

Common Root Causes of Pressure Vessel Failures: A Review

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Abstract – Present rules in fabrication codes, such as BSI PD6493, are aimed to reduce the probability of failures in welded pressure vessels subjected to cyclic pressure or vibrations. Yet, several leaks and ruptures have recently occurred in pressure vessels and pipes. Common aspects of these failures are crack initiation in weld metal and heat affected zone of welds, all related to an insufficient design of the reinforcement and poor execution of the welding procedure. Weld inadequacy is in one case a result of an increase in thickness as an attempt to increase safety; which also increased cyclic stresses due to excessive weight of the vessel. In this article, a brief overview of various pressure vessel failure mechanisms has been presented w.r.t impact toughness of thermally aged specimen, effects of absorbed hydrogen and thermal aging on crack-tip plastic zone in welded steel, fatigue crack mechanism of welded austenitic steel and effects of fatigue crack growth of thermally aged welded steel. About 39 published studies (1976-2015) are reviewed in this paper. It is marked from the literature survey articles that pressure vessels remain unsafe unless carefully designed, operated and inspected at regular intervals. **Copyright © 2016 Penerbit Akademia Baru - All rights reserved.**

Keywords: Integrity, pressure vessels, fracture mechanics, failure mechanisms, heat affected zone

1.0 INTRODUCTION

This review gives an overview of mechanism involved in the failure of pressure vessels, problems associated with these mechanisms. Developments in pressure vessels during the nineteenth and early twentieth centuries were accompanied by all-too-frequent terrible pressure vessel explosions. Tragic accidents such as the SS Sultana (1865) and the Grover Shoe Factory explosion (1904) led to the development of basic standards for manufacturing and operation of pressure vessels. Further advances in metallurgy, welding technology and non-destructive testing helped, but an actual understanding of the science and mechanics of pressure vessel failure did not finally arrive until late twentieth century. Even in the twenty-first century, the catastrophic failure of a boiler pressure vessel in the SS Norway in Miami harbor in 2003, which killed eight crew, was a reminder that pressure vessels remain hazardous unless carefully designed, operated and inspected [1].

2.0 MECHANISM OF FAILURE OF PRESSURE VESSEL

2.1 Impact Toughness of Thermally Aged Welded A516 Steel

Reactor pressure vessels (RPV) and pipelines are commonly constructed using welded pressure vessel grade steels and stainless steel liners. These pressure vessel steels required good ductility and weld-ability. The vessels wall materials used in oil refineries and chemical plants undergoes both physical and chemical changes because of various separation and conversion processes. These steel vessels operate in corrosive and high temperature environments. The operating temperature typically ranges from -29 to 427 °C. Prolonged exposure of the steel to these conditions could lead to deleterious effects such as embrittlement, loss of toughness, creep rupture of the steel [2,3] and a shift in ductile-to-brittle transition temperature (DBTT) to higher temperatures [4,5] Hence, vessels constructed with the steels, brittle fracture triggered by trans-granular cleavage in the DBTT region represents a potentially catastrophic failure mode. Therefore, one can term, cleavage fracture in the DBTT region exhibits a 'weakest link' phenomenon [6-8]. The occurrence of brittle fracture depends on the toughness of weld metal (WM) and of the heat affected zone (HAZ), which is generally lower than the base metal. The DBTT depends on many factors such as neutron flux, in case of nuclear vessel material, loading rates during service and outages, etc. which is usually experimentally captured by testing Charpy impact specimens. Commercial industry requires pressure vessel steel with sufficient strength and toughness, for both economic and safety reasons. Failures of pressure vessels and pressure piping related accidents are often fatal and involved loss of capital investment [9].

