

Failure of Mechanical Equipment Due to Welding Imperfections

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Abstract

Each of welding processes has some disadvantages and limitations; For instance existence of welding imperfections that might be due to poor workmanship or design issues such as cracks, porosity, lack of fusion, incomplete penetration, spatters and others. Failure of Schenectady T2 tanker in 1943 is a good example of brittle fracture where the crack initiated due to presence of notches in steels that are sensitive at low temperature.

Keywords: Welding; Microstructure; Base metal

Introduction

Welding is one of the most important techniques of joining metals homogeneously in refinery and petrochemical industry with various geometries and sizes in low overall cost. There are several types of welding process such as Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (GTAW) etc. The objective of this paper is to provide an overview of the main weldment defects in mechanical equipment (pressure vessels, pipes, and tanks), detection of these defects using Non Destructive Testing (NDT) methods and how these imperfections may lead to cracks initiation and hence a fracture occurs. This report will also show Engineering Critical Assessment used to evaluate cracks exist in mechanical equipment that is on operation.

Main Welding Defects in Mechanical Equipment

There are about 26 types of welding defects for different welding processes and for different weld joint design per ISO 5817. These defects could be on the surface of the weld, inside the weld, in the root pass or even on the base metal close to the welding area like heat affected zone (HAZ), portion of the base metallurgy whose mechanical properties or microstructure have been altered by the heat of welding per API 577. Figure 1a shows the different types of welding defects in butt and fillet weld joints. Examples of on the surface defects arc strike, undercut and spatters, which are a molten metal splashed over the surface due to high welding current used as shown in Figure 1b. Examples of defects inside the weld are porosity, slag inclusions, lack of fusion etc. Porosity is entrapped hydrogen or oxygen gas inside the weld due to insufficient shielding from the electrode flux, while slag inclusion is de-oxidation product from welding flux. Moreover, lack of fusion is poor adhesion between the weld and base metal due to incorrect welding setting or design. Figures 1c and 1d show these defects. On the other hand, cracks may exist on the weld or between weld-base metal during solidification or after cooling 'delayed cracking' as shown in Figure 1e [1,2].

Non-Destructive Testing (NDT) Techniques

In order to check the soundness of the weld for the equipment without damaging or destroying it, the manufacturers or fabricators are using NDT methods. There are several types of these such as Penetrant Testing, Radiographic Testing (RT), Ultrasonic Testing (UT), Magnetic Testing (MT) and of course Visual Testing (VT). There are also advanced NDT techniques used for welding critical services such as Time of Flight Diffraction Ultrasonic (TOFD). Some of these methods will be discussed briefly in this report.

Penetrant Testing is simple and low cost technique used to detect open to surface defects such as crack by using three different sprayers

i.e., penetrant, developer and cleaner sprayers. The applying procedure of this method is by cleaning the surface and applies the penetrant which is in red color, and then after five minutes the area cleaned off with use of the cleaner followed by applying the developer which is in white color to bleed out the penetrant and make a color contrast. The crack will be visible easily after application as in Figure 2. The disadvantages of this method are; used only for open to surface defects, temperature limit of 125 F maximum, cannot be used to measure flaw size [3,4] (Figure 2).

Another NDT method is Ultrasonic Testing which is a manual and effective to measure the defect size as well as detect internal defects in the weld by sending a beam of sound waves with frequency range (>20,000 cycles per second). If there is any defect the waves will be reflected back to the probe and amplitude intensity displayed on the screen. The disadvantages are requiring certified operator, even with the certified personnel it is difficult to recognize the type of welding defect and no permanent record of the measured defects [3,4].

Radiographic Testing is one of the most effective techniques used to detect internal defects by sending X-rays from radioactive source (Ir 192 or Cobalt 60) placed at one side of the weld and on the other side an image film is placed with image quality indicator (IQI). The main disadvantages of this method are health hazardous, high cost and very sensitive to the defect orientation for example if there is a crack parallel to the X-rays as shown in Figure 3, it appears on the film as a dot and the interpreter will recognize it as porosity instead of the crack, that is why it is not recommended to use RT for crack detection or to be used at several different shooting angles at the same joints which means more cost [3,4].

