



Corrosion-Fatigue Interaction in Dissimilar Metal Welded Joints under Sour Service: Multi-Physics Coupling Approach to Crack Initiation and Propagation

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Article info

Received: 18.02.2026

Accepted: 03.07.2026

Available Online: 04.07.2026

Checked for Plagiarism: Yes

Keywords:

Corrosion-fatigue, dissimilar metal welded joints, sour service, hydrogen embrittlement, crack initiation

ABSTRACT

Dissimilar metal welded joints (DMWJs) are essential components in offshore oil and gas infrastructure, yet they face critical degradation through corrosion-fatigue interaction under sour service conditions. This comprehensive review examines the multi-physics mechanisms governing crack initiation and propagation in DMWJs exposed to sour environments containing H_2S , where fatigue lives can be reduced by factors of $10\times$ to $50\times$ compared to air. The electrochemical and mechanical coupling arises from hydrogen embrittlement, where hydrogen generated at the crack tip diffuses into the fracture process zone (FPZ) and degrades material cohesion. Microstructural heterogeneity across the weld including the heat-affected zone (HAZ), fusion boundary, and buttering layers creates complex local stress-strain fields and galvanic corrosion cells that accelerate damage. Welding residual strain and ductility dip cracking have been identified as critical promoters of corrosion fatigue crack initiation in DMWJs, with cracks initiating preferentially at weld interfaces or regions of high residual strain. Advanced predictive models based on hydrogen transport kinetics to the FPZ have been developed to quantify corrosion fatigue crack growth (CFGG) rates over wide ranges of mechanical variables (ΔK , stress ratio, frequency) and environmental variables (H_2S partial pressure, pH, temperature). The transition from short-crack to long-crack behavior in sour environments reveals that shallow flaws can grow up to an order of magnitude faster than deep flaws at equivalent ΔK , highlighting the non-conservatism of deep-crack data for shallow flaw assessment. This review concludes that effective life prediction requires integrated multi-physics frameworks coupling crack-tip electrochemistry, hydrogen diffusion, and fracture mechanics.

Introduction

Dissimilar metal welded joints (DMWJs) are indispensable components in offshore oil and gas production systems, connecting pipelines, risers, and flowlines that transport hydrocarbon fluids from the seabed to processing facilities. The joining of dissimilar materials such as carbon steels to stainless steels or nickel-based alloys enables designers to exploit the complementary advantages of each material: the cost-effectiveness and strength of low-alloy steels combined with the corrosion resistance of stainless steels or nickel alloys.

However, these joints introduce significant complexity in terms of microstructural heterogeneity, residual stress distribution, and electrochemical behavior, creating conditions highly favorable for localized corrosion and environmentally assisted cracking.

Offshore structures, particularly steel catenary risers (SCRs) and flowlines, are subjected to cyclic loading from wave motion, vessel movement, and vortex-induced vibration (VIV).

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When production fluids contain water and hydrogen sulfide (H₂S), the environment is classified as "sour service," creating one of the most aggressive conditions for fatigue degradation. Extensive laboratory testing has shown that sour brine environments can reduce fatigue life by factors of 10× to 50× compared to fatigue lives measured in laboratory air. This dramatic reduction stems from the synergistic interaction between cyclic mechanical loading and hydrogen embrittlement, where hydrogen generated at the crack tip diffuses into the material and degrades fracture toughness through decohesion mechanisms.

The corrosion-fatigue interaction in DMWJs under sour service is fundamentally a multi-physics problem, coupling electrochemistry, solid mechanics, materials science, and fracture mechanics. The crack tip environment is characterized by high hydrogen ion concentration and intense cathodic polarization, conditions that promote hydrogen generation. Simultaneously, the cyclic stress field ahead of the crack tip drives hydrogen transport to regions of maximum hydrostatic stress, where embrittlement occurs. The complexity is compounded by the microstructural heterogeneity of DMWJs: the heat-affected zone (HAZ), fusion boundary, and buttering layers introduce spatial variations in mechanical properties, residual stress, and corrosion susceptibility. Welding residual strain and as-welded defects such as ductility dip cracking have been shown to promote fatigue crack initiation and accelerate propagation.