The application of immense heat in a welded joint of a pressure vessel steel, to fuse the base plate and weld metal (electrode) for strong permanent joint results in a mechanical and metallurgical inhomogeneity due to the weld thermal cycle in the base metal (BM), the HAZ and the WM. Weldments are thus, identified as a particular concern because they are often a life-limiting feature, and since existing ASME Boiler & Pressure Vessel [10](B&PV) code rules do not adequately consider the high-temperature creep failure modes that can arise as a function of geometry, loading and material combination [11]. Particularly tensile residual stresses near the weld area and HAZ may cause stress raising, fatigue failure and fracture.

Various studies showed that cracks have been found in different regions of the weld with different orientation in the weld zone, such as centerline cracks, transverse cracks and micro-cracks in the underlying WM or HAZ [12-14], thus rendering this region to be the most susceptible for crack initiation and growth. Once structural crack is present, fracture mechanics is employed to characterize the crack growth behavior as function of working load and other parameters.

Steels in general are ductile at high temperatures and brittle at lower temperature. This material behavior is normally presented as the ductile-brittle transition curve and plotted as fracture energy or toughness versus temperature. A typical ductile-brittle transition curve is shown in Figure 1. Pressure vessels, under normal operating conditions, are designed to operate at temperature above the onset of upper shelf toughness in order to avoid the brittle fracture. During planned outages and emergency start-up / shutdown sequences of the plants, these vessels undergo severe thermal

gradients thorough out their service life. The existence of these thermal gradient's has been a concern in many welded structures since it increases the crack driving force and reduces resistance to brittle fracture. Moreover, in reactor pressure vessel the criteria for safety include consideration of the effect of neutron irradiation over time on the ferritic steels which makes the steel brittle and shifts the material's ductile-to-brittle transition curve to a higher temperature range (the dashed line in Figure 1). The shift decreases operation margins in both the temperature and pressure and is inevitable in the aging process of reactor pressure vessel.

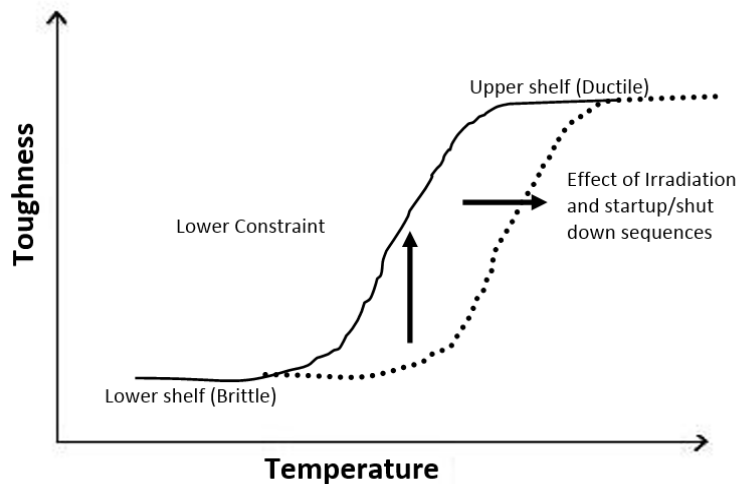


Figure 1: Ductile-brittle transition curve of steels and the effects of irradiation startup / shut down sequence and constraint on the shift of the curve

During service, reactor pressure vessel is subjected to moderately high pressure and temperatures, neutron irradiations and cyclic fatigue. The most likely degradation sites are typically weldments. The most severe and significant degradation mechanism is neutron irradiation embrittlement, which may be exacerbated by thermal aging. The accumulated effects over a long period of time due to irradiation and thermal aging causes range of mechanical properties, most significantly an increase in the DBTT. Ferritic steels used in power-plant components undergo a ductile-to-brittle fracture transition as the temperature is decreased. At low temperatures, fracture occurs by completely brittle cleavage mechanisms with low levels of absorbed energy. At high temperatures, fracture occurs by ductile dimple mechanisms with absorption of considerable energy. In the transition region, fracture is of a mixed mode. A variety of tests have been used to characterize the ductile-to-brittle transition behavior, and, correspondingly, a variety of definitions of transition temperature have emerged. A comprehensive review of various test techniques may be found in the literature [15,16].