After completion of the NDT methods ASME & API standards mandate testing the entire piping system or hydrocarbon plant by hydrostatic test. This is considered as the last line of defense before turning in the plant for operation to make sure it will operate safely without failure. This test can be performed with use of clean water with

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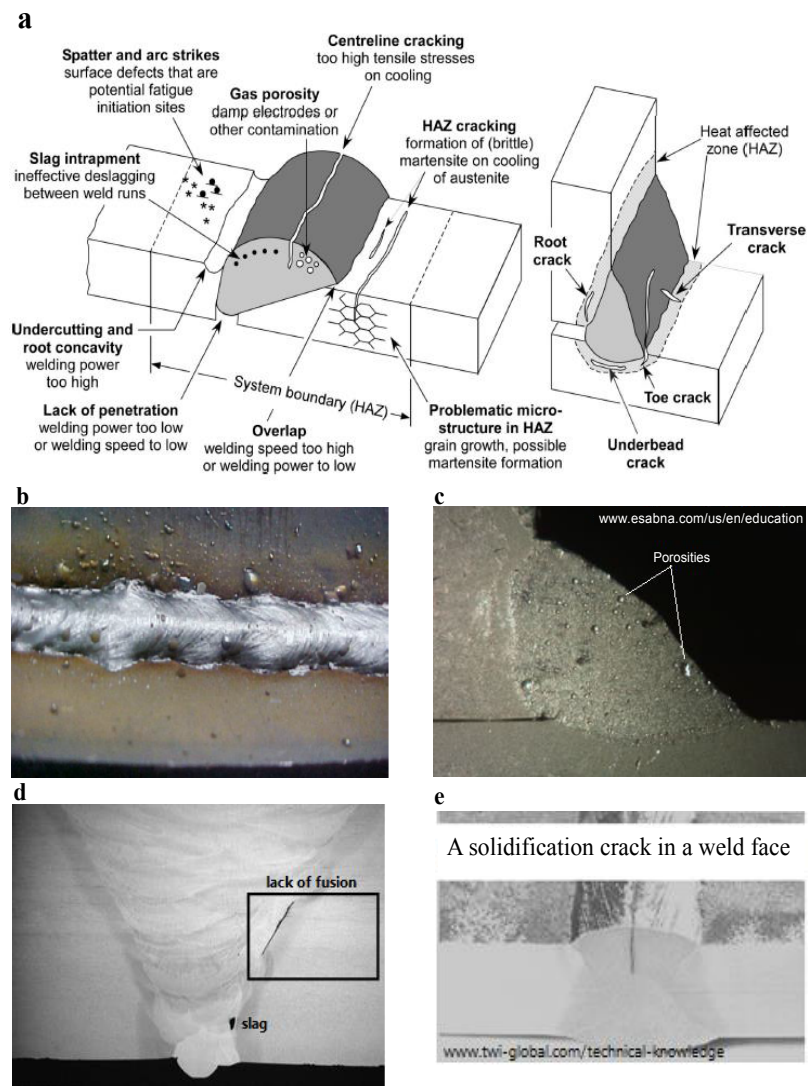
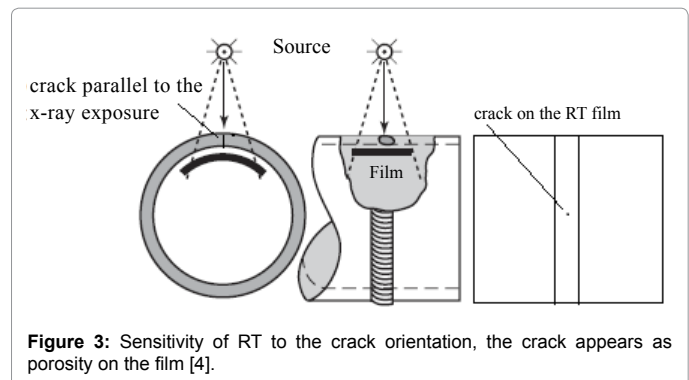


Figure 1: (a). Different types of welding defects in butt weld (left) and fillet weld (right) [2]. (b). Spatters over weld and base metal; (c). Porosities inside a fillet weld. (d). Lack of fusion and slag in butt weld [3]; (e). Solidification crack on the weld face.



