iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

THICK WALL LARGE SOUR SERVICE PIPE AND REQUIRED TOUGHNESS ACCEPTANCE CRITERIA

Cynthia Chiamaka Ezeh[1], O.A. Jeremiah[2*]
Researcher and Technology Development Lead, FEDDO Integrated Service, Lagos, Nigeria,
chiamaka.ezeh@feddogroup.com
Chief Executive Officer, FEDDO PTY LTD, Perth, Australia,
dare.jeremiah@feddogroup.com

ABSTRACT
Thick-walled large-diameter pipes used in sour service environments are subject to extreme mechanical and chemical demands, particularly in oil and gas operations where exposure to hydrogen sulfide (H_2S) introduces a high risk of sulfide stress cracking and brittle fracture. This paper addresses the critical need for robust toughness acceptance criteria to ensure the mechanical integrity and long-term reliability of such components under high-pressure and corrosive conditions. The study focuses on the integration of fracture mechanics, material science, and structural engineering to evaluate how pipe wall thickness, diameter, and operating conditions affect failure risks in sour service applications. Central to this analysis is the role of material toughness—especially crack tip opening displacement (CTOD) and Charpy impact energy—in mitigating the likelihood of brittle fracture during service. The paper reviews existing industry standards, including those in NACE and API specifications, and critiques their adequacy in accounting for the specific demands of thick-walled pipe applications. Additionally, the paper explores testing methodologies and selection criteria for high-toughness materials suitable for thick-wall fabrication. Finite element modeling and case-based fracture analysis are used to propose refined acceptance thresholds that better reflect real-world operating loads, wall constraints, and defect tolerances. The discussion also highlights manufacturing and welding considerations that influence toughness and structural integrity. By establishing more rigorous, dimension-sensitive criteria, the study provides practical guidance for pipeline designers, engineers, and material suppliers aiming to qualify thick-walled sour service pipes for safe deployment. The findings emphasize the importance of tailored acceptance limits in preventing critical failure, reducing lifecycle risk, and enhancing overall system resilience in demanding operational environments.

Keywords:
Sour Service, Thick-Walled Pipe, Toughness Criteria, Fracture Mechanics, H_2S Corrosion, Structural Integrity

1. INTRODUCTION

1.1 Background on Sour Service Pipeline Applications

Sour service pipeline systems are essential components in oil and gas infrastructure that operate in environments containing hydrogen sulfide (H_2S). These environments are classified as corrosive and pose a significant threat to the structural integrity of pipelines due to hydrogen-induced cracking (HIC) and sulfide stress cracking (SSC) [1]. Sour service pipelines are typically deployed in upstream or midstream systems where reservoirs or produced fluids naturally contain H_2S concentrations above acceptable limits. Given the toxic, flammable, and corrosive nature of H_2S, these pipelines are subjected to strict regulatory and metallurgical requirements [2].

Pipelines in sour environments often operate under high-pressure and high-temperature (HPHT) conditions, especially in deepwater or unconventional fields. These conditions amplify the risk of brittle fracture and crack propagation due to the combined effects of stress, corrosive attack, and the presence of critical defects. In many cases, these pipelines must function for decades with minimal allowable failure rates, making safety-critical performance a primary consideration during design and qualification [3].

Furthermore, sour service conditions often mandate the use of specialized metallurgies such as quenched and tempered low-alloy steels or corrosion-resistant alloys (CRAs). These materials are selected for their resistance to SSC and HIC, but they must also maintain sufficient fracture toughness and ductility under harsh operating conditions [4]. The standards governing these systems, including NACE MR0175/ISO 15156 and API 5L, provide guidelines on chemical composition, heat treatment, and inspection protocols, but application-specific evaluation is often necessary.

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

In this context, mechanical toughness becomes a decisive factor in pipeline qualification. Unlike general-purpose transmission lines, sour service pipelines are not only exposed to internal pressure but also face elevated safety margins due to potential personnel hazard and environmental consequences [5]. As a result, defining toughness acceptance criteria is a matter of operational reliability, regulatory compliance, and risk mitigation across the lifecycle of the pipeline system.

1.2 Challenges Posed by Thick Wall Configurations

As exploration and production operations move into deeper reservoirs and higher-pressure domains, pipeline wall thickness requirements have increased accordingly. Thick-wall pipelines, often exceeding 25 mm in wall thickness, are now a common design choice for sour service conditions to accommodate elevated hoop stresses and external pressure differentials [6]. However, these configurations introduce significant fabrication and operational challenges.

One of the primary concerns with thick-wall pipe is weldability. The welding of thick sections, particularly under constrained sour service conditions, demands rigorous preheat control, interpass temperature management, and post-weld heat treatment (PWHT). The risk of hydrogen entrapment during multi-pass welding is higher, especially in the heat-affected zone (HAZ), which becomes a critical region for SSC initiation [7]. Additionally, ensuring full joint penetration and avoiding defects such as lack of fusion or slag inclusion becomes more difficult with increasing wall thickness.

Stress concentration effects also become more pronounced in thick sections. Geometrical transitions, misalignments, or notches induce higher local stress intensities, which, when combined with sour environments, can significantly reduce the resistance to crack initiation and propagation. Mechanical mismatching between base and weld metal can further compound this risk [8].

From a testing and qualification perspective, evaluating fracture toughness in thick-wall materials is inherently more complex. Standard small-scale Charpy V-notch (CVN) specimens may not accurately reflect constraint conditions present in the actual structure. The need for full-thickness compact tension (CT) or single-edge notched bend (SENB) specimens arises, often requiring elaborate test setups and compliance monitoring [9].

Moreover, microstructural heterogeneity is more pronounced in thicker products due to differences in cooling rates across the section. This can lead to variable mechanical properties, with central zones exhibiting lower toughness or different transformation products than outer layers. Therefore, defining conservative acceptance criteria for such wall thicknesses is both a technical and procedural necessity in sour service qualification [10].

1.3 Objective and Article Scope

The objective of this article is to establish and justify a set of mechanical toughness acceptance criteria specifically for thick-wall pipeline systems in sour service applications. The study focuses on the interplay between material properties, fracture mechanics, and environmental susceptibility that together define the minimum requirements for safe operation.

Unlike traditional evaluations based on yield strength or tensile properties alone, this article emphasizes fracture toughness—measured under constraint-sensitive conditions—as a core performance metric. It considers the influence of welding, notch acuity, and SSC-prone environments on the structural reliability of thick-wall pipes.

The article is structured to provide a foundation on material behavior under sour service, outline critical fabrication risks, and evaluate testing methodologies suitable for thick-wall configurations. Finally, it proposes a set of toughness acceptance values aligned with realistic defect assessment procedures. These recommendations aim to enhance design robustness and ensure long-term service integrity in safety-critical pipeline environments [11].

2. UNDERSTANDING SOUR SERVICE AND FAILURE MECHANISMS

2.1 Hydrogen Sulfide Environments and Sulfide Stress Cracking

Hydrogen sulfide (H_2S) is a highly reactive compound found in sour petroleum environments and is notorious for its ability to degrade metal integrity through sulfide stress cracking (SSC). This form of environmentally assisted cracking occurs when tensile stress, a susceptible microstructure, and H_2S are present simultaneously [5]. The chemical interaction between iron and hydrogen sulfide can be simplified as:

Sulfide Stress Cracking Reaction:

$$\mathbf{Fe^{2+} + H_2S \rightarrow FeS + 2H^+}$$

Where:

- Fe^{2+} is a ferrous ion resulting from iron dissolution.
- H_2S is hydrogen sulfide present in sour environments.
- FeS is iron sulfide, a corrosion product that may be deposited on the steel surface.

