matched weld joints with small and large surface cracks for high strength low alloy steel of penstock structures has been performed by the J-R curve approach. Suminet 80P (SM 80P) grade steel plate was butt welded by submerged arc welding. Three tensile panels with surface cracks positioned in the base metal (BM), weld metal (WM) and the heat affected zone (HAZ) were tested at room temperature. A continuous measurement of force versus crack mouth opening displacement and crack extension was monitored during the test by the compliance method. In addition, J-R curves were built for three parts of the weld joint. Crack driving force (CDF) is obtained for various values of applied stresses ratio and it plotted as a function of crack depth ratio. The CDF curve is plotted in a diagram together with the respective R-curve of the material, at each intersection point between the R-curve and CDF curve gives the maximum load carrying capacity of the penstock structure, after which the fracture instability will occur. Through the results, it was found that the penstock in the heat affected zone could safely withstand the working pressure of 10.23 MPa in the presence of a large surface flaw and the crack will be stable upto 0.42. The penstock in the welded area could safely withstand the working pressure of 13.01 MPa in the presence of a short surface flaw and the crack will be stable upto 0.31.

keywords— high-strength steel, penstock, welding, fracture mechanics..

1. Introduction

Fracture mechanics is the study of the behavior of structure with cracks to determine the criteria for the growth of preexisting cracks in materials. It is an important tool used to improve the performance of mechanical components. There are three different modes of loading that a crack can experience , as illustrated in Figure 1. Opening mode - Mode I: tensile stress is normal to the crack plane; Sliding mode- Mode II : shear stress is parallel to the crack plane and perpendicular to the crack front; Tearing mode Mode III : shear stress is parallel to the crack plane and parallel to the crack front. Only the opening mode is considered in this work [1,2].

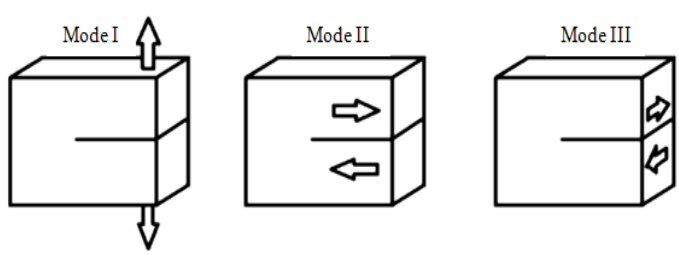

Fig.1. Fracture modes.

Fracture mechanics can be divided into Linear Elastic Fracture Mechanics (LEFM), where the cracked body shows a linear elastic behavior, with a stress-strain linear relation, and Elasto-Plastic Fracture Mechanics (EPFM), where the plastic field near the crack tip is taken into account. Cracks appearing in structures due to imperfections in design, manufacturing, service or maintaining, can exert an influence on their reliability and safety. Therefore, it is important to determine how existing cracks can threat integrity of structures and their components. Fracture mechanics provides theories and parameters useful for such tasks. One of the fracture mechanics parameters is J-integral, suitable for quantifying crack driving force when material ahead of crack tip exhibits elastic-plastic behavior. When dealing with a crack growing from initial length a, J-integral values should be obtained for a number of crack extensions (Δa). Such results can be presented in J-Δa sets of values. A J-R curve show applied Integral J versus crack extension [3]. In order to construct J-R curve, The ASTM E 1820 that covers J-integral testing is used [4]. The British standard BS 7448: part 1 [5] is equivalent in scope to ASTM E 1820. There are two alternative methods of J-testing provided by ASTM standard E 1820: The basic procedure and the resistance curve procedure. The basic procedure involves monotonically loading the specimen to fracture or to a particular displacement, depending on the material behavior. The Resistance curve procedure requires that the crack growth be monitored during the test. To construct R-curve, it is convenient to divide the J into elastic and plastic components as follows according to ASTM E1820:

$$J = J_{el} + J_{Pl} \tag{1}$$

$$J_{el} = K^2 \frac{(1-\nu^2)}{E} \tag{2}$$

$$K = \frac{P}{B\sqrt{W}} f(a/w) \tag{3}$$

If side groove specimen are used, then

$$K = \frac{P}{\sqrt{B B_N W}} f(a/w) \tag{4}$$

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ASTM E 1820 including a simplified method for computing J

plastic from area under load-displacement curve:

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_o} \quad (5)$$

J_{el} = elastic component of J, J_{pl} = plastic component of J, K = stress intensity factor, v = Poisson's ratio, E = Young's modulus, p = the applied load, $B = the\ gross\ thickness$ w = the specimen width, a = the crack length, BN = net thickness (for side-grooved specimens). b_o = the initial ligament length, ⍰ = dimensionless constant , f (a/w) = a dimensionless geometry function, Apl = the plastic area under the load-displacement curve.