Figure 2: Crack is visible after applying the three sprayers.

specific PH based on the material and other requirements that must be followed in the codes at pressure of 1.5 design pressures but shall not exceed 0.9 of the yield strength. In case of a serious defect exists in the weld that was not discovered by other NDT methods, a failure will occur as shown in Figure 4. As alternative where water cannot be used, a pneumatic test is performed with use of air at pressure of 1.1 design



pressure, but this is rarely done because of high stored energy that leads to a disaster in case of failure.

Welding Imperfections and Their Effect on Fracture

Some welding defects can be considered as fracture cause from the

first stage such as cracks. Moreover, in terms of fracture mechanics lack of fusion and lack of penetration are also considered are long cracks that contribute to the crack driving force against the resistance of the material to crack propagation as shown in Figure 5a [5].

Furthermore, other defects which might cause crack initiation such as slag inclusions and spatters. For the spatters, due to difference in temperature with the hit surface there will be a local restraint which causes a tensile residual stresses in the droplets and hence the impurities will act as crack initiation as show in Figure 5b [6].

On the other hand, there are defects may not cause crack initiation depend on the location of the defect in weld such as porosity. For instance, surface porosity may have an effect of fracture that depends on its volumetric size; the strength of the weld is influenced as well. Therefore, the welding defects can be classified into three categories as follows [7]:

- Crack and crack like imperfections such as lack of fusion which cause a fracture and must be avoided.
- Imperfections act as crack initiation sites due to its geometry or sharp edges which cause the stress concentration and increase in the residual stress during solidification such as spatters, angular misalignment, slag inclusions, undercut and weld toe. Consequently, this type of defects may initiate fatigue crack during service.

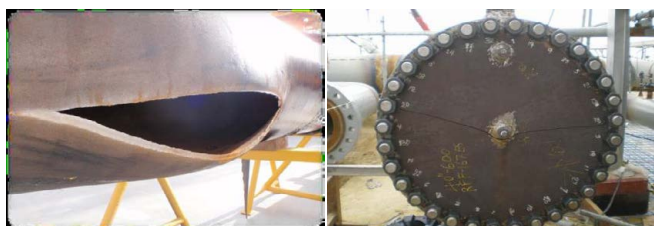


Figure 4: Two failures occurred during hydro test due to existence of welding defects.

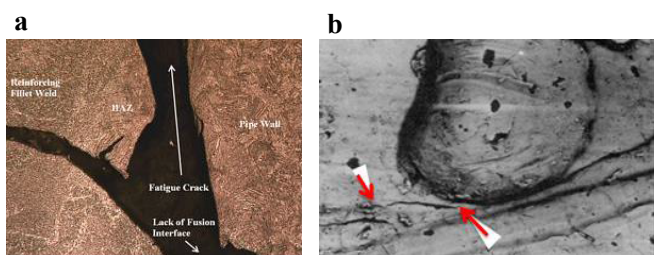


Figure 5: (a). Lack of fusion is considered as long crack [6]; (b). Spatter causes crack initiation [2].

- Imperfection which does not have any effect of fracture and fatigue life such as porosity due to its round shape geometry without having sharp edges and hence no stress concentration. Harrison proved using fatigue data of porosity that the severity of the porosity could be evaluated by only one factor which is the volume of defect and test the results revealed similar fatigue strength [8].