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

• H^+ represents hydrogen ions, which may diffuse into the steel and contribute to hydrogen embrittlement.
This equation describes the chemical basis of sulfide stress cracking (SSC), where hydrogen atoms generated by the corrosion process can enter the steel microstructure and lead to embrittlement and cracking under tensile stress. In this reaction, ferrous ions (Fe^{2+}) combine with H_2S to form iron sulfide (FeS), liberating hydrogen ions (H^+) that subsequently diffuse into the steel microstructure [6]. These hydrogen atoms migrate to areas of high stress concentration, such as inclusions, voids, or grain boundaries, where they recombine into molecular hydrogen. The accumulation of this molecular hydrogen creates internal pressure that can initiate and propagate cracks under even modest levels of applied or residual tensile stress [7].

This process is further exacerbated in quenched and tempered steels, which are typically used in sour service applications for their high strength. While these steels are generally harder and more resistant to plastic deformation, their microstructure—especially in regions affected by welding—can become highly sensitive to hydrogen uptake [8]. The heat-affected zone (HAZ) is particularly vulnerable due to microstructural heterogeneity and tensile residual stresses introduced during fabrication.

The susceptibility to SSC is influenced by numerous variables, including pH, H_2S partial pressure, applied stress, and metallurgical cleanliness. Guidelines such as NACE TM0177 provide test methods to quantify cracking resistance, yet real-world susceptibility can differ significantly based on wall thickness and stress distribution.

Ultimately, understanding the chemistry and diffusion behavior of atomic hydrogen in steel is crucial for accurately assessing SSC risk in sour service pipelines, particularly in safety-critical installations operating under high pressure or temperature [9].

2.2 Brittle Fracture and Ductile-to-Brittle Transition

Brittle fracture remains one of the most catastrophic failure modes in pressure-containing components, especially under low-temperature or dynamic loading conditions. Unlike ductile failure, which involves substantial plastic deformation, brittle fracture occurs with little to no warning and is driven by crack propagation through cleavage planes [10].

The susceptibility of a material to brittle fracture is strongly governed by its microstructure and operating temperature. In steels, a well-documented phenomenon is the ductile-to-brittle transition, which marks a temperature range below which the material exhibits brittle behavior. This transition is not abrupt but occurs over a narrow band, where the energy absorbed during fracture drops significantly [11].

The primary microstructural contributors to this transition include grain size, inclusion morphology, and phase distribution. For instance, larger grains and harder microstructures such as martensite or bainite can raise the transition temperature, making the material more susceptible to brittle behavior at service conditions. Steels used in sour service pipelines are often quenched and tempered to optimize toughness; however, the tempering process must be carefully controlled to balance strength and ductility [12].

Welding and heat treatment further complicate this behavior. The heat-affected zone (HAZ) may develop hard phases that elevate the local ductile-to-brittle transition temperature. If service temperatures approach or fall below this critical range, crack initiation from a pre-existing flaw may lead to unstable fracture propagation across the pipe wall [13].

Traditional fracture mechanics tests, such as Charpy V-notch (CVN) and crack tip opening displacement (CTOD), help quantify the energy required to propagate a crack and provide insight into the transition behavior. However, these metrics must be correlated with actual stress states and constraint conditions, particularly in thick-wall pipes where triaxial stress states dominate.

Accurately defining and lowering the ductile-to-brittle transition range is crucial for ensuring fracture resistance in pipeline steels operating in sour and subambient environments [14].

2.3 Interaction of Wall Thickness and Crack Driving Forces

Wall thickness plays a pivotal role in defining the stress distribution and fracture response of pressure-containing components. In the context of sour service pipelines, the transition from thin- to thick-walled designs alters the crack driving force (CDF) and the local constraint at the crack tip, significantly impacting fracture initiation and propagation behavior [15].

For thin-walled pipelines, internal pressure results in relatively uniform hoop and axial stresses distributed across the wall section. These systems typically exhibit lower constraint at the crack tip, promoting more ductile crack growth and allowing energy absorption before failure. However, in thick-walled configurations, the stress field becomes more triaxial, especially near the internal surface where pressure acts directly [16].

This increase in triaxiality elevates the crack tip constraint, making the material more susceptible to brittle fracture even if it possesses sufficient fracture toughness under standard test conditions. The severity of this effect is

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

particularly pronounced for shallow surface flaws, which may experience high local stresses while still remaining undetectable by traditional inspection methods.

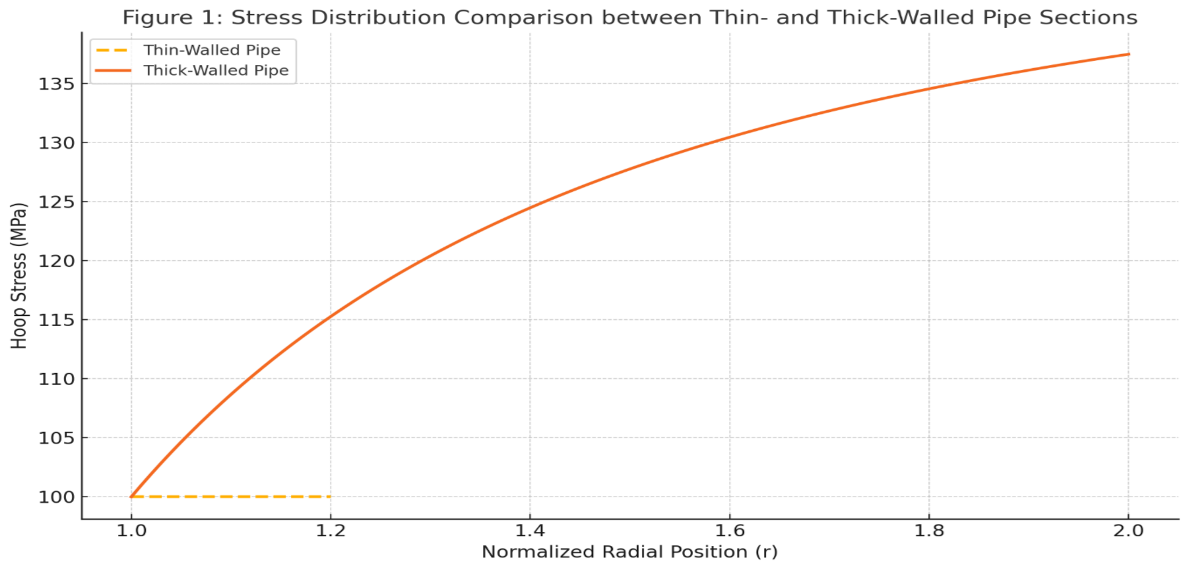

Figure 1: Stress Distribution Comparison between Thin- and Thick-Walled Pipe Sections under Internal Pressure

Figure 1 illustrates the internal pressure-induced stress gradient across different wall thickness profiles. It is evident that in thick walls, the maximum hoop stress is concentrated closer to the inner diameter, and the overall constraint level at potential flaw sites is substantially elevated.
Moreover, residual stresses from welding or cold expansion are not uniformly distributed in thick sections. These can interact with operational loads to further intensify the CDF. For accurate defect assessments, engineering critical assessments (ECAs) must incorporate wall-thickness-specific constraint adjustments to ensure that mechanical toughness criteria reflect in-service loading conditions [17].

3. FRACTURE MECHANICS FUNDAMENTALS FOR THICK PIPES

3.1 Linear Elastic Fracture Mechanics (LEFM) Application

Linear Elastic Fracture Mechanics (LEFM) is widely used to evaluate fracture behavior under conditions where the material remains predominantly elastic prior to failure. This framework is particularly applicable in the early assessment of crack propagation in high-strength, low-ductility materials, such as those found in sour service pipeline systems [11]. In LEFM, the key parameter is the stress intensity factor (K_I), which quantifies the intensity of the stress field near the crack tip. It is calculated using:
Stress Intensity Factor (K_I):

$$K\_I = Y \times \sigma \times \sqrt{(\pi a)}$$

Where:
• K_I is the Mode I stress intensity factor (MPa·$m^{1/2}$).
• Y is the geometry correction factor.
• σ is the applied nominal stress (MPa).
• a is the crack length (m).
This equation is used in Linear Elastic Fracture Mechanics (LEFM) to evaluate crack tip stress fields.
In sour service conditions, LEFM is especially relevant because hydrogen embrittlement reduces the ductility and toughness, shifting failure mechanisms from plastic yielding to brittle crack advance. This makes accurate stress intensity calculations essential for integrity assessments, particularly under sustained loads or during hydrotest conditions [13].