In order to evaluate of the critical crack size of surface flaw(point of instability) by using a resistance curve of material and crack driving force curve of structure, the following proposed procedures are used: Consider surface flaw geometry as shown in Figure 2, where: d is the depth of crack at the center and 2a is the crack length of surface.

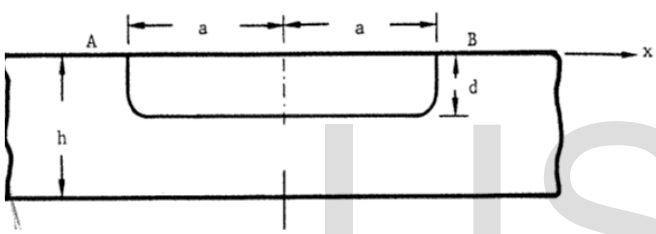

Fig. 2. The surface flaw geometry

Procedure is as follows:

- Construct the $\sqrt{J_R}$ curve of the material of the structure using suitable specimen.
- Construct $\sqrt{J*}$ curves for the structure at various crack depths and applied stress using a suitable model.
- Determine the point of instability, which defined at the point of tangency between the crack driving force curves and J-R curve.

2. Experimental procedure

The approach to welded structure designs is that the weld metal strength under- matches the strength of the base metal. This means that the yielding will start in weld joint, and the base metal will start to yield when the strength of weld joint reaches (strain hardening) a level of base metal yield strength. In these experiments the Sumiten 80P (SM 80P) grade steel plate (16 mm thick) was butt welded (X-shaped preparation) by submerged arc welding using consumables of 80B wire and MF38 flux, where these combinations under-matched weld joints are obtained. Three tensile panels with surface cracks positioned in the base metal (BM), weld metal(WM),and heat-affected zone (HAZ) were tested at room temperature. A semi-elliptical small and large surface crack (SSF, d = 2.0 : 3.0 mm, LSF, d = 4.5 : 5.3 mm) was produced by electrical discharge machine at BM, WM, and HAZ. The objective of this was to induce stable crack extension, and this test requires continuous measurement of force versus crack mouth opening displacement and crack extension was monitored during the test by the compliance method.

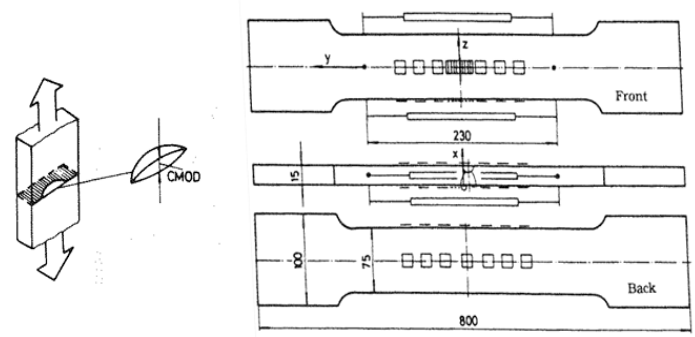

Fig. 3. Preparation of samples for tensile panel test

2.1 Materials

Under-matched weldments are recommended for high strength low alloy steel (HSLA) with yield strength of above 700 MPa in order to avoid cold cracks, that means the strength of weld metal is designed to be lower compared to base metal. Chemical composition and tensile properties of materials are given in Table 1 and Table 2, respectively.

Table 1.Chemical composition of materials(Weight %)

C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	Fe
0.10	0.20	0.23	0.009	0.018	1.24	3.1	0.29	0.05	0.08	Bal.

Table 2.Mechanical properties of materials

Strength (MPa)	Base metal (BM)	Weld metal (WM)	Heat affected zone (HAZ)
Yield strength(σy)	750	718	734
Tensile strength(σut)	820	791	800

2.2 Crack driving force curves of BM, HAZ and WM

Crack driving forces (CDF) are calculated for various values of crack depth ratio (d/h) for pressure vessels (penstock) with the shell parameter equal to zero (λ=0). Crack driving force of cylindrical shell could be calculated using the model proposed by Ratwani, Erdogan and Irwin, [6], as shown in Figure 4:

$$J^* = \frac{JE}{4a\sigma_Y^2} \quad (6)$$

One should notice that the crack driving force curves were determined for various values of stresses ratio (PR/hσy), in non-dimensional form, independent of material tensile properties.

2.3 The J-R curves of small and large surface flaw of

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BM, WM and HAZ

When the crack driving force equals or exceeds the fracture toughness of the material, the crack starts to grow, therefore the J-R curves for different components (BM , WM , HAZ) and different depth of small and large surface flaw (SSF, LSF) were determined using the direct measurement of the J-integral, as indicated in Figure 5.