Acceptance Criteria of Welding Imperfections

The discovered welding defect using NDT methods should be evaluated to identify whether within the acceptable limits or not. Each NDT method has different criteria in the construction and in service codes of pressure vessels, storage tanks and piping i.e., ASME-VIII for pressure vessels, ASME-B31.3 for piping and API-650 for storage tanks. Some of the acceptance criteria from codes are listed in Table 1 [9-11].

Assessment of Welding Imperfections in Terms of Fracture Mechanics

Sometimes the design and material properties fall outside the scope of the construction codes or a flaw that is beyond acceptance code limit is found in mechanical equipment already placed in service. In this case fracture mechanics approach is required for evaluation i.e., Engineering Critical Assessments (ECA) methods, such as BS7910, R6, Fitness for Service Network (FITNET) and API 579-1/ASME FFS-1. The most common method used in refinery and hydrocarbon plants is API 579. It was first published in 2000 in USA to evaluate discovered flaws or damage in in operation mechanical equipment to decide if the equipment will continue in operation safely without failure till the repaired performed. This code is considered as a supplementary to ASME B31.3, API 650, ASME VIII and API 570. Section 9 from API 579 (FFS) is used for assessment of crack like imperfections in welds which will be discussed in detail. This method depends on Failure Assessment Diagram (FAD) for flaws evaluation by calculating Toughness ratio K_r and load ratio L_r and then the point coordinate plot on to determine the acceptability for continue in service if it is on or below the curve as shown in Figure 6 [12,13].

There are three level of assessments in section 9 based on the conservatively and the amount of information required; level-1 which is a basic level that require a minimum inspection and can be conducted by an engineer or inspector, to the most advance level, i.e., level-3 which is performed for most detail evaluation and requires very detailed inspection as well as analysis is based on numerical techniques such as the finite element method and it must be done by engineers of at least two years' experience in FFS. The assessment steps will be discussed through a case study from API 579 [13].

Type of Defect	Piping (ASME B31.3)	Pressure Vessel (ASME Sec. VIII)	Tanks (API 650)
Spatter	Not acceptable	Not acceptable	Not acceptable
Crack	Not acceptable	Not acceptable	Not acceptable
Porosity	1/4t, or 5/32 in. (4 mm), whichever is smaller	1/4t, or 5/32 in. (4 mm), whichever is smaller	1/4t, or 5/32 in. (4 mm), whichever is smaller
Incomplete penetration and lack of fusion	Not acceptable	Not acceptable	Vertical not permitted Horizontal Max 10%t
Slag Inclusion	$L \leq t/3$, $W \leq 2.5$ mm (3/32 in.) and $\leq t/3$ cumulative $L \leq t$ in any 12t weld length	2/3 T, T is thickness of plate	max T in length of 6T
Hollow Bead	Not Listed	Not Listed	Not Listed

Table 1: Examples of welding acceptance criteria for RT method [9,10,11].