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

LEFM-based engineering critical assessments (ECAs) form the basis for determining acceptable flaw sizes in weld zones, pipe bodies, and fittings. By comparing calculated KIK_IKI values to experimentally measured KICK_{IC}KIC, engineers can assess whether existing flaws pose a risk under defined loading conditions. However, for materials that exhibit some plasticity before fracture, LEFM may be too conservative. This necessitates an elastic-plastic approach for high-toughness steels used in sour service [14].

3.2 Elastic-Plastic Behavior and CTOD

When materials exhibit significant plastic deformation at the crack tip before fracture, elastic-plastic fracture mechanics (EPFM) becomes more appropriate than LEFM. EPFM characterizes crack tip behavior using parameters such as the Crack Tip Opening Displacement (CTOD), which reflects the ductility of a material and its ability to absorb energy before failure [15].

CTOD is commonly denoted as: Crack Tip Opening Displacement (CTOD):

$$\mathbf{CTOD = \delta / B}$$

Where:

- CTOD is the Crack Tip Opening Displacement (mm).
- δ is the physical opening displacement at the crack tip (mm).
- B is the specimen thickness (mm).

CTOD provides a measure of a material's resistance to crack propagation under plastic deformation.

CTOD provides a direct physical measure of the material’s capacity to resist crack propagation under plastic deformation. Unlike KIK_IKI, which represents stress intensity under linear conditions, CTOD quantifies actual displacement at the crack tip, making it especially useful for ductile steels in sour environments, where constraint conditions can vary widely with thickness and geometry [16].

In thick-wall sour service pipelines, the level of triaxial stress at the crack front is high. This increases the constraint and reduces the size of the plastic zone, effectively making the material behave more brittle. Therefore, even though CTOD is a ductility-based measure, its value is significantly influenced by thickness, weld mismatch, and flaw orientation. Empirical studies show that as thickness increases, required CTOD values for stable crack arrest must also increase for a given flaw size and stress level [17].

Standard CTOD testing protocols, such as those outlined in BS 7448 or ISO 12135, typically involve single-edge notch bend (SENB) or compact tension (CT) specimens machined from parent or weld metal. The resulting CTOD values are then compared against critical limits to establish fitness-for-service.

For sour service applications, where hydrogen-induced embrittlement is a concern, CTOD must be measured under conditions that simulate in-service exposure. Pre-charging specimens with hydrogen or testing in H_2S-saturated environments ensures relevant fracture resistance data. CTOD is also a key acceptance parameter in Engineering Critical Assessments (ECA), ensuring that the material can tolerate realistic defect sizes throughout its service life [18].

3.3 Influence of Pipe Diameter and Wall Thickness on Fracture Resistance

Pipe geometry, particularly outer diameter and wall thickness, significantly impacts the fracture resistance behavior of steel pipelines. As the wall thickness increases, the stress state at the crack tip transitions from plane stress to plane strain, resulting in elevated constraint and a reduced ability of the material to undergo plastic deformation before fracture [19].

In thin-walled pipelines, the stress distribution allows for lower crack tip constraint, facilitating stable ductile tearing. However, in thick-walled configurations, the same flaw experiences higher triaxial stress, increasing the likelihood of brittle fracture under identical loading. This necessitates elevated CTOD performance or more stringent toughness criteria to ensure fracture avoidance [20].

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

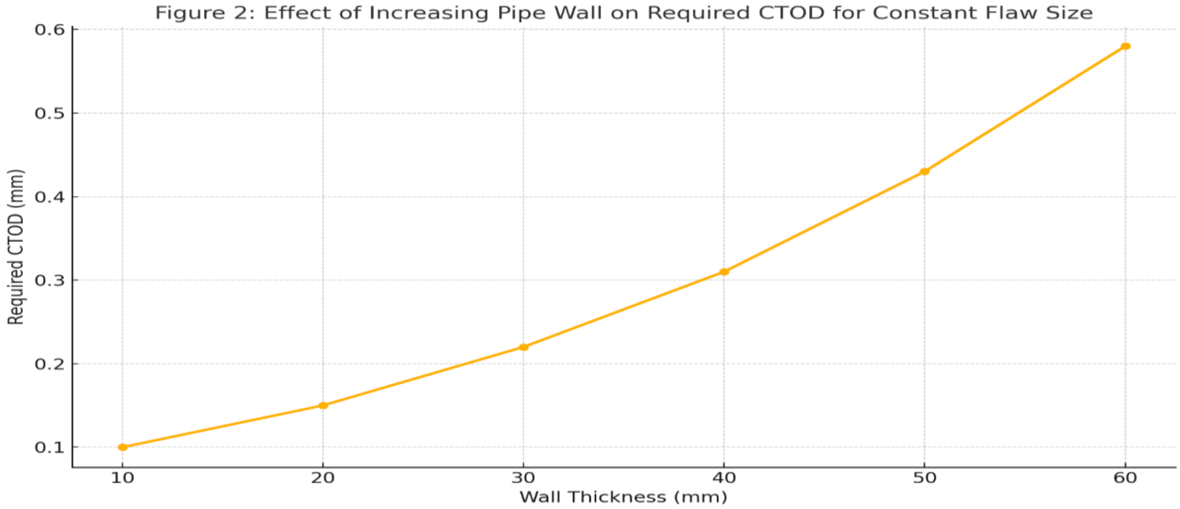

Figure 2: Effect of Increasing Pipe Wall on Required CTOD for Constant Flaw Size

Figure 2 illustrates how the required CTOD value increases with wall thickness for a constant flaw size and stress level. The chart demonstrates that beyond a certain thickness threshold (often >20 mm), the toughness demand grows non-linearly due to stress field intensification near the crack tip. This trend highlights the inadequacy of using flat-plate specimen data for fracture analysis in large-diameter, thick-wall pipes.

Moreover, pipe diameter introduces curvature effects that affect crack driving force (CDF). Larger diameters tend to reduce axial constraint and distribute stress more evenly, slightly reducing the severity of crack propagation compared to smaller diameter pipes under similar pressure. However, weld-induced residual stresses, more common in thicker sections, can offset this benefit and must be incorporated into fracture assessments [21].

To account for these geometric effects, ECAs must integrate pipe geometry explicitly into fracture models, often using finite element simulations or analytical solutions for constraint factors. These inputs inform the selection of minimum CTOD or KIK_IKI acceptance values required to tolerate worst-case embedded or surface-breaking flaws over the operational life of the pipeline [22].

Therefore, understanding the synergistic influence of pipe diameter and wall thickness is crucial in defining valid and conservative toughness acceptance criteria for sour service pipelines operating under high pressure and hydrogen exposure.

4. TESTING STANDARDS AND MATERIAL QUALIFICATION

4.1 Overview of Relevant Standards

Pipeline materials exposed to sour service conditions are governed by a framework of international standards and technical documents designed to ensure material integrity under hydrogen sulfide (H_2S) exposure, elevated pressures, and potential fracture scenarios. Among the most influential documents are NACE TM0177, ISO 15156, and industry-specific material requirements from API 5L and API 5CT [15].

NACE TM0177 outlines laboratory test methods for evaluating resistance to sulfide stress cracking (SSC) in metallic materials. It includes multiple test environments and specimen geometries designed to simulate downhole or transmission line conditions where H_2S-induced embrittlement is a concern. The document serves as a baseline qualification tool for alloy selection, heat treatment validation, and weld integrity assurance [16].

ISO 15156, which is harmonized with NACE requirements, is structured in three parts to address steels, corrosion-resistant alloys (CRAs), and user-specific recommendations for oilfield equipment. It prescribes environmental exposure limits, hardness thresholds, and test conditions for qualifying materials for H_2S-containing environments. Notably, it emphasizes that material selection must be contextual and supported by empirical testing, especially for non-standard wall thicknesses or unconventional geometries [17].