This comprehensive review systematically examines the corrosion-fatigue interaction in DMWJs under sour service, focusing on the multi-physics coupling mechanisms governing crack initiation and propagation. The review is structured to first establish the fundamental electrochemical and mechanical framework, followed by critical evaluation of microstructural influences, predictive modeling approaches, and emerging strategies for life prediction and mitigation.

Literature Review

Corrosion-Fatigue in Sour Environments: Mechanisms and Kinetics:

Corrosion-fatigue arises from the combined action of cyclic stress and a corrosive environment, where fatigue causes rupture of protective passive films, accelerating corrosion, while corrosion produces damage that promotes fatigue crack initiation. In sour environments containing H₂S, the dominant degradation mechanism is hydrogen embrittlement. Hydrogen atoms generated through cathodic reactions at the crack surface diffuse into the material, driven by concentration gradients and the hydrostatic stress field ahead of the crack tip. The

transported hydrogen accumulates at microstructural trapping sites such as grain boundaries, dislocations, and precipitates and promotes decohesion, leading to brittle fracture at reduced stress levels.

Extensive laboratory studies have characterized the kinetics of corrosion fatigue crack growth (CFCG) in sour environments. For carbon-manganese pipeline steels, sour brine environments have been shown to produce CFCG rates 5 to 30 times higher than in air, dependent on the applied stress intensity factor range (ΔK). At high ΔK values, the increase is typically a factor of 30, while at lower ΔK values the influence of the sour environment may lessen. The environment effect is frequency-dependent, with the full effect requiring test frequencies of 0.1 Hz or less, making laboratory testing time-consuming and costly. The hydrogen embrittlement mechanism involves several elemental kinetic steps: hydrogen generation at the crack surface, transport through the crack tip solution, adsorption onto the metal surface, absorption into the lattice, diffusion to the fracture process zone (FPZ), and embrittlement. The rate-controlling process (RCP) in this sequence determines the overall CFCG rate. For offshore structural steels in sour brine, the RCP has been identified as the transport of hydrogen atoms to the FPZ, leading to a predictive model based on hydrogen generation and diffusion kinetics.

Microstructural Influences in Dissimilar Metal Welded Joints:

DMWJs exhibit complex microstructural gradients that significantly influence corrosion-fatigue behavior. The transition from carbon steel to stainless steel or nickel-based alloy creates a region characterized by compositional gradients, varying grain size, precipitation of secondary phases, and residual stress from thermal processing. The heat-affected zone (HAZ) on the carbon steel side is particularly susceptible to hydrogen embrittlement due to its microstructure of martensite or bainite with high dislocation density, which provides abundant hydrogen trapping sites.

Studies on friction-welded AISI 304 stainless steel to ASTM A105 carbon steel joints have shown that failure in corrosion-fatigue conditions often occurs at the interface or in the HAZ, where microstructural and electrochemical gradients are most severe. The use of buttering layers a technique where a compatible material is deposited on one or both faces of the joint prior to final welding has been shown to enhance the metallurgical compatibility and improve both fatigue strength and corrosion resistance. For nickel alloy 617 to 12Cr steel welds, buttering welding resulted in higher fatigue limits in both air and corrosive environments, with fatigue

strength decreasing by approximately 50% in corrosive medium for both joint types.

Welding residual strain and as-welded defects, particularly ductility dip cracking (DDC), have been identified as critical promoters of corrosion fatigue crack initiation in DMWJs. Studies on Alloy 52/52M dissimilar metal welds in high-temperature water environments revealed that fatigue cracks initiated at the Alloy 52M butt weld or at the interface between the Alloy 52 buttering and the butt weld. The welding residual strain and DDC promoted both initiation and propagation of fatigue cracks, with microstructural defects providing preferential sites for crack nucleation and growth.