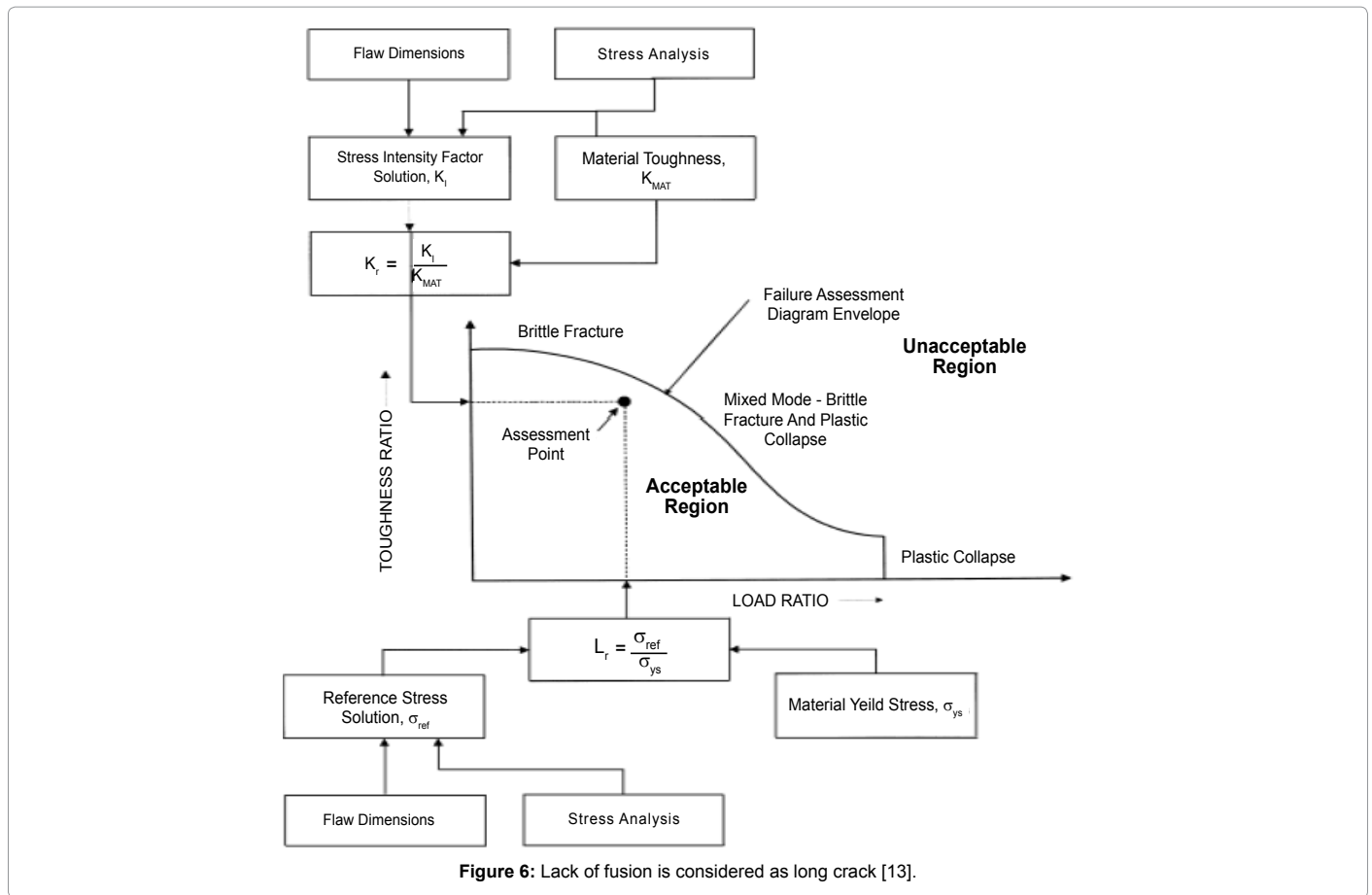


Figure 6: Lack of fusion is considered as long crack [13].

Case Study

A crack was discovered during routine inspection in the external circumferential weld of 20 in in plant pipe which was constructed per ASME B31.3 [13].

Level-1 assessment was used and found not satisfactory, hence Level-2 assessment will be used for evaluation.

Step-1 Collect pipe data, operating conditions and inspection data

Pipe Data:

- Material=SA-106 Grade B Year 2003
- Design Conditions=3.0 MPa at 250°C
- Fluid Density=0.8
- Pipe Outside Diameter=508 mm (NPS 20)
- Pipe Thickness=9.53 mm (Schedule 20)
- Uniform Metal Loss=0.0 mm
- FC=0.0 mm
- Weld Joint Efficiency=1.0
- PWHT=No

Operating conditions

- P=2 MPa
- T=20 C.

Inspection data

Using UT method the crack was measured at depth of 3 mm located at external circumferential surface of the weld.