API 5L and API 5CT provide specifications for line pipe and casing/tubing, respectively. These standards govern not only chemical composition and dimensional tolerances but also include toughness testing protocols such as Charpy V-notch (CVN) testing and fracture toughness requirements for sour service grades. In thick-wall

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

applications, API 5L PSL 2 mandates full-body or strip-sample testing with optional CTOD or drop weight tear testing (DWTT) depending on project risk classification [18].

Together, these standards form the compliance backbone for engineering assessments and procurement. However, each has limitations when applied to thick-wall or highly constrained configurations. As such, engineering judgment and project-specific supplemental testing are often necessary to validate fracture resistance in high-consequence environments [19].

4.2 Test Methods: Charpy Impact, CTOD, and SENT

Mechanical toughness testing plays a crucial role in assessing the resistance of pipeline steels to fracture initiation and propagation. Several test methods are widely accepted in industry, each offering unique insights into material behavior under stress. For thick-wall, sour service pipelines, the most commonly used tests include the Charpy V-notch (CVN) test, Crack Tip Opening Displacement (CTOD) test, and the Single-Edge Notched Tension (SENT) test [20].

The Charpy impact test is the most traditional method. It uses a notched specimen struck by a pendulum to measure the energy absorbed during fracture. While cost-effective and simple, Charpy results are often criticized for poor constraint correlation and lack of realism in representing large-scale flaw behavior in thick-wall geometries [21].

The CTOD test offers a more representative evaluation for materials in ductile regimes. It measures the crack opening displacement at the onset of stable tearing. Typically performed using compact tension (CT) or single-edge notch bend (SENB) specimens, CTOD captures the material's plastic deformation capability, making it highly relevant for thick sections exposed to hydrogen-assisted cracking [22].

The SENT test has gained popularity in recent years due to its low constraint configuration, which more closely replicates actual pipeline conditions. SENT tests are especially useful for assessing flaw tolerance in girth welds and are increasingly used in engineering critical assessments (ECA) for offshore and deepwater pipelines. They provide toughness values under loading modes that simulate internal pressure-induced longitudinal stresses [23].

Table 1: Comparison of Mechanical Test Methods for Toughness in Thick-Wall Pipe

Test Method	**Primary Use**	**Constraint Level**	**Key Advantages**	**Key Limitations**
Charpy CVN	QC & Material Spec	High	Fast, low-cost	Not size-representative
CTOD	Fracture Resistance	Moderate-High	Relevant to plasticity	Requires complex setup
SENT	Weld Defect ECA	Low	Field-representative	Fewer historical datasets

This table underscores the importance of selecting test methodologies that align with application-specific loading and geometric realities in sour service pipelines.

4.3 Acceptance Criteria Trends in Industry

Recent developments in pipeline materials engineering reflect a shift toward application-specific toughness acceptance criteria, particularly in sour service and high-consequence areas. Traditional reliance on Charpy impact values is increasingly being supplemented—or replaced—by fracture toughness parameters such as CTOD and SENT, particularly for thick-wall or welded components [24].

One major trend is the increased emphasis on constraint-sensitive testing, where the test specimen geometry more accurately reflects the in-service stress state of the pipeline. CTOD and SENT tests, when properly configured, offer more realistic fracture resistance estimates, especially when surface-breaking flaws or weld heat-affected zones are the critical regions of interest.

Another notable evolution is the growing reliance on full-scale testing or segment-specific sampling, especially in offshore projects and high-pressure onshore systems. These programs allow engineers to observe the actual flaw behavior under combined thermal, mechanical, and environmental loads. They also enable correlation between notch geometry, residual stress state, and plastic zone development, which are often not captured in small-scale laboratory specimens [25].

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

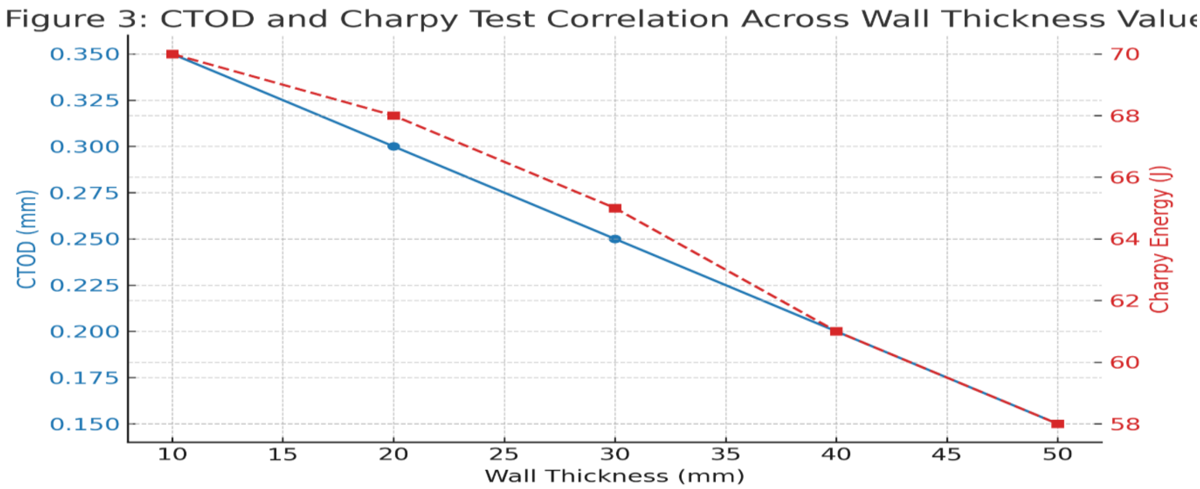

Figure 3: CTOD and Charpy Test Correlation across Wall Thickness Values

Figure 3 presents an empirical correlation showing how CTOD values decrease with increasing wall thickness for a constant Charpy impact energy. This decoupling reflects the elevated constraint in thicker sections, emphasizing that a given CVN energy cannot be universally applied across varying geometries. It reinforces the importance of context-specific toughness metrics in engineering critical assessments (ECA).
These trends point to a risk-based material qualification approach, where acceptance criteria are tailored to actual service conditions. This reduces over-conservatism in benign zones and strengthens safeguards where crack growth potential is highest. By integrating advanced testing methods with ECA models, the industry is moving toward more accurate and economical fracture control strategies in sour service environments [26].

5. DESIGN CONSIDERATIONS FOR TOUGHNESS ACCEPTANCE

5.1 Crack Arrest and Fracture Propagation in Heavy Wall Pipes

In high-pressure sour service pipelines with thick walls, the ability of a material to resist unstable crack propagation is as critical as preventing crack initiation. This resistance is quantified by the energy release rate (G_c), which indicates the energy available for crack growth per unit of crack area. In the context of Linear Elastic Fracture Mechanics (LEFM), this is related to the fracture toughness by the equation:
Energy Release Rate (G_c):

$$G_c = K_{IC}^2 / E$$

Where:
- G_c is the critical energy release rate (J/m^2), representing the energy required to propagate a crack.
- K_{IC} is the fracture toughness ($MPa \cdot m^{1/2}$), indicating the material's resistance to crack propagation.
- E is Young's modulus (MPa), representing the stiffness of the material.

This equation is used in Linear Elastic Fracture Mechanics (LEFM) to evaluate the toughness necessary to prevent unstable crack propagation, especially in thick-wall, high-pressure pipeline systemsA higher G_c implies greater resistance to crack propagation. In heavy wall pipes, where **stress intensity is elevated** due to triaxiality, achieving a high K_{IC}^2 becomes necessary to maintain sufficient energy dissipation to arrest crack growth. The need is intensified under sour service conditions, where hydrogen embrittlement may lower effective toughness values, thus reducing K_{IC}^2 and, consequently, G_c [20].
Thick-wall geometries intensify local stress fields near the crack tip. Unlike thin-walled components where stress redistributes more easily, heavy sections tend to concentrate energy near the flaw, accelerating unstable crack growth unless adequate arrest toughness is built into the material. Empirical studies have shown that crack velocities in thick pipes increase more rapidly and require higher toughness to arrest propagation at critical defect sizes.