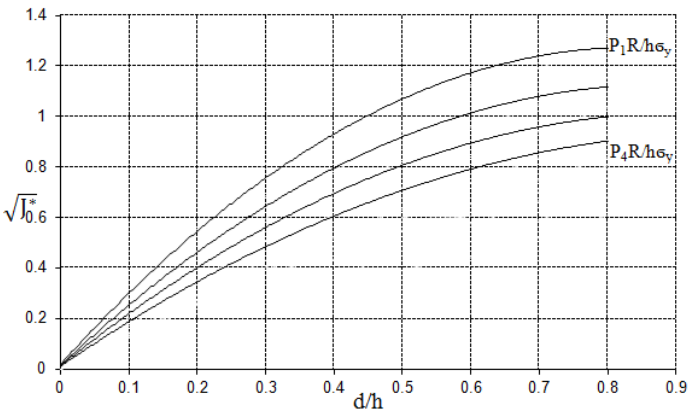

Fig. 4. The CDF of the penstock model

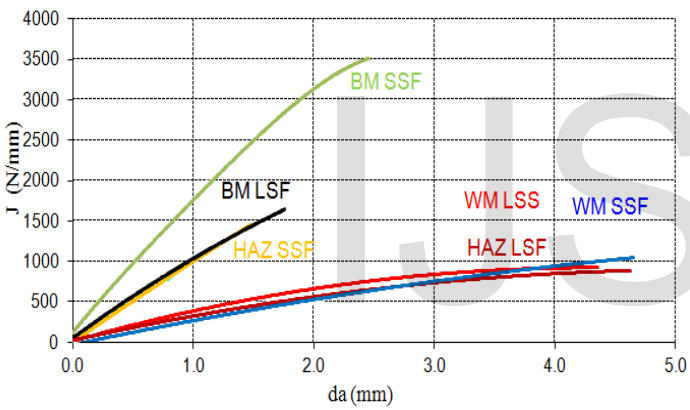

Fig. 5. The J-R curves of WM, BM and HAZ (SSF, LSF)

3. Results and Discussion

The procedure of J-R curves for large surface flaws as indicated in Figure 5, the base metal showed higher resistance to propagation of the crack and heat affected zone which had lower resistance. The heterogeinity of microstructure in HAZ plays a main role in this behavior. Furthermore, J-R curves for small surface flaw curve of weld metal showing lower resistance to the crack growth while the base metal with SSF shows higher resistance to the crack growth. This means that the existing small surface flaw in the weld metal will grow faster than others and the leakage and failure is expected to happen in this location. The CDF curves in Figure 4, are now plotted against J-R curves in Figure 5, as indicated in Figures 6, 7 and 8,for BM, WM and HAZ, respectively. As can be seen in Figure 6, for the measured length of surface crack with large surface flaw (depth of crack, d= 4.74 mm), the point of instability was reached at pressure 11.95 MPa, and for a small surface flaw (depth of crack, d = 2.38 mm), the point of instability reached a pressure of 15.77 MPa, and the crack will be stable up to: SSF (d/h) = 0.245 and da =1.54 mm; LSF (d/h) = 0.38 and da = 1.34 mm. Figure 7 shows that, the point of instability of large surface flaw of weld metal reached a pressure of 11.16 MPa and crack growth will be stable up to a depth ratio of 0.46 and crack extension (da = 2.42 mm), while for a small surface flaw, the pressure of instability was 13.01 MPa and the crack will be stable up to a depth ratio of 0.31 and crack extension (da = 2.85 mm). As indicated in Figure 8, the point of instability of small surface flaw reached a pressure of 15.27 MPa and the crack will be stable up to a depth ratio of 0.23 and maximum stable crack extension was (da = 1.65 mm). For a large surface flaw the pressure of instability was 10.23 MPa, and crack will be stable up to a depth ratio of 0.42 and crack extension (da = 1.56 mm). Based on the above mentioned, the point of tangency between the R-curve and CDF curve gives the maximum load carrying capacity of the penstock which is called the instability point. The instability point is corresponding to the critical pressure, i.e., the critical value of crack size. Before the instability point there is a stable crack growth and fracture does not yet occur, while after this point the crack growth will be unstable and fracture will occur where the driving force is more than the material resistance. The most critical part of a pressure vessel is the HAZ in the welded joint, because crack-like defects are inevitable [7]. The most critical case of a penstock is LSF in HAZ , as illustrated in Figure 8, with the point of instability when a pressure reaches 10.23 MPa, and stable crack growth up to a depth ratio of 0.42. Furthermore, the crack depth of HAZ is more (LSF, d = 5.168 mm) compared to BM (LSF, d = 4.74 mm) and WM (LSF, d = 4.94 mm).