Step-2 Calculate stress ratio L_r for both primary stress (pressure) and secondary stress (residual) by first calculating stress reference σ_r

For primary stress by using Net Section Axial Force and Bending Moment (KCSCCL1)

$$R_o = D/2 = 508.00/2 = 254.00 \text{ mm (pipe radius)}$$

$$R_i = R_o - t = 254.00 - 9.53 = 244.47 \text{ mm (internal pipe radius)}$$

$$M/\pi (R_o^4 - R_i^4) = (36.8) (10)^6 / \pi \{ (254.00)^4 - (244.47)^4 \} = 0.01984 \text{ N/mm}^3$$

The membrane and bending components for primary stress are

$$P_m = \frac{pR_i^2}{R_o^2 - R_i^2} = \frac{3 \times 244.47^2}{254^2 - 244.47^2} = 37.75 \text{ Mpa}$$

$$P_{bg} = \frac{M}{\pi (R_o^4 - R_i^4)} = \frac{R_o}{0.25} = 20.2 \text{ Mpa}$$

Also Partial Safety Factor (PSF) needs to be determined=1.5

So $P_m = 1.5 \times 37.75 = 56.62 \text{ Mpa}$ and $P_{bg} = 30.3 \text{ Mpa}$

$$\sigma_{ref}^p = \frac{M_r}{2} + \sqrt{N_r^2 + \frac{M_r^2}{4}}$$

$$M_r = P_{bg} \frac{3\pi (R_o^4 - R_i^2)}{16 [R_o (R_o - a)^3 - R_i^4]} = 23.65 \text{ Mpa}$$

$$\sigma_{ref}^p = \frac{M_r}{2} + \sqrt{N_r^2 + \frac{M_r^2}{4}} = 95.8 \text{ Mpa}$$

$$L_r^p = \frac{\sigma_{ref}^p}{\sigma_{ys}} = \frac{95.8}{240} = 0.399 \text{ where } \sigma_{ys} \text{ is yield stress from the same code}$$

For secondary stress

The membrane and bending components for secondary stress are

$$Q_m = \sigma_0 + \frac{\sigma_1}{2} + \frac{\sigma_2}{3} + \frac{\sigma_3}{4} + \frac{\sigma_4}{5} \text{ and } Q_b = \frac{-\sigma_1}{2} - \frac{\sigma_2}{2} - \frac{9\sigma_3}{20} + \frac{6\sigma_4}{15}$$

The stresses represent residual stress distribution over the thickness and can be determined from best fit fourth polynomial by generating graph using (Figure 7)

$$\sigma^R(x) = \sigma_0 + \sigma_1 \frac{x}{t} + \sigma_2 \left(\frac{x}{t}\right)^2 + \sigma_3 \left(\frac{x}{t}\right)^3 + \sigma_4 \left(\frac{x}{t}\right)^4$$

Therefore;

$$\sigma_0 = 231$$

$$\sigma_1 = -608.8$$

$$\sigma_2 = -2806.8$$

$$\sigma_3 = 8474.7$$

$$\sigma_4 = -5084.2$$

By substitution

$$\sigma Q_m = 92.9 \text{ Mpa and } Q_b = -72 \text{ Mpa}$$

$$\sigma_{ref}^{SR} = \frac{Q_b + \sqrt{Q_b^2 + 9[ZQ_m(1-\alpha)^2]^2}}{3(1-\alpha)^2}$$

$$\tau = \frac{t}{R_0} = \frac{9.53}{508} = 0.037$$

$$\tau = \frac{t}{R_0} = \frac{9.53}{508} = 0.037$$

$$Z = \left[1 - \alpha \left(\frac{2 - 2\tau + \alpha\tau}{2 - \tau} \right) \right]^{-1} = 1.45$$

$$\therefore \alpha_{ref}^{SR} = \frac{-72 + \sqrt{72^2 + 9[1.45 \times 92.9(1-0.3)^2]^2}}{3(1-0.3)^2} = 93.2 \text{ Mpa}$$

$$\therefore L_r^{SR} = \frac{\alpha_{ref}^{SR}}{\alpha_{ys}} = \frac{93.2}{240} = 0.388$$