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

Crack arrest behavior is not governed solely by material parameters; temperature, internal pressure, and pipe diameter also play significant roles. Lower temperatures can reduce ductility and fracture energy, while high operating pressures increase the stress intensity factor K_IC^2, raising the likelihood of unstable growth. Hence, determining G_c and ensuring its sufficiency through targeted toughness requirements is vital for structural safety, particularly in safety-critical systems transporting sour fluids under pressure [21].

5.2 Toughness Thresholds vs. Applied Stress Intensity

The integrity of sour service pipelines is maintained by ensuring that the material's fracture toughness exceeds the applied stress intensity, which is influenced by loading, flaw size, and geometry. This relationship is typically managed through conservative engineering critical assessments (ECA) that balance operational demands against material performance.

Fracture resistance must be above a defined toughness threshold to prevent crack propagation. In practical terms, this means ensuring that the material's K_IC^2 or CTOD value remains higher than the maximum anticipated stress intensity factor K_IC^2 during operation. These values are derived based on pipe pressure, wall thickness, and flaw depth, incorporating safety margins for hydrogen degradation in sour environments [22].

Table 2: Fracture Toughness Requirements Under Varying Pipe Pressures and Temperatures

Pipe Pressure (MPa)	**Wall Thickness (mm)**	**Temperature (°C)**	**Minimum Required CTOD (mm)**	**Minimum K_IC (MPa·m$^{1/2}$)**
6.9	19	25	0.18	100
10.3	25	0	0.28	115
13.8	32	-10	0.33	125
17.2	38	-20	0.42	140

As shown in Table 2, toughness requirements increase with both pressure and wall thickness. Cold service temperatures also demand higher crack arrest capacity due to reduced plastic deformation and embrittlement risk. These values are typically determined via fracture testing on heat-specific material samples, especially for seam welds and girth welds.

It is critical to recognize that welds and heat-affected zones may not achieve the same toughness levels as base metal, so additional conservatism is often applied. Advanced FEA simulations and probabilistic ECA models further refine these thresholds by incorporating residual stresses and flaw shape irregularities. The industry's increasing reliance on data-driven models and parametric assessments reflects an evolving effort to optimize material use without compromising safety in sour gas applications [23].

5.3 Weld Zones and Heat-Affected Zone (HAZ) Effects

In sour service pipelines, weld zones and their adjacent heat-affected zones (HAZ) represent critical areas for fracture risk, particularly due to localized changes in microstructure, hardness, and residual stress. These effects are amplified in thick-wall configurations, where multi-pass welding and high heat input introduce substantial metallurgical gradients [24].

The HAZ undergoes rapid thermal cycling, resulting in phase transformations that can reduce fracture toughness. For example, coarse-grained HAZ (CGHAZ) can develop high hardness and lower ductility, making it susceptible to hydrogen-assisted cracking under H_2S exposure. Moreover, hardness peaks can exceed SSC thresholds, requiring careful monitoring during welding procedure qualification [25].

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

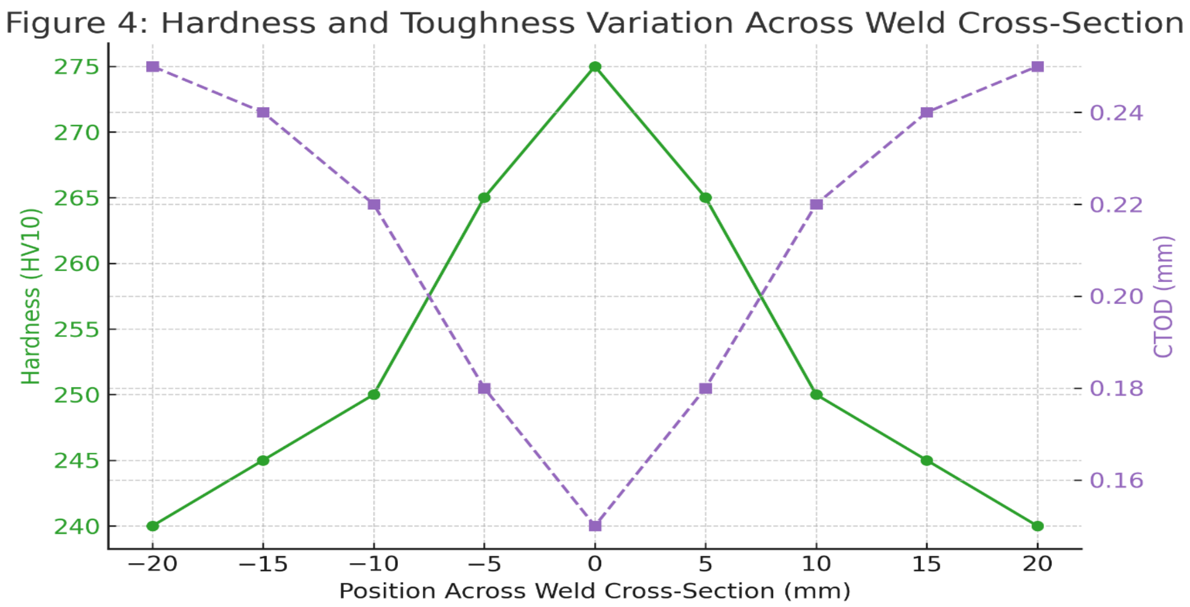

Figure 4: Hardness and Toughness Variation Across Weld Cross-Section

Figure 4 illustrates how hardness and CTOD values fluctuate across the weld cross-section, typically peaking in the HAZ and declining toward the fusion line. These variations are critical for sour service applications, where uniform toughness cannot be assumed.

Residual stresses introduced during welding further exacerbate the situation. These stresses may not fully relax during cooling and can remain tensile in nature, especially in circumferential welds. In sour service, where hydrogen diffusion toward stressed regions is facilitated, the combination of high hardness and tensile stress is a known precursor for sulfide stress cracking (SSC). Hence, accurate characterization of weld-induced residual stress fields is essential for fitness-for-service evaluations [26].

Post-weld heat treatment (PWHT) is commonly applied to reduce residual stresses and temper hard microstructures. However, in thick sections, uniform temperature control during PWHT is challenging, potentially leading to incomplete tempering or over-aging in different regions of the weldment.

Additionally, repair welds are often more critical than original girth welds due to higher restraint and variable metallurgy. Repair procedures should be qualified separately and tested for both toughness and hardness compliance under sour service simulation conditions.

Ultimately, weld zones must be rigorously assessed using a combination of mechanical testing, hardness mapping, and fracture mechanics odelling to ensure they meet the same—or higher—reliability standards as base materials in sour environments [27].

6. CASE STUDIES AND FIELD VALIDATION

6.1 Pipe Failure in Sour Gas Service Due to Low CTOD

A well-documented failure case in a high-pressure sour gas pipeline highlights the critical importance of fracture toughness, particularly Crack Tip Opening Displacement (CTOD), in preventing brittle fracture. In this instance, a transmission line transporting H_2S-rich gas at sub-zero ambient temperatures experienced sudden pipe rupture during a routine pressure cycle [23]. Post-failure analysis identified a planar flaw in the fusion line of a girth weld, with evidence of cleavage fracture radiating from the flaw tip.

Material records showed that the pipe and weld met all API 5L PSL2 Charpy impact requirements, yet no CTOD testing had been performed. Fractography revealed minimal plastic deformation at the crack tip and a brittle, river-pattern morphology, indicating low energy absorption. Subsequent laboratory testing on sister joints showed CTOD values below 0.10 mm at the operating temperature of –15°C, confirming insufficient resistance to crack propagation under the combined effects of pressure, low temperature, and hydrogen embrittlement [24].

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

Finite Element Analysis (FEA) demonstrated that under peak operating conditions, the stress intensity factor (K_I) at the flaw tip exceeded the critical CTOD-based resistance. The absence of high-toughness welding consumables and the presence of under-bead hardness peaks in the Heat-Affected Zone (HAZ) further aggravated susceptibility to brittle failure. Despite satisfying conventional Charpy toughness requirements, the system failed because those values did not reflect the constraint-sensitive fracture behavior present in the thick-wall weldment.