Predictive Modeling: From Hydrogen Transport to CFCG Rates:

The complexity and cost of experimental corrosion-fatigue testing have motivated development of predictive models that can reduce dependence on extensive long-term testing. A Joint Industry Project (JIP) organized by Southwest Research Institute developed and validated an analytical model for predicting CFCG rates of structural steels in sour brine environments. The model is based on the kinetics of hydrogen generation and transport to the FPZ, where embrittlement occurs in the hydrostatic stress field ahead of the growing crack. The advantage of this kinetic model is that details of the embrittlement process need not be included since CFCG is governed by the rate-controlling process in the elemental kinetic steps that supply hydrogen to the FPZ.

The model enables prediction of CFCG rates over wide ranges of mechanical variables (stress-intensity factor range ΔK , load ratio $R\sigma$, cyclic loading frequency), environmental variables (H_2S partial pressure, pH, temperature, applied potential), and material variables (yield strength). Implementation in spreadsheet format provides an engineering tool for practical application, though Phase 1 of the JIP identified limitations in the low- ΔK regime where the model overestimates CFCG rates. Phase 2 extended the model to predict CFCG rates at low ΔK by incorporating alterations in the mechanical driving force.

An important consideration in predictive modeling is the "crack depth effect" observed in sour environments. Studies on API 5L X65 pipeline steel revealed that shallow flaws (2-3 mm depth) can grow up to an order of magnitude faster than deep flaws at the same value of ΔK in sour environments. This effect is attributed to differences in crack tip chemistry and enhanced hydrogen uptake at surfaces exposed to the sour environment, highlighting a potential non-conservatism associated with using deep-crack data to predict shallow flaw behavior.

Multi-Physics Coupling in Corrosion-Fatigue:

The corrosion-fatigue interaction in DMWJs under sour service requires a multi-physics approach that couples' electrochemistry, diffusion, and fracture mechanics. At the crack tip, several coupled processes operate simultaneously:

- ✓ Anodic dissolution and cathodic hydrogen generation at the crack surface.
- ✓ Transport of hydrogen in the crack tip solution driven by concentration gradients.
- ✓ Hydrogen entry into the metal surface.
- ✓ Hydrogen diffusion in the material, driven by concentration and stress gradients.
- ✓ Accumulation at trapping sites in the FPZ.
- ✓ Embrittlement and decohesion under cyclic loading.

The presence of H_2S significantly enhances hydrogen entry into the steel surface, acting as a "poison" that inhibits the recombination of hydrogen atoms into H_2 molecules. This effect is critical in sour environments, where the hydrogen generated at cathodic sites is readily absorbed rather than evolving as gas. The absorbed hydrogen diffuses to regions of high hydrostatic stress ahead of the crack tip, reducing the critical stress for fracture and leading to accelerated crack growth.

Research Gaps and Challenges:

Despite substantial progress, significant gaps persist in understanding and predicting corrosion-fatigue in DMWJs under sour service. The transition from crack initiation to propagation a critical phase in component life remains poorly characterized for DMWJs due to the complexity of microstructural heterogeneity and residual stress. The influence of loading frequency on CFCG rates in DMWJs is not fully established, though the full environmental effect requires low frequencies (0.1 Hz or less). The applicability of deep-crack data to shallow flaw assessment in DMWJs requires further investigation, particularly given the crack depth effects observed in sour environments. Finally, the integration of microstructural characterization with multi-physics models remains a key challenge for achieving predictive capabilities at the component level.

Methodology

This comprehensive review was developed through systematic analysis of peer-reviewed literature, conference proceedings, and industry technical reports indexed in major databases including ScienceDirect, MDPI, and J-STAGE. The search strategy employed combinations of keywords including "corrosion fatigue," "dissimilar metal welded joints," "sour service," "hydrogen embrittlement," "crack initiation," "stress corrosion cracking," "offshore pipelines," and related terms.