The objective of this paper is (a) to discuss the different impact toughness behavior of welded A516 steel and (b) to describe the effect of thermal aging and subsequent shift on DBTT for HAZ

of welded A516 steel. The observed curves are explained in terms of absorbed energy (Joules) and temperature ($^{\circ}\text{C}$). The observed fracture mechanisms due to thermal aging in the HAZ region are described. The DBTT value for each curve is taken as the corresponding value of an average of maximum and minimum absorbed energy value. All the tests are performed at ambient temperature.

2.2 Effects of Absorbed Hydrogen and Thermal Aging on Crack-Tip Plastic Zone in Welded

Previous research has identified possible mechanisms of hydrogen reaction embrittlement in steels, namely hydrogen blistering, internal embrittlement and environmental embrittlement. The presence of internal hydrogen produces a plastic loss in austenitic stainless steel. At high temperature and pressure, this internal hydrogen facilitates de-carburization, promotes inter-granular cracking and forms blistering in steels [17]. The pressure of molecular hydrogen causes the formation of brittle cracks in hydrogenated low carbon steel [18]. Constant extension-rate test on Type 216 steel samples pre-exposed to concentrated synthetic ground water at 80-150 $^{\circ}\text{C}$ showed evidence of environmental (hydrogen)-assisted cracking and moisture-induced ductility loss [19]. The susceptibility of steels with different heat treatment to hydrogen embrittlement was evaluated in terms of mechanical properties [20]. While tensile strength, yield and hardness increase with increasing hydrogenation time up to five hours, significant reduction in ductility was measured.

In a welded joint, the application of immense heat to fuse the base plate and weld metal (electrode) for a strong permanent joint resulted in a heterogeneous heat affected zone (HAZ). This zone is a common source for defects such as hard inclusions, blisters by trapped gas and micro-cracks that developed during fast cooling of the welded joint. Exposure to absorbed hydrogen can cause deleterious effects including the formation and propagation of brittle cracks. In controlled laboratory experiment hydrogen can be introduced in the specimen by gaseous hydrogen charging in an oxygen-free copper chamber with tantalum hydride at temperature in excess of 700 $^{\circ}\text{C}$ [21]. Others use high-pressure (20-35 MPa) hydrogen autoclave at 350 $^{\circ}\text{C}$. In the electrochemical method the metal specimen is soaked in dilute solution of sulphuric acid with a corrosion inhibitor. A controlled current is supplied to the cathodically-charged sample in the cell. The concentration of absorbed hydrogen is quantified in part-per-million (ppm) or represented by hydrogen charging time duration.

3.0 FATIGUE FRACTURE MECHANISM OF WELDED AUSTENITIC STAINLESS STEEL INLAY

Austenitic stainless steels are widely used in pressure vessel fabrication because of their low cost, versatile mechanical properties, excellent weld-ability, resistance to corrosion and availability in pre-fabricated forms. In oil refineries and chemical plants these vessels operate in corrosive environments in the temperature range from $-29\text{ }^{\circ}\text{C}$ to $427\text{ }^{\circ}\text{C}$. Prolonged exposures at these conditions may result in strength degradation and creep rupture of the steel [22]. In heavy-wall vessels operating in similar service environment it is common to apply welded austenitic steel weld overlay to low alloy steels, thereby taking advantage of the high strength and relatively low cost of the base metal while retaining the superior corrosion resistance of the welded stainless steel overlay [23]. The stainless steel overlay vessel is primarily constructed by welding each exhibiting different microstructures. The application of heat for the fusion process greatly affects the microstructure, phase changes and mechanical properties of the steel in the vicinity of the welded region. These changes often lead to a decrease in toughness of the welded joints. In addition the localized temperature gradients in the weld and heat affected zone (HAZ) resulted in different microstructures throughout the HAZ and the associated residual stresses.