This case underscores the limitations of impact energy-based qualification methods for fracture-critical service. It highlights the necessity of constraint-sensitive mechanical testing, such as CTOD or SENT, for assessing pipeline reliability in sour gas applications. Moreover, it shows that flaw tolerance must be evaluated using fracture mechanics rather than empirical safety factors alone—particularly when hydrogen-related embrittlement mechanisms are active [25].

6.2 Successful Qualification with Modified Acceptance Criteria

In contrast to failure cases, successful pipeline qualification has been achieved through fracture mechanics-based acceptance models that adjust toughness requirements according to pipe geometry, operating environment, and anticipated flaw size. A North Sea sour gas export line, built with 32 mm thick-wall pipe, serves as a relevant example of this approach.

Rather than relying on standardized Charpy energy limits, project engineers implemented a CTOD-based qualification framework rooted in Engineering Critical Assessment (ECA). Extensive testing was conducted on parent metal, HAZ, and weld metal, using Single-Edge Notch Tension (SENT) and Compact Tension (CT) specimens. These specimens were exposed to sour-simulated environments to account for H_2S-induced degradation [26].

The project team identified that standard minimum CTOD values (e.g., 0.15 mm) were insufficient to ensure arrest of postulated flaws under maximum pressure. As a result, acceptance criteria were increased to 0.25 mm for HAZ regions and 0.20 mm for weld metal, based on analytical modeling of crack propagation behavior. These values were derived using constraint-adjusted fracture toughness calculations combined with maximum anticipated stress intensity factors at operational pressures and low ambient temperatures.

No service failures were reported after five years of operation, and periodic inspections verified flaw stability. The use of modified CTOD thresholds, aligned with flaw-specific assessments, improved safety margins while avoiding over-conservative material rejection. Additionally, this methodology allowed for the use of more cost-effective materials, as qualification was focused on actual structural integrity rather than meeting arbitrary mechanical property targets [27].

This example illustrates how informed adjustments to acceptance criteria, grounded in fracture mechanics, can lead to enhanced reliability and economic efficiency in sour service pipeline projects.

6.3 Data-Driven Risk-Based Acceptance Models

Modern fracture control strategies are shifting toward probabilistic, data-driven approaches that consider variability in material properties, loading conditions, flaw dimensions, and environmental degradation mechanisms. These models move beyond deterministic safety factors and instead focus on quantifying the probability of failure across a realistic range of operating scenarios.

In one advanced model, pipeline operators integrated statistical distributions for CTOD values (from mill and weld qualification data), flaw detection limits (from NDT records), and operating stress profiles (from SCADA systems). This enabled the construction of Probability of Failure (PoF) curves, which link CTOD performance to defect tolerance thresholds under various pressure and temperature combinations [28].

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

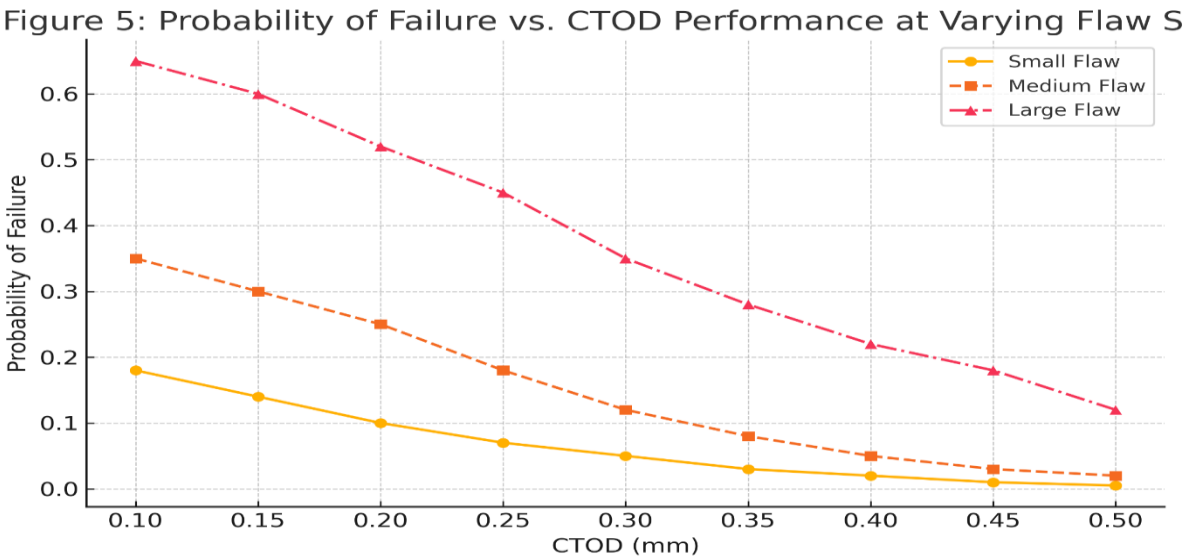

Figure 5: Probability of Failure vs. CTOD Performance at Varying Flaw Sizes

Figure 5 illustrates a family of curves showing how increasing flaw size elevates PoF at a fixed CTOD level. It also highlights how modest improvements in fracture toughness—e.g., increasing CTOD from 0.15 mm to 0.25 mm—can reduce PoF by an order of magnitude for critical flaw lengths. These insights support targeted material specification, where critical regions such as girth welds or elbows receive enhanced toughness requirements.

By leveraging Bayesian updating and Monte Carlo simulations, these models can dynamically refine acceptance criteria based on new inspection or operating data. This reduces unnecessary conservatism and enables real-time decision-making, especially in aging infrastructure or environments where risk must be actively managed.

Data-driven risk-based acceptance frameworks are gaining industry adoption as part of digital twin initiatives, linking predictive analytics to material qualification. They reflect a paradigm shift from pass/fail testing toward performance-based engineering, where acceptance is justified by measurable safety margins under known uncertainties [29].

7. INDUSTRY GAPS AND RECOMMENDATIONS

7.1 Material Variability and Overspecification Concerns

Sour service pipeline design historically favors conservative material selection and qualification strategies to account for unknowns in fracture behavior, hydrogen susceptibility, and environmental interactions. While this approach provides safety assurance, it often results in material overspecification, particularly in thick-wall applications where fracture mechanics-based design is not routinely applied [27].

Overspecification may lead to increased costs, extended lead times, and the unnecessary rejection of otherwise serviceable pipe and weldments. Variability in mechanical toughness—such as CTOD or $K_{(IC)}$ values—is expected across heats and processing conditions, but the use of blanket minimum acceptance criteria does not accommodate these nuances. For example, weld zones in thick-wall configurations often display a natural scatter in toughness properties, and current standards lack mechanisms to incorporate statistical justification for acceptance [28].

This concern is further compounded by the fact that traditional impact energy metrics (e.g., Charpy) do not capture constraint effects relevant in thick-walled geometries. As a result, overly conservative interpretations of these values lead to underutilization of material potential. Engineering teams are often forced to specify premium steels, increased wall thicknesses, or dual-weld qualification systems—all of which escalate project cost and complexity without proportionate gains in fracture resistance [29].

The challenge lies in balancing conservatism with economic feasibility, especially in large-scale projects where small material inefficiencies are multiplied. Accepting a broader range of material performance, where supported by Engineering Critical Assessment (ECA), may reduce waste and streamline fabrication while still ensuring

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

safety margins. Increasing reliance on mechanics-based assessment and statistical variation analysis offers a pathway for reducing unnecessary conservatism without compromising on sour service integrity [30].

7.2 Proposals for Enhanced Standards

To address shortcomings in current sour service qualification standards for thick-wall pipelines, multiple proposals have emerged advocating for performance-based criteria tailored to geometry and application. These enhancements seek to reconcile fracture mechanics insights with real-world fabrication and service challenges [31].