Step-3 Calculating stress intensity factor

For primary stress

$$\therefore K_I^p = \left[G_0 \left(\sigma_0 + p_c \right) + G_1 \sigma_1 \left(\frac{a}{t} \right) \right] \sqrt{\pi a}$$

Where $\sigma_0 = \sigma_m^p + \sigma_b^p$ and $\sigma = -\sigma$ membrane and bending components for stress intensity factor.

$$\sigma_m^p = \left[\frac{pR_i^2}{R_0^2 - R_i^2} \right] + \left[2 \frac{M(R_0 - R_i)}{\pi(R_0^4 - R_i^4)} \right] = 57.5 \text{ Mpa multiply by PSF}$$

$$(1.5) = 86.2 \text{ Mpa}$$

$$\sigma_b^p = 2 \frac{M(R_0 - R_i)}{\pi(R_0^4 - R_i^4)} = 0.37 \text{ Mpa multiply by PSF (1.5)} = 0.56 \text{ Mpa}$$

$$\therefore \sigma_0 = 86.8 \text{ Mpa and } \sigma_1 = -1.12 \text{ Mpa}$$

G_0 and G_1 from Appendix A = 1.576 and 0.845 respectively

By substituting the values in K_I^p , the $K_I^p = 13.3 \text{ Mpa}\sqrt{\text{mm}}$

For secondary stress

The stress intensity factor can be calculated using

$$K_I^{SR} = \left[G_0 \left(\sigma_0 + p_c \right) + G_1 \sigma_1 \left(\frac{a}{t} \right) + G_2 \sigma_2 \left(\frac{a}{t} \right)^2 + G_3 \sigma_3 \left(\frac{a}{t} \right)^3 + G_4 \sigma_4 \left(\frac{a}{t} \right)^4 \right] \sqrt{\pi a}$$

Where G_0, G_1, G_2, G_3 and G_4 from Appendix A = 1.576, 0.845, 0.603, 0.478

And 0.4189 respectively. And by substituting for the residual stresses;

$$K_I^{SR} = 13.6 \text{ Mpa}\sqrt{\text{mm}}$$

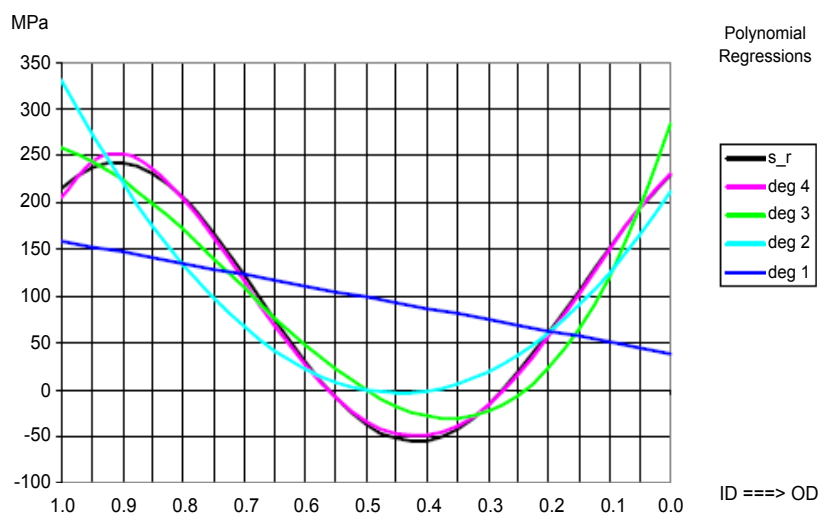
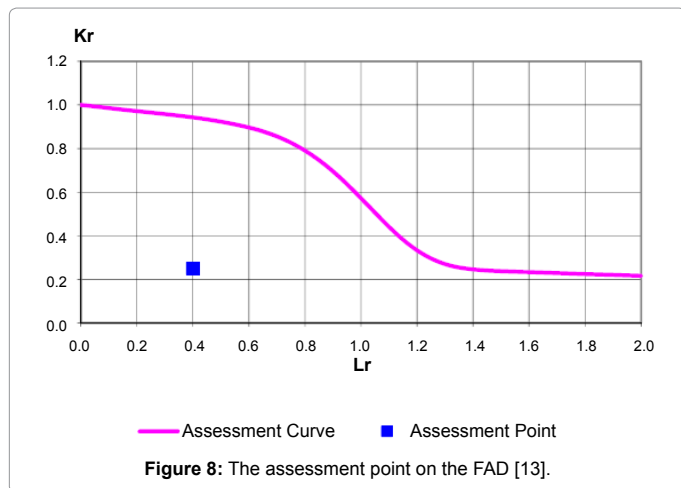