The micro hardness values (HV) of the base metal (BM), HAZ and the solidified weld metal (WM) of austenitic steel were reported to be in the ranges 159–173, 155–241 and 161–218, respectively [24]. Several commercially available steels have been studied for applications in reactor pressure vessel [23,25-28].

3.1 Effects of Absorbed Hydrogen on Fatigue Crack Growth Behavior of Thermally Aged Welded Steel

Problems encountered in heavy-section piping occur at welded joints, damage-assessment techniques need to be focus on these regions rather on the base metal [14,29]. The microstructure of a fusion weld in a pipe is very complex and comprised of as many as seven distinct regions [5]. The welding thermal cycle produces peak temperatures and cooling rates that are highest at the fusion boundary. In a single-pass weld in ferritic steel, four distinct regions can in identified in the heat affected zone (HAZ) alone (Coarse-grain, Grained-refined, Inter-critical and Tempered HAZ region). The HAZ of multi-pass weld is even more complex, and, as a result of multiple heat treatments, may contain more than four regions. The weldment is thus a composite material consisting of base metal (BM), three of more HAZ regions and the weld metal. Previous research found that most number of cracks are found in HAZ region of material [13,29]. Moreover, HAZ of 2.2Cr-1Mo steel weld exhibits inferior rupture strength to the BM [30] and formation of carbides in HAZ results in deteriorated corrosion resistance as compared to the WM and BM [31]. This zone (HAZ) is a common source for defects such as hard inclusions, blisters by trapped gas and micro-cracks that developed during fast cooling of the welded joint.

Fatigue crack growth (FCG) behavior, in the intermediate range of a crack growth rate, can be represented by a power-law relation or Paris-Erdogan relationship [32] and is mostly influenced by material and micro-structural state (e.g. grain diameter, tempering conditions, cold working

etc.), mechanical properties (e.g. yield strength, critical stress intensity factor, etc.) and upon experiment conditions (e.g. load ratio, frequency, temperature-thermal aging, specimen geometry and environment) [33].

Exposure to absorbed hydrogen and thermal aging can cause deleterious effects including the formation and propagation of brittle cracks. Hydrogen embrittlement (HE) is one of the most serious problems in high strength steels [34]. Moreover FCG behavior is enhanced in hydrogen environment for many structural steels [35,36]. In controlled laboratory experiment hydrogen can be introduced in the specimen by gaseous hydrogen charging in an oxygen-free copper chamber with tantalum hydride at temperature in excess of 700 °C [21]. Others use high-pressure (20-35 MPa) hydrogen autoclave at 350 °C. In the electrochemical method the metal specimen is soaked in dilute solution of sulphuric acid with a corrosion inhibitor. A controlled current is supplied to the cathodically-charged sample in the cell. The concentration of absorbed hydrogen is quantified in part-per-million (ppm) or represented by hydrogen charging time duration.

4.0 DAMAGE AND STRUCTURAL INTEGRITY ASPECTS

Principles of fracture mechanics can be used to study the fracture behavior of structure and the influence of parameters such as flaw size and stresses. This method is based on stress analysis, and it does not depend on experience to translate laboratory results into practical design information so long as the engineer can determine the fracture toughness, applied stress, and flaw size in a structural member. Fracture mechanics quantifies the critical combination of these three variables: applied stress, flaw size, and fracture toughness.

In circumstances where it is necessary to examine critically the integrity of fusion welded joints in new or existing constructions by the use of non-destructive testing methods, it is also necessary to establish acceptance levels for flaws revealed. The derivation of acceptance levels for flaws in welds is based on the concept of fitness for purpose. In this principle, a weld in a particular fabrication is considered to be adequate for its purpose provided the conditions to cause failure are not reached, after allowing for some measure of abuse in service. A distinction has to be made between acceptance based on quality control and acceptance based on fitness for purpose.