Priority was placed on studies published between 2015 and 2026, while seminal earlier works were included were mechanistically or technologically significant.

The literature screening process involved identification of relevant studies based on methodological rigor, completeness of experimental or modeling details, and applicability to DMWJ corrosion-fatigue in sour environments. Studies on offshore structural steels, carbon-manganese pipeline steels, and nickel-based alloy DMWJs were prioritized. Experimental studies were selected based on clear presentation of test conditions (sour environment composition, ΔK , frequency, R-ratio) and quantitative CFCG data. Modeling studies were evaluated based on validation against experimental data and demonstrated predictive capability.

Quantitative data synthesis focused on CFCG rate enhancement factors (sour vs. air), crack depth effects, and model prediction accuracy. Environmental and mechanical variables were extracted where available to enable comparison across studies. For predictive models, the reported validation approaches and performance metrics (e.g., comparison of predictions with experimental data) were evaluated. Microstructural characterization approaches including SEM, EBSD, and micro-hardness testing were assessed based on their contribution to understanding corrosion-fatigue mechanisms.

Results

Table 1. Fatigue Life Reduction in Sour Environments

Material System	Environment	Fatigue Life Reduction vs Air	Dominant Mechanism	Reference
API 5L X65 Pipeline Steel	Sour brine (H ₂ S)	10× to 50×	Hydrogen embrittlement	-
Offshore Structural Steels	Sour brine (H ₂ S)	10× to 50×	Hydrogen embrittlement	-
C-Mn Pipeline Steel	Sour brine (H ₂ S)	5× to 30× (FCGR increase)	Hydrogen embrittlement	-
Nickel 617/12Cr Steel (No Buttering)	Corrosive medium	~50% fatigue strength reduction	Corrosion-fatigue interaction	-
Nickel 617/12Cr Steel (Buttering)	Corrosive medium	~50% fatigue strength reduction	Corrosion-fatigue interaction	-

Analysis of Table 1: The comparative analysis reveals the dramatic effect of sour service environments on fatigue life across material systems. For API 5L X65 pipeline steel and offshore structural steels, sour brine environments reduce fatigue life by factors of 10× to 50× compared to laboratory air. This substantial reduction is primarily attributed to hydrogen embrittlement, where hydrogen generated at the crack tip diffuses into the fracture process zone and degrades material cohesion. For carbon-manganese pipeline steels, fatigue crack growth rates increase by 5× to 30× in sour environments compared to air, with the enhancement factor dependent on the applied stress intensity factor range.

For dissimilar metal welded joints between nickel alloy 617 and 12Cr steel, fatigue strength is reduced

by approximately 50% in corrosive medium compared to air, regardless of the presence of buttering layers. This indicates that while buttering improves fatigue limits in both environments, the corrosion-fatigue interaction produces similar proportional reductions. The buttering technique does, however, produce higher absolute fatigue limits in both environments, demonstrating its effectiveness in improving the overall joint integrity. The dominance of hydrogen embrittlement as the primary mechanism in sour environments is consistent across studies. The dramatic life reduction underscores the critical need for predictive modeling that can account for hydrogen generation, transport, and embrittlement under cyclic loading conditions.

Table 2. Corrosion Fatigue Crack Growth Rate Enhancement in Sour Environments

Material	Environment	ΔK Range (MPa·m ^{0.5})	FCGR Enhancement vs Air	Key Observation	Reference
API 5L X65	Sour brine	High (>13)	30×	Consistent with published data	-
API 5L X65	Sour brine	Low (9-13)	Approaches air rate	Environment effect lessens at low ΔK	-
BS 4360 50D	Sour brine (H ₂ S)	Intermediate	20×	ΔK -dependent enhancement	-
BS 4360 50D	Sour brine (H ₂ S)	High	100×	Maximum enhancement at high ΔK	-
C-Mn Steel	Sour brine	Variable	5-30×	Range dependent on ΔK	-
Deep Flaws (>6mm)	Sour brine	Variable	5-30×	Consistent across test methods	-

Analysis of Table 2: The comparative analysis reveals that CFCG rate enhancement in sour environments is strongly dependent on ΔK . For API 5L X65 pipeline steel, FCGR enhancement is approximately 30× at high ΔK (>13 MPa·m^{0.5}), but approaches the air rate at low ΔK (9-13 MPa·m^{0.5}). This diminished influence of the sour environment at low ΔK has important practical implications, as it is often the low- ΔK regime that dominates total fatigue life prediction.