Key proposals include expanding the acceptance envelope for fracture toughness by recognizing constraint effects in thick sections, especially those above 40 mm wall thickness. A second recommendation promotes routine use of constraint-sensitive testing, such as CTOD or SENT, with flaw-specific modeling in lieu of blanket Charpy impact values. This shift would improve flaw tolerance evaluations and align qualification procedures with actual failure mechanisms observed in service [32].

Table 3: Suggested Criteria for Sour Service Pipes >40 mm Wall Thickness

Region	**Minimum CTOD (mm)**	**Max Hardness (HV10)**	**Suggested Test Method**	**Comments**
Base Metal	≥ 0.20	≤ 250	SENT or CTOD	Full-thickness notch recommended
HAZ – Fine Grain	≥ 0.25	≤ 250	SENT	Test orientation in weld direction
HAZ – Coarse Grain	≥ 0.30	≤ 248	CTOD + Hardness Map	May require PWHT or post charging
Weld Metal	≥ 0.20	≤ 255	SENT or CTOD	Include simulated sour conditioning

These proposals also encourage the adoption of hybrid qualification protocols, where destructive mechanical testing is combined with validated simulation or digital twin-based extrapolation. Such models could interpolate toughness performance across untested regions or operating states, reducing sample size and test redundancy.

Finally, enhanced standards should promote data transparency and continuous feedback loops from field performance. By integrating operational defect data into qualification frameworks, material criteria can evolve beyond static thresholds and respond dynamically to observed conditions, offering a more robust and economically viable sour service material strategy [33].

7.3 Digital Twin and Simulation for Future Material Design

Advancements in computational odelling and real-time monitoring have given rise to digital twin technology, which presents new opportunities for optimizing material selection and qualification in sour service pipeline systems. A digital twin is a dynamic, virtual representation of a physical asset that continuously updates using sensor inputs, historical performance, and predictive algorithms [34].

In the context of material design, digital twins can simulate fracture response under varying flaw geometries, wall thicknesses, temperatures, and internal pressures. These models integrate fracture mechanics principles with actual field data to predict performance margins and identify regions of elevated risk before destructive failure occurs. When paired with laboratory-derived toughness parameters (e.g., CTOD, K_{IC}), digital twins offer a predictive platform for virtual qualification, reducing the dependency on exhaustive mechanical testing.

A key advantage is the ability to simulate defect growth under different sour gas compositions, temperatures, or pressure cycles. Material performance in untested conditions, such as combined loading or post-repair welds, can be projected with high confidence. This capability supports more flexible, adaptive material specifications—especially in brownfield developments where retrofitting or requalification is necessary [35].

Moreover, coupling digital twin frameworks with AI-driven analytics allows for live feedback into standards development, offering early warning for toughness deviations or emerging defect patterns. This not only improves in-service reliability but also informs procurement by identifying optimal material batches based on predictive performance models rather than uniform code requirements.

Simulation-supported design further enables cost reduction by minimizing overqualification and streamlining heat-specific approvals. With appropriate validation, digital twin environments could evolve to become an integral

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

part of engineering critical assessments, test planning, and failure root cause analysis in sour service material strategy [36].

By embracing simulation and digital integration, the future of material qualification can shift from empirical conservatism toward data-informed confidence, creating safer and more efficient pipeline systems.

8. CONCLUSION

8.1 Summary of Key Findings

This article has provided a detailed examination of the critical factors influencing the structural integrity of thick-wall sour service pipelines. A central finding is the importance of wall thickness in altering fracture behavior. Increased wall thickness introduces higher triaxial stresses at the crack tip, thereby elevating constraint levels and making standard toughness values insufficient unless geometry-specific adjustments are applied. Thicker sections demand higher fracture toughness and often necessitate constraint-sensitive testing techniques to reflect real-world flaw behavior accurately.

Another key takeaway is the role of material selection, especially in hydrogen sulfide (H_2S) environments. The interaction between metallurgical microstructure, residual stress, and hydrogen embrittlement requires meticulous control of chemical composition, heat treatment, and hardness across both base and weld metals. The need for region-specific acceptance criteria, such as for the heat-affected zone (HAZ) or weld fusion line, is clearly justified to ensure structural reliability.

Additionally, the findings support the transition from empirical methods—such as Charpy impact testing—to mechanics-based criteria like Crack Tip Opening Displacement (CTOD) and Single-Edge Notch Tension (SENT) testing. These methods are more representative of actual fracture performance under sour conditions, offering better correlation with failure mechanics and more accurate defect tolerance predictions.

Overall, successful qualification of sour service pipelines requires a multi-parameter approach that considers geometry, environment, material variability, and realistic loading conditions. This holistic view not only strengthens safety margins but also allows for material optimization and cost-effective project execution. The future of pipeline integrity in sour environments lies in adopting fracture mechanics-based acceptance models, supported by modern testing techniques and computational simulations that align qualification with service realities.

8.2 Practical Guidelines for Pipe Design

Based on the insights presented throughout this study, several practical guidelines emerge for the safe and cost-effective design of thick-wall sour service pipelines. First and foremost, designers should adopt constraint-sensitive fracture testing methods such as CTOD or SENT instead of relying solely on Charpy impact values. These tests offer better resolution of toughness behavior in high-constraint regions such as the HAZ, weld metal, and heavy-wall transition zones.

Secondly, all material zones—including base metal, coarse-grained HAZ, and weld fusion lines—should be qualified individually using region-specific acceptance criteria. This ensures that fracture resistance is not generalized across the weldment but tailored to actual risk areas. Recommended thresholds for CTOD and hardness should reflect the local geometry, anticipated flaw size, and sour environment conditions.

Furthermore, projects should implement Engineering Critical Assessments (ECA) as a standard part of material selection and flaw acceptance. These assessments integrate stress intensity analysis, toughness measurements, and flaw size distributions to define allowable flaw tolerances. ECAs are particularly valuable for evaluating repair welds, girth welds, or areas with known stress concentrations.

Designers should also consider incorporating post-weld heat treatment (PWHT) where necessary to temper high hardness in critical zones and relieve residual stresses. PWHT procedures must be carefully controlled, especially in thick-wall pipe, to ensure uniformity across the section.

Lastly, whenever feasible, full-scale or large-scale mechanical testing should be conducted for high-consequence segments. These tests provide valuable empirical data that can be used to validate simulations and refine qualification standards.

By integrating these practices, pipeline engineers can significantly enhance safety, extend service life, and reduce maintenance cycles—all while optimizing material procurement and minimizing overspecification.

8.3 Future Research and Implementation Outlook

Looking ahead, the development and application of advanced tools and methodologies present a promising path for further enhancing the design and qualification of sour service pipelines. One of the most significant opportunities lies in the integration of computational modeling and simulation, particularly through digital twin

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

environments that replicate pipeline behavior under dynamic operating conditions. These tools can simulate defect evolution, stress redistribution, and fracture propagation with high accuracy, reducing dependence on destructive testing and allowing for predictive maintenance planning.

Research should focus on improving multiphysics models that incorporate material plasticity, hydrogen diffusion, and fracture mechanics. When calibrated against real-world data, these models can serve as surrogates for physical testing in certain scenarios, especially where sample size is limited or material availability is constrained. The incorporation of environmental variables such as pressure cycling, temperature fluctuation, and H_2S concentration adds further realism to these simulations.

In parallel, the adoption of hybrid qualification strategies—where limited physical testing is complemented by validated computational models—can provide efficient and cost-effective solutions. For example, instead of conducting CTOD testing on all regions, engineers can focus on critical zones and use simulations to extrapolate performance across less sensitive areas. This approach allows for risk-prioritized material evaluation without compromising safety.

Another key area of future research is the application of probabilistic safety margins. Traditional deterministic acceptance criteria may not capture the inherent variability in material properties and flaw distribution. Probabilistic models, which incorporate statistical uncertainty, can enable more nuanced decisions by quantifying the likelihood of failure rather than relying solely on minimum thresholds. These models are especially valuable for life extension of aging assets or pipelines with non-conforming but structurally stable features.