Quality control levels are both arbitrary and usually conservative, and are of considerable value in the monitoring of weld quality during production. Flaws, at or less severe than such quality control levels, are acceptable for further considerations. If flaws more severe than the quality control levels are revealed, automatic rejection is not necessary but decision on whether rejection and/ or repairs are justified may be based on fitness for purpose, either in the light of previously documented experience with similar material, stress and environmental combinations or on the basis of engineering critical assessment (ECA). In this research there is more concern for ECA.

American petroleum institution (API) (API RP-579, 1999) and British standard institution (BSI) [37] recommended some practical procedures and codes to analyze the structure of fracture in welded joints for its fitness for purpose. The crack driving force is affected by the magnitude and

gradient of the tensile residual stresses in the through thickness direction. Also, crack size affects the crack driving force. Thus, it is important to evaluate the magnitude and distribution of residual stresses through the thickness of the weldment.

There are three levels of assessment depending on the complexity and accuracy of the desired analysis. Level 1, preliminary level, provides a simplified method of fracture assessment but with low accuracy. Level 2, normal assessment, is based on strip yield model approach. This level gives improved accuracy over Level 1 without much of analysis complexity. Level 3, advanced assessment, permits greater accuracy but involves even greater complexity and more material data.

The Level 2 method is based on the strip yield model approach and does not have an arbitrary safety factor incorporated. To perform this assessment, two dimensionless parameters K_r and S_r should be calculated first as follows:

$$K_r = \frac{K_I}{K_{mat}} + \delta \quad (1)$$

$$S_r = \frac{\sigma_n}{\sigma_f} \quad (2)$$

where

K_I is the stress intensity factor.

K_{mat} is the material fracture toughness measured by stress intensity factor.

ρ is the plasticity correction factor (shown in Figure 1).

σ_f is the flow strength = average of yield and ultimate strength yet maximum of $1.2 \sigma_{yield}$

$\sigma_{(n)}$ is the effective net section stress;

$$\sigma_{(n)} = 1.2/P^*(1-aBV) + 3.2(c^2 IDB)(1-aIB) \quad (3)$$

where

a, B, and c are the dimensions characterize the crack size. D is the circumference of the pressure vessel.

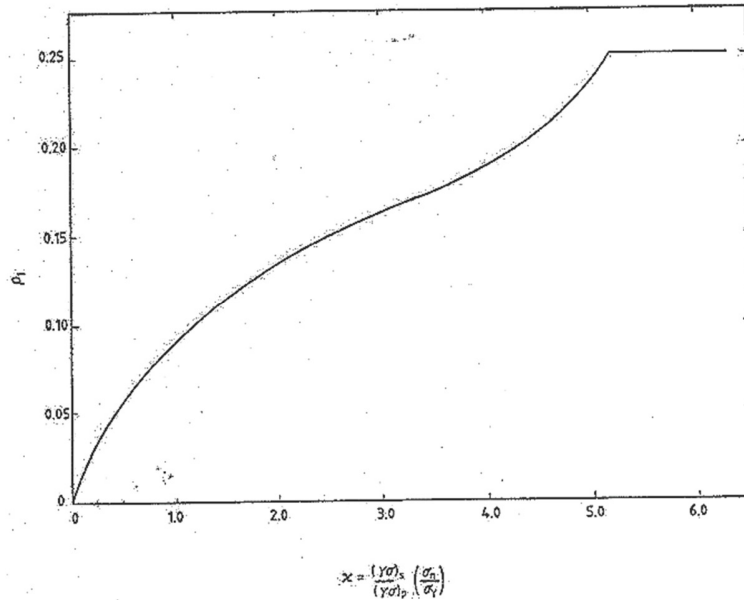


Figure 2: Calculation of plasticity correction factor, ρ [37]

To calculate ρ (plasticity correction factor), we need to calculate variables, x and ρ_1 from Figure 2. This ρ will then be used in equation 1 to calculate K_r and finally S_r from equation 2.