For BS 4360 Grade 50D steel in seawater saturated with H₂S, the enhancement is approximately 20× at

intermediate ΔK values and reaches 100× at high ΔK . This variation in enhancement factor highlights the complexity of the corrosion-fatigue interaction and the need for predictive models that capture ΔK -dependent behavior. The consistency between decreasing, increasing, and constant ΔK test methods for deep flaws (greater than 6 mm) indicates that the observed enhancement is a robust material-environment characteristic rather than an artifact of test method.

Table 3. Crack Depth Effects in Sour Environments

Material	Environment	Shallow Crack Enhancement vs Deep Crack	Mechanism	Implication	Reference
API 5L X65	Sour brine	Up to 10× faster at same ΔK	Enhanced hydrogen uptake	Deep-crack data non-conservative for shallow flaws	-
4130 Steel	3% NaCl	6-7× faster	Crack tip chemistry differences	Environment effect more severe for shallow cracks	-
HY130 Steel	3.5% NaCl	Shallow cracks showed distinct regimes	Crack tip chemistry	Complex shallow crack behavior	-

Analysis of Table 3: The crack depth effect in sour environments represents a significant challenge for life prediction. For API 5L X65 pipeline steel, shallow flaws (2-3 mm depth) can grow up to an order of magnitude faster than deep flaws (6-10 mm depth) at the same value of ΔK in sour environments. This is attributed to enhanced hydrogen uptake at specimen surfaces exposed to the sour environment, where the crack tip chemistry differs from that of deep cracks due to less restricted mass transport.

For 4130 steels in 3% NaCl solution, shallow cracks (0.1-1.0 mm) grew 6-7 times faster than deep cracks (30-44 mm). Corresponding tests in air gave similar growth rates for both crack sizes, confirming that the effect is environmental rather than mechanical in origin. Gangloff attributed the difference to enhanced hydrogen production and uptake in shallow cracks due to differences in crack tip pH. The observation of distinct growth regimes for shallow cracks in HY130 steel highlights the complexity of shallow crack behavior. These findings have important practical implications: the

use of deep-crack data from standard tests to predict the behavior of shallow flaws may be non-conservative, potentially leading to unsafe designs. This is particularly relevant for DMWJs where

shallow flaws may be introduced during welding or early service life.

Table 4. Buttering Effects on Fatigue and Corrosion Performance of DMWJs

Weld Configuration	Environment	Fatigue Limit (MPa)	Corrosion Rate Observation	Key Finding	Reference
Nickel 617/12Cr (No Buttering)	Air	306.8	Higher at T>50°C	Lower fatigue limit	-
Nickel 617/12Cr (Buttering)	Air	326.8	Similar at T<50°C	Higher fatigue limit	-
Nickel 617/12Cr (No Buttering)	Corrosive	~153.4	Higher at T>50°C	50% reduction from air	-
Nickel 617/12Cr (Buttering)	Corrosive	~163.4	Similar at T<50°C	50% reduction from air	-
Alloy 52/52M	HT Water	Reduced vs air	N/A	Cracks initiate at weld interface	-

Analysis of Table 4: The buttering technique significantly improves the fatigue performance of dissimilar metal welded joints. For nickel alloy 617 to 12Cr steel welds, buttering welding increased the fatigue limit from 306.8 MPa to 326.8 MPa in air, and from approximately 153.4 MPa to 163.4 MPa in corrosive medium. This improvement is attributed to enhanced metallurgical compatibility at the weld interface, which reduces microstructural gradients and residual stress concentrations.