Figure 7: Through wall residual stress distribution [13].

Type of Discontinuity	Welding Processes	Typical NDE	Practical Solution
Lack of fusion (LOF)	All	UT	Proper heat input, proper welding technique.
Incomplete Penetration	All	RT, UT, VT	Proper heat input, proper joint design.
Slag Inclusion	SMAW, FCAW,SAW	RT, UT	Proper welding technique, cleaning, avoid excessive weaving.
Porosity	All	RT, UT	Low hydrogen, low sulfur environment, proper shielding.

Table 2: Practical solution to prevent reoccurrence.



Step-4 Fracture toughness

$$K_{IC} = 36.5 + 3.084 \exp[0.036 (T - T_{ref} + 56)]$$

T_{ref} from Appendix A for curve B carbon Steel and $\sigma_{ys} = 240$ MPa;

$$T_{ref} = 10C$$

$$\therefore K_{IC} = 69.7 \text{ MPa}\sqrt{m}$$

Step-5 Calculate the mean fracture toughness K_{mat}^{mean}

The ratio of $\frac{K_{mat}^{mean}}{K_{IC}}$ can be calculated from Appendix B using

$$\frac{K_{mat}^{mean}}{K_{IC}} = \frac{1}{B_0 + B_1\Delta T + B_2\Delta T^2 + B_3\Delta T^3 + B_4\Delta T^4 + B_5\Delta T^5}, \text{ at } \sigma = 1$$

and $\Delta T = 20 - 10 = 10C$

$$\frac{K_{mat}^{mean}}{K_{IC}} = \frac{1}{0.6252} = 1.6$$

$$K_{mat}^{mean} = 1.6 \times 69.7 = 111.52 \text{ MPa}\sqrt{m}$$

Step-6 calculates the toughness ratio K_r

$$K_r = \frac{K_I^P + \Phi K_I^{SR}}{K_{mat}}$$

By using Appendix C with $L_r^P = 0.399$ and $L_r^{SR} = 0.388$

$$\psi = 0.029 \text{ So } \frac{\Phi}{\Phi_o} = 1 + \frac{\psi}{\phi} = 1.071$$

$$\phi = 0.405$$

$$\therefore K_r = \frac{K_I^P + \Phi K_I^{SR}}{K_{mat}} = \frac{13.3 + 1.071 \times 13.6}{111.52} = 0.2498$$

Step-7 Plot the assessment point in FAD

$$(L_r^P, K_r) = (0.399, 0.2498) \text{ (Figure 8)}$$

So, the assessment point is below the curve, hence the pipe will continue in service safely till next inspection for repair. If the assessment point on or above the curve, level-3 assessment will be used.

Conclusion

This report reveals that the critical welding defects leads to crack initiation and as a consequence fracture failure might occur. As a recommendation to reduce the residual stress in the weld is by performing post weld heat treatment. Moreover, proper joint design to eliminate sharp edges and hence high stress concentration is also recommended. Furthermore, the best way to prevent the defects from occurring by following the welding essential variables listed in approved welding procedure specification per ASME XI as well as following the practical solution to prevent reoccurrence as mentioned (Table 2).

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