where x from Figure 1 is;

$$x = \frac{(\gamma\delta)_s}{(\gamma\delta)_p} \frac{(\delta)n}{(\delta)y} \quad (4)$$

For;

$$\frac{(\delta)n}{(\delta)y} < 0.8 \quad ; \quad \rho = \rho_1$$

$$0.8 < \frac{(\delta)n}{(\delta)y} < 1.05 \quad ; \quad \rho = 4\rho_1 \left(1.05 - \frac{(\delta)n}{(\delta)y} \right)$$

$$1.05 < \frac{(\delta)n}{(\delta)y} \quad ; \quad \rho = 0$$

Where;

$$\rho_1 = 0 \quad ; \quad x < 0$$

$$\rho_1 = 0.1x^{0.174} - 0.007x^2 + 0.00003x^5; 0 < x \leq 5.2$$

$$\rho_1 = 0.25; x > 5.2$$

The resulting point from calculating K_r and S_r should then be plotted in the failure assessment diagram shown in Figure 3. This diagram shows that the on hand situation is safe if the plotted point falls in the inside region of the assessment line.

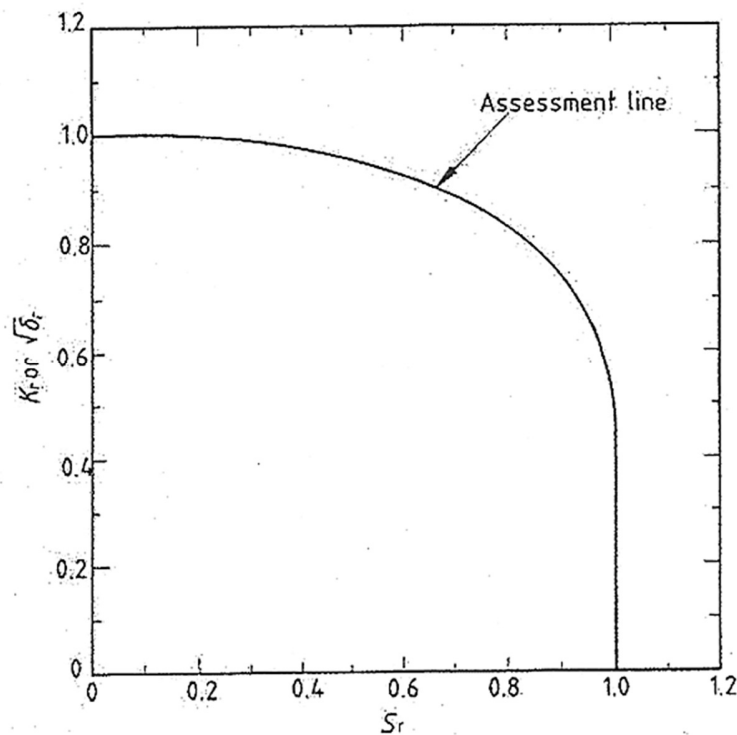


Figure 3: Failure assessment diagram of level 2 [37]

Researcher discussed hydrogen embrittlement behavior during long term services for 2.25Cr-1Mo steel[38]. He estimated the remaining life of 2.25Cr-1Mo reactor subjected to hydrogen embrittlement by introducing hydrogen threshold stress intensity factor, K_{IH} , and hydrogen assisted crack growth rate da/dt .

$$\frac{da}{dt} = 2.40 * 10^{-24} * K_I^{11.7} \tag{5}$$

Where, $\frac{da}{dt}$ is in $\frac{mm}{hr}$ and K_I is in $MPa\sqrt{m}$.

The fracture modes for hydrogen embrittlement can vary from inter-granular fracture, trans-granular ductile failure; cleavage fracture or mixed fracture depends on the materials as shown in Table 1.