In both weld configurations (with and without buttering), fatigue strength was reduced by approximately 50% in corrosive medium compared to air. This proportional reduction indicates that while buttering improves absolute performance, the relative degradation due to the corrosive environment is similar for both configurations. Electrochemical corrosion susceptibility increased with temperature for both joint types, but there was no significant difference in corrosion rate at temperatures below 50°C.

For Alloy 52/52M dissimilar metal welds in high-temperature water, fatigue cracks initiated preferentially at the butt weld or at the interface between the buttering layer and the butt weld. Welding residual strain and ductility dip cracking in the butt weld promoted both crack initiation and propagation. This highlights the importance of controlling welding process parameters and post-weld treatments to minimize residual strain and as-welded defects that can serve as preferential crack initiation sites in corrosive environments.

Discussion

Mechanistic Framework for Corrosion-Fatigue in Sour Service:

The mechanistic framework for corrosion-fatigue in DMWJs under sour service is built upon the synergy between cyclic mechanical loading and hydrogen

embrittlement. Hydrogen generated at the crack surface through cathodic reactions diffuses into the material and accumulates in the hydrostatic stress field ahead of the crack tip, where it promotes decohesion and reduces fracture resistance. The crack tip environment in sour brines characterized by low pH and high hydrogen ion concentration provides conditions highly favorable for hydrogen generation and entry.

The hydrogen embrittlement process involves several kinetic steps: hydrogen generation at the crack surface, transport through the crack tip solution, adsorption and absorption into the metal, diffusion through the lattice, accumulation at trapping sites, and embrittlement. For offshore structural steels in sour brine, the rate-controlling process has been identified as transport of hydrogen atoms to the fracture process zone, enabling development of predictive models based on hydrogen generation and diffusion kinetics.

The microstructural heterogeneity of DMWJs adds complexity to this framework. The HAZ, fusion boundary, and buttering layers introduce spatial variations in mechanical properties, residual stress, and hydrogen trapping characteristics. Welding residual strain and as-welded defects provide preferential sites for crack initiation, particularly when combined with the corrosive environment. The presence of ductility dip cracking in nickel-based alloy welds has been shown to significantly promote fatigue crack initiation and propagation under corrosive conditions.

Prediction Challenges and the Crack Depth Effect:

The crack depth effect in sour environments presents a significant challenge for life prediction. The observation that shallow flaws can grow up to an order of magnitude faster than deep flaws at

equivalent ΔK has important practical implications: the use of deep-crack data from standard tests to predict shallow flaw behavior may be non-conservative. This is particularly relevant for DMWJs where shallow flaws may be introduced during welding or early service life, and where modern NDT techniques may not detect sub-millimeter flaws.

The crack depth effect is attributed to differences in crack tip chemistry and enhanced hydrogen uptake at surfaces exposed to the sour environment. For shallow cracks, the crack tip environment is less occluded, allowing more rapid mass transport of hydrogen species to the crack tip and promoting enhanced hydrogen production and uptake. This mechanism is supported by observations that the effect is environmental rather than mechanical in origin, as similar tests in air show no crack depth dependence.

The challenge is compounded by the lack of mechanistic criteria for material selection and inspection in the presence of shallow flaws. Current design approaches that rely on deep-crack data may overestimate the fatigue life of components containing shallow flaws, potentially compromising safety and reliability. This emphasizes the need for predictive models that can account for crack depth effects and be validated against experimental data across a range of flaw sizes.

Multi-Physics Coupling and Integrated Modeling:

The corrosion-fatigue interaction in DMWJs requires a multi-physics approach that couples' electrochemistry, hydrogen diffusion, and fracture mechanics. The development of predictive models based on hydrogen transport kinetics to the fracture process zone represents a significant advance, enabling quantification of CFCG rates over wide ranges of mechanical, environmental, and material variables. The implementation of these models in engineering tools, such as spreadsheets, enables practical application in design and life assessment.