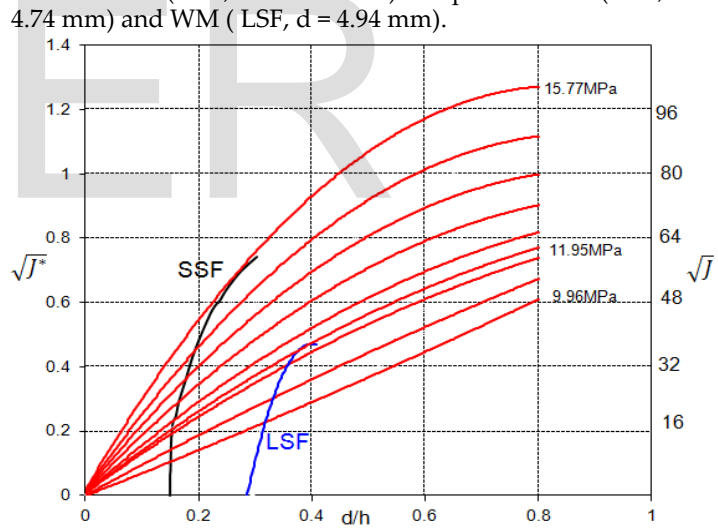

Fig.6. Determining the point of instability of BM of penstock(SSF, LSF)

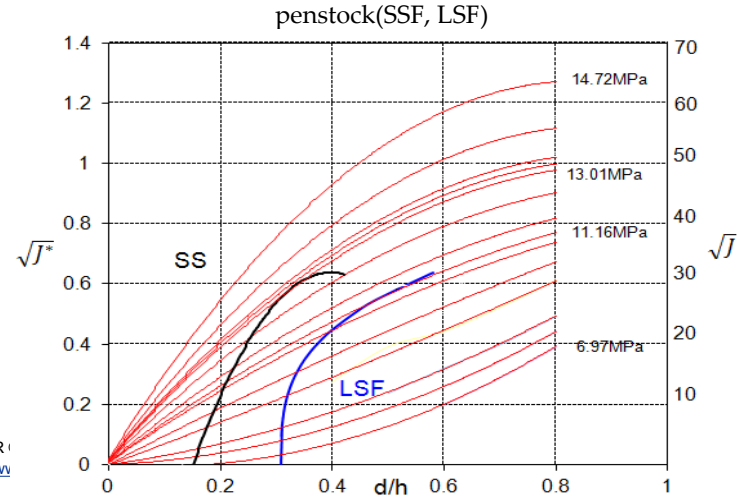

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Fig.7. Determination the point of instability of WM of penstock(SSF, LSF)

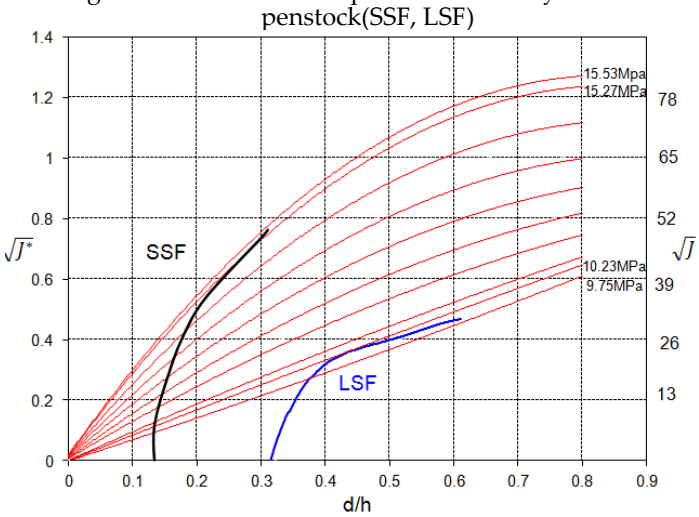

Fig.8. Determination the point of instability of HAZ of penstock(SSF, LSF)

4. Conclusions

- Fracture mechanics can be applied to determine the extent of the stable crack and the crack size critical by applying crack growth resistance curve, expressed by J-R curve, and the crack driving force, CDFs.
- Welded joint is a critical region in the penstock structure and any welded construction. In this study presented here the HAZ is the most critical region.
- The penstock in the heat affected zone could safely withstand the working pressure of 10.23 MPa in the presence of a large surface flaw and the crack will be stable upto 0.42.
- The penstock in the welded area could safely withstand the working pressure of 13.01 MPa in the presence of a short surface flaw and the crack will be stable upto 0.31.

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