Table 1: Modes of Fracture

Modes of HE Fracture	Types of materials
mixed mode	High strength steel
Intergranular	Nickel alloy and steel with segregation of impurities elements such as S, As, Sb
Cleavage	Ti, Nb, Zr based alloy- form stable hydride, exhibiting a stress-induced hydride formation and cleavage mechanism
Transgranular	Nickel alloy and steel with segregation of impurities elements such as S, As, Sb, but with high tensile stress

Figure 4 shows the model obtained from his experimental data for 2-1/4 Cr- 1 Mo steel (Base Metal)[38]. He used embrittlement J-factor to estimate the toughness degradation of material, i.e. ductile-to-brittle transition temperature (DBTT) and hydrogen threshold stress intensity factor (K_{IH}). The embrittlement J- factor is calculated from the material brittle chemical composition as follows:

$$\text{Embrittlement J-factor} = (\text{Si} + \text{Mn}) \cdot (\text{P} + \text{Sn}) \times 10^4 \quad (6)$$

Where Si, Mn, P and Sn are the respective element content in weight percent.

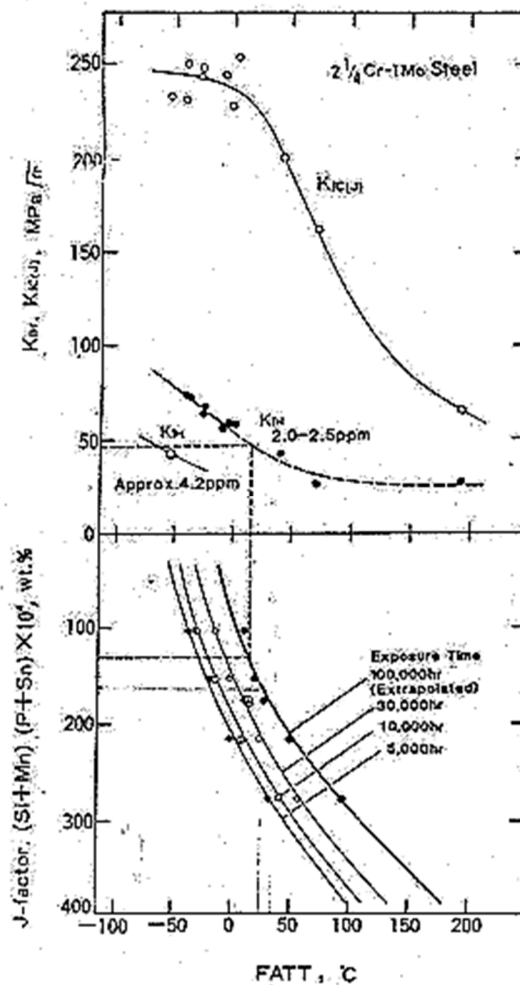


Figure 4: Evolution of the possibility of hydrogen assisted crack growth into the base metal [38]

Extensive amount of experimental data have been gathered on the base metal to construct Fig. 3. Data on the $K_{IC}(J)$ plot represents the value of fracture toughness of the specific base metal at room temperature. Each value of fracture toughness on this plot corresponds to a certain value of embrittlement J-factor and ductile to brittle transition temperature (DBTT) for a given exposure time. The same is true for K_{IH} , the hydrogen threshold stress intensity factor, plot.

Figure 4 shows a sample data of how K_{IH} is calculated for an embrittlement J-factor of approximately 140 after 100,000 hours of operation. In this sample case, the K_{IH} is obtained a little less than 50. Toughness degradation resulting from temper embrittlement of 2.25Cr-1Mo steel with high embrittlement J-factor of 350 showed a DBTT of 135 OC after 100,000 hours of operation. Using DBTT value, the degraded toughness due to temper embrittlement is obtained to be $95 \text{ MPa}\sqrt{\text{m}}$. From Figure 3, also the hydrogen threshold intensity factor is obtained to be $30 \text{ MPa}\sqrt{\text{m}}$.