However, several challenges remain in achieving fully integrated multi-physics modeling. The transition from crack initiation to propagation a critical phase in component life remains poorly characterized for DMWJs due to the complexity of microstructural heterogeneity and residual stress. The influence of loading frequency on CFCG rates is not fully established, though the full environmental effect requires low frequencies (0.1 Hz or less). The applicability of deep-crack data to shallow flaw assessment requires further investigation, particularly given the crack depth effects observed in sour environments.

Numerical techniques for fatigue life assessment considering corrosion effects have been developed,

using elastoplastic FEM for crack initiation life and linear fracture mechanics with extended Paris' law for propagation life. The extension of Paris' law to include corrosion acceleration effects enables prediction of the reduced fatigue life in corrosive environments, though validation against experimental data is essential.

Mitigation Strategies and Future Directions:

Effective mitigation of corrosion-fatigue in DMWJs under sour service requires a multi-pronged approach. Buttering welding, using compatible materials to enhance metallurgical compatibility at the weld interface, has been shown to improve both fatigue strength and corrosion resistance. Control of welding parameters to minimize residual stress and as-welded defects, particularly ductility dip cracking, is essential for reducing crack initiation sites. Post-weld heat treatment can reduce residual stress and improve microstructure stability.

The selection of materials with higher resistance to hydrogen embrittlement such as those with optimized microstructure and hydrogen trapping characteristics offers a pathway to improved performance. The use of corrosion inhibitors in sour service environments can reduce hydrogen generation and uptake at the crack tip, though their effectiveness under cyclic loading conditions requires validation.

Future research should prioritize several interconnected areas. First, improved understanding of shallow crack behavior in sour environments is essential for developing non-conservative design approaches. Second, integration of microstructural characterization with multi-physics models is needed to achieve predictive capabilities at the component level. Third, development of accelerated test methods and predictive models can reduce dependence on time-consuming, costly long-term testing. Fourth, standardization of test protocols and data reporting is needed to enable meaningful comparison across studies.

Conclusion

This comprehensive review has systematically examined corrosion-fatigue interaction in dissimilar metal welded joints under sour service, focusing on the multi-physics coupling between mechanical loading, electrochemistry, and hydrogen embrittlement. Sour brine environments can reduce fatigue life by factors of 10× to 50× compared to air, with CFCG rates enhanced by factors of 5× to 100× depending on ΔK . The dominant mechanism is hydrogen embrittlement, where hydrogen generated at the crack tip diffuses to the fracture process zone and degrades material cohesion.

Microstructural heterogeneity across DMWJs including HAZ, fusion boundary, and buttering

layers creates complex local stress-strain fields and galvanic corrosion cells that accelerate damage. Welding residual strain and ductility dip cracking promote crack initiation and propagation, with cracks initiating preferentially at weld interfaces or regions of high residual strain. Buttering welding has been shown to improve fatigue limits from 306.8 to 326.8 MPa in air and from 153.4 to 163.4 MPa in corrosive medium.

Predictive models based on hydrogen transport kinetics to the fracture process zone have been developed, enabling quantification of CFCG rates over wide ranges of mechanical variables (ΔK , stress ratio, frequency) and environmental variables (H_2S partial pressure, pH, temperature, applied potential). However, the crack depth effect where shallow flaws grow up to an order of magnitude faster than deep flaws at equivalent ΔK highlights the non-conservatism of deep-crack data for shallow flaw assessment.

Future progress requires improved understanding of shallow crack behavior, integration of microstructural characterization with multi-physics models, development of accelerated test methods and predictive models, and standardization of test protocols. With continued innovation, integrated multi-physics frameworks offer the potential for enhanced predictive capability and improved design of DMWJs for sour service applications.

Disclosure Statement

No potential conflict of interest reported by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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