Furthermore, ongoing collaboration between industry, regulatory bodies, and academic researchers will be essential in shaping next-generation standards. Future codes must evolve to include simulation-based validation, region-specific criteria, and adaptive inspection protocols, ensuring that pipeline integrity is not only preserved but enhanced through digital and data-driven innovation.

REFERENCE

1. Chatzidouros EV, Traidia A, Devarapalli RS, Pantelis DI, Steriotis TA, Jouiad M. Effect of hydrogen on fracture toughness properties of a pipeline steel under simulated sour service conditions. International Journal of Hydrogen Energy. 2018 Mar 15;43(11):5747-59.
2. Wang X, Wang D, Dai F, Shen K. Effect of post-weld heat treatment on microstructure and fracture toughness of X80 pipeline steel welded joint. Mater Sci Eng A. 2018;735:1–10.
3. Jonsta P, Jonsta Z, Vlckova I, Sojka J. Influence of physical-metallurgical factors on resistance of API carbon steels to sulphide stress cracking. Commun Sci Lett Univ Zilina. 2018;20(4):41–6.
4. Olden V, Alvaro A, Akselsen OM. Hydrogen diffusion and hydrogen influenced critical stress intensity in an API X70 pipeline steel welded joint—experiments and FE simulations. Int J Hydrogen Energy. 2012;37(15):11474–86.
5. Traidia A, Alfano M, Lubineau G, Duval S, Sherik A. An effective finite element model for the prediction of hydrogen induced cracking in steel pipelines. Int J Hydrogen Energy. 2012;37(19):16214–30.
6. Chong TVS, Kumar SB, Lai MO, Loh WL. Effects of wet H2S containing environment on mechanical properties of NACE grade FeMn steel pipeline girth welds. Eng Fract Mech. 2014;131:485–503.
7. Hejazi D, Haq A, Yazdipour N, Dunne D, Calka A, Barbaro F, et al. Effect of manganese content and microstructure on the susceptibility of X70 pipeline steel to hydrogen cracking. Mater Sci Eng A. 2012;551:40–9.
8. ASTM E1820. Standard Test Method for Measurement of Fracture Toughness. West Conshohocken (PA): ASTM International; 2009.
9. API Specification 5L, Line Pipe, Forty-Sixth Edition, April 2018. Washington (DC): American Petroleum Institute; 2018.
10. NACE TM0177-2016. Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H2S Environments. Houston (TX): NACE International; 2016.
11. NACE TM0284-2016. Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking. Houston (TX): NACE International; 2016.
12. Martínez-Pañeda E, Golahmar A, Niordson CF. A phase field formulation for hydrogen assisted cracking. Comput Methods Appl Mech Eng. 2018;342:742–61.
13. Passelègue FX, Brantut N, Mitchell TM. Fault reactivation by fluid injection: Controls from stress state and injection rate. Geophys Res Lett. 2018;45(12):1–9.

iJETRM
International Journal of Engineering Technology Research & Management
Published By:
https://www.ijetrm.com/

14. Chatzidouros EV, Papazoglou VI, Pantelis DI. Hydrogen effect on a low carbon ferritic–bainitic pipeline steel. Int J Hydrogen Energy. 2014;39(27):18498–505.
15. Jemblie L, Olden V, Mainçon P, Akselsen OM. Cohesive zone modelling of hydrogen induced cracking on the interface of clad steel pipes. Int J Hydrogen Energy. 2017;42(43):28622–34.
16. Hardie H, Charles EA, Lopez AH. Hydrogen embrittlement of high strength pipeline steels. Corros Sci. 2006;48(12):4378–85.
17. Wang R. Effects of hydrogen on the fracture toughness of a X70 pipeline steel. Corros Sci. 2009;51(12):2803–10.
18. Beltrán MA, González JL, Rivas D, Hernández F, Dorantes H. On the role of microstructural properties on mechanical behavior of API-X46 steel. Procedia Struct Integr. 2017;3:57–67.
19. Joo MS, Suh DW, Bhadeshia HKDH. Mechanical anisotropy in steels for pipelines. ISIJ Int. 2013;53(7):1305–14.
20. ASTM E399. Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc of Metallic Materials. West Conshohocken (PA): ASTM International; 2012.
21. Wang P, Wang J, Zheng S, Qi Y, Xiong M, Zheng Y. Effect of H2S/CO2 partial pressure ratio on the tensile properties of X80 pipeline steel. Corros Sci. 2012;60:59–68.
22. Huang HH, Tsai WT, Lee JT. Cracking characteristics of A516 steel weldment in H2S containing environments. Mater Sci Eng A. 1994;188(2):219–27.
23. Tang JQ, Gong JM, Zhang XC, Tu ST. Comparison on the cracking susceptibility of different low alloy steel weldments exposed to the environment containing wet H2S. Eng Fail Anal. 2006;13(6):1057–64.
24. Wang P, Lv Z, Zheng S, Qi Y, Wang J, Zheng Y. Tensile and impact properties of X70 pipeline steel exposed to wet H2S environments. Int J Hydrogen Energy. 2015;40(35):11514–21.
25. Zheng S, Qi Y, Chen C, Li S. Effect of hydrogen and inclusions on the tensile properties and fracture behaviour of A350LF2 steels after exposure to wet H2S environments. Corros Sci. 2012;60:59–68.
26. Wang X, Wang D, Dai F, Shen K. Effect of post-weld heat treatment on microstructure and fracture toughness of X80 pipeline steel welded joint. Mater Sci Eng A. 2018;735:1–10.
27. Chatzidouros EV, Traidia A, Devarapalli RS, Pantelis DI, Steriotis TA, Jouiad M. Effect of hydrogen on fracture toughness properties of a pipeline steel under simulated sour service conditions. Int J Hydrogen Energy. 2018;43(12):5747–59.
28. Olden V, Alvaro A, Akselsen OM. Hydrogen diffusion and hydrogen influenced critical stress intensity in an API X70 pipeline steel welded joint—experiments and FE simulations. Int J Hydrogen Energy. 2012;37(15):11474–86.
29. Traidia A, Alfano M, Lubineau G, Duval S, Sherik A. An effective finite element model for the prediction of hydrogen induced cracking in steel pipelines. Int J Hydrogen Energy. 2012;37(19):16214–30.
30. Chong TVS, Kumar SB, Lai MO, Loh WL. Effects of wet H2S containing environment on mechanical properties of NACE grade FeMn steel pipeline girth welds. Eng Fract Mech. 2014;131:485–503.
31. Hejazi D, Haq A, Yazdipour N, Dunne D, Calka A, Barbaro F, et al. Effect of manganese content and microstructure on the susceptibility of X70 pipeline steel to hydrogen cracking. Mater Sci Eng A. 2012;551:40–9.
32. San Marchi C, Somerday BP, Nibur KA, Stalheim DG, Boggess T, Jansto S. Fracture and fatigue of commercial grade API pipeline steels in gaseous hydrogen. InPressure vessels and piping conference 2010 Jan 1 (Vol. 49255, pp. 939-948).
33. Wang JJ, Ren F, Tan T, Liu K. The development of in situ fracture toughness evaluation techniques in hydrogen environment. International Journal of hydrogen energy. 2015 Jan 30;40(4):2013-24.
34. Dong CF, Xiao K, Liu ZY, Yang WJ, Li XG. Hydrogen induced cracking of X80 pipeline steel. International Journal of Minerals, Metallurgy, and Materials. 2010 Oct;17:579-86.
35. Stalheim D, Boggess T, Bromley D, Jansto S, Ningileri S. Continued microstructure and mechanical property performance evaluation of commercial grade API pipeline steels in high pressure gaseous hydrogen. InInternational Pipeline Conference 2012 Sep 24 (Vol. 45141, pp. 275-283). American Society of Mechanical Engineers.
36. Gonzalez JL, Ramirez R, Hallen JM, Guzman RA. Hydrogen-induced crack growth rate in steel plates exposed to sour environments. Corrosion. 1997 Dec 1;53(12).