For a certain value of embrittlement J-factor and an estimated exposure time, the K_{IH} and K_{IC} can be calculated. K_{IC} is the material toughness and K_{IH} is the hydrogen threshold stress intensity factor. If the actual stress intensity factor (K_I) is greater than K_{IC} , than catastrophic failure is expected. If it lies somewhere between K_{IC} and K_{IH} , the crack will propagate. The crack will not propagate when the stress intensity factor is less than K_{IH} . When K_I lies somewhere between K_{IC} and K_{IH} , crack growth rate can be computed from Equation 5. This is to ensure safe inspection interval before fast fracture.

5.0 ADDITIONAL ASPECTS FOR CONSIDERATION

The application of immense heat in a welded joint of a pressure vessel steel, to fuse the base plate and weld metal (electrode) for strong permanent joint results in a mechanical and metallurgical inhomogeneity due to the weld thermal cycle in the BM, the HAZ and the WM. Weldments are thus, identified as a particular concern because they are often a life-limiting feature, and since existing ASME Boiler & Pressure Vessel [39](B&PV) code rules do not adequately consider the high-temperature creep failure modes that can arise as a function of geometry, loading and material combination [11].

Various studies showed that cracks have been found in different regions of the weld with different orientation in the weld zone, such as centerline cracks, transverse cracks and micro-cracks in the underlying WM or HAZ [12-14], thus rendering this region to be the most susceptible for crack initiation and growth. Once structural crack is present, fracture mechanics is employed to characterize the crack growth behavior as function of working load and other parameters.

As most of the problems encountered in heavy-section piping occur at welded joints, damage-assessment techniques need to be focused on these regions rather on the base metal [14,29]. The microstructure of a fusion weld in a pipe is very complex and comprised of as many as seven distinct regions [5]. The welding thermal cycle produces peak temperatures and cooling rates that are highest at the fusion boundary. In a single-pass weld in ferritic steel, four distinct regions can be identified in the HAZ alone (Coarse-grain, Grained-refined, Inter-critical and Tempered HAZ region). The HAZ of multi-pass weld is even more complex, and, as a result of multiple heat treatments, may contain more than four regions. The weldment is thus a composite material consisting of BM, three or more HAZ regions and the weld metal. Previous research found that most number of cracks is found in HAZ region of material [13,29]. Moreover, HAZ of 2.2Cr-1Mo steel weld exhibits inferior rupture strength to the BM [30] and formation of carbides in HAZ results in deteriorated corrosion resistance as compared to the WM and BM [31]. The HAZ is a common source for defects such as hard inclusions, blisters by trapped gas and micro-cracks that developed during fast cooling of the welded joint.

6.0 CONCLUSION

Present rules in fabrication codes are aimed to reduce the probability of failures in pressure vessels subjected to cyclic pressure or vibrations. Yet, several leaks and ruptures have recently occurred at flanges in pressure vessels and pipes. A review a brief overview of various pressure vessel failure mechanisms has been presented w.r.t impact toughness of thermally aged specimen, effects of absorbed hydrogen and thermal aging on crack-tip plastic zone in welded steel, fatigue crack mechanism of welded austenitic steel and effects of fatigue crack growth of thermally aged welded steel. Pressure vessel integrity appears to have a bright future as pressure vessel integrity practices and technologies must continue to evolve. As the world's energy needs continue to rise with growing international industrialization, the world's pressure vessels infrastructure will have to meet the increasing pressures of demand. Stainless steels are widely used in pressure vessels. In order to maintain their fiscal health and safety, researchers will continue to advances in integrity practices and development. Principles of fracture mechanics can be used to study the fracture behavior of structure and the influence of parameters such as flaw size and stresses. Problems encountered in material occur at welded joints, damage-assessment techniques need to be focus on these regions. Owner specifications should aim to avoid manufacturing vices, especially in critical regions where fatigue conditions due to vibrations and pulsations are foreseen, and where the consequences of a leak could be high. Inspection should play a key role during manufacturing of these joints, since NDT inspection after construction would not reliably detect gross weld defects.

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