

Article

Impact of Welding Standards on Heat Affected Zone: A Critical Review of the Methods, Consumables, and Environmental Degradation on the Performance of API 5L X52 in Sour Service

Abid Ur Rehman ^{1,*}, Muhammad Arsalan Khan ²¹ OGDCL, Oil and Gas Development Company Limited, Islamabad, Pakistan² Department of Mechanical Engineering, University of Engineering & Technology, Peshawar 25000, Pakistan

* Correspondence: Abid Ur Rehman (abid931@gmail.com)

Abstract: The Heat-Affected Zone (HAZ) is one of the major parameters which determines the structural integrity in welded API 5L X52 pipelines, especially in a sour gas service containing Hydrogen Sulphide (H₂S) [1]. This thorough review paper performed the analysis of different international standards including Det Norske Veritas Germanischer Lloyd DNVGL-ST-F101, American Petroleum Institute API 1104, National Association of Corrosion Engineers NACE MR0175 and American Society of Mechanical Engineers ASME B31.8. The researcher analysed the governing and regulation of Heat Affected Zone microstructure and associated properties including strength, hardness and toughness through the specifications like heat values, time between passes and Post Weld Heat Treatment (PWHT), welding specifications and qualification of welding procedures, welders and consumables [2]. By collecting and analysing the data from recent studies (2018-2025), the researchers found out that the standards focusing on prescribing strict recipes for welding and qualification procedures like DNVGL-ST-F101, including explicit heat input limits (typically 1.0-2.0 kJ/mm), obligatory post-weld heat treatment (PWHT), and rigorous consumable qualifications, perform well in Heat Affected Zone in sour gas service. The maximum hardness retirement i.e. 22 HRC (248 HV) obligated for sour media creates a critical limitation that forces optimization of welding procedures. The standards which focus on final quality or the end results rather than prescribing any specific method for producing the weld (Performance-based standards) like API 1104 remains less stringent which results in greater variation in properties around the weld i.e. the HAZ area impacting the service reliability in a worse manner during the sour media [3]. Contemporary world adopting new digital welding techniques for monitoring during weld production, prediction of the microstructural properties of HAZ based on machine learning and other advanced methods like hybrid welding processes which combines different precision welding techniques provide promising results for production of high quality and reliable welds which offer enhanced safety and reliability during sour service [4].

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1. Introduction

1.1. Background and Significance

Welded joints represent potent weak links in the pipeline transportation system of oil and gas which constitutes the critical energy infrastructure worldwide. The region that undergoes changes in microstructure during welding without converting its state from

solid to liquid which is also termed as Heat Affected Zone (HAZ) draws attention in general for sweet service environment and in particular for sour media in API 5L X52 pipelines. Characterized by the presence of hydrogen sulfide (H₂S), sour service environment initiates intense degradation mechanisms including sulfide stress cracking (SSC), hydrogen-induced cracking (HIC), and stress-oriented hydrogen-induced cracking (SOHIC) [5]. The heterogeneous molecular structure of the material at HAZ and its mechanical properties make the pipeline material exponentially weak and make it greatly endangered due to these failure modes [6].

1.2. The Role of Welding Standards

HAZ characteristics and its metallurgical properties are controlled indirectly by the specifications, welding methods, ranges prescribed for heat input parameter, specifications of welding consumables and recommendations developed in the form of Welding standards. HAZ management is performed in a completely different way in the different philosophical standards due to the adherence to the strict recipes for welding and qualification procedures in the prescriptive standards like DNVGL-ST-F101 and the focus on the final quality or the end results presenting a less stringent approach in the performance-based standards like API 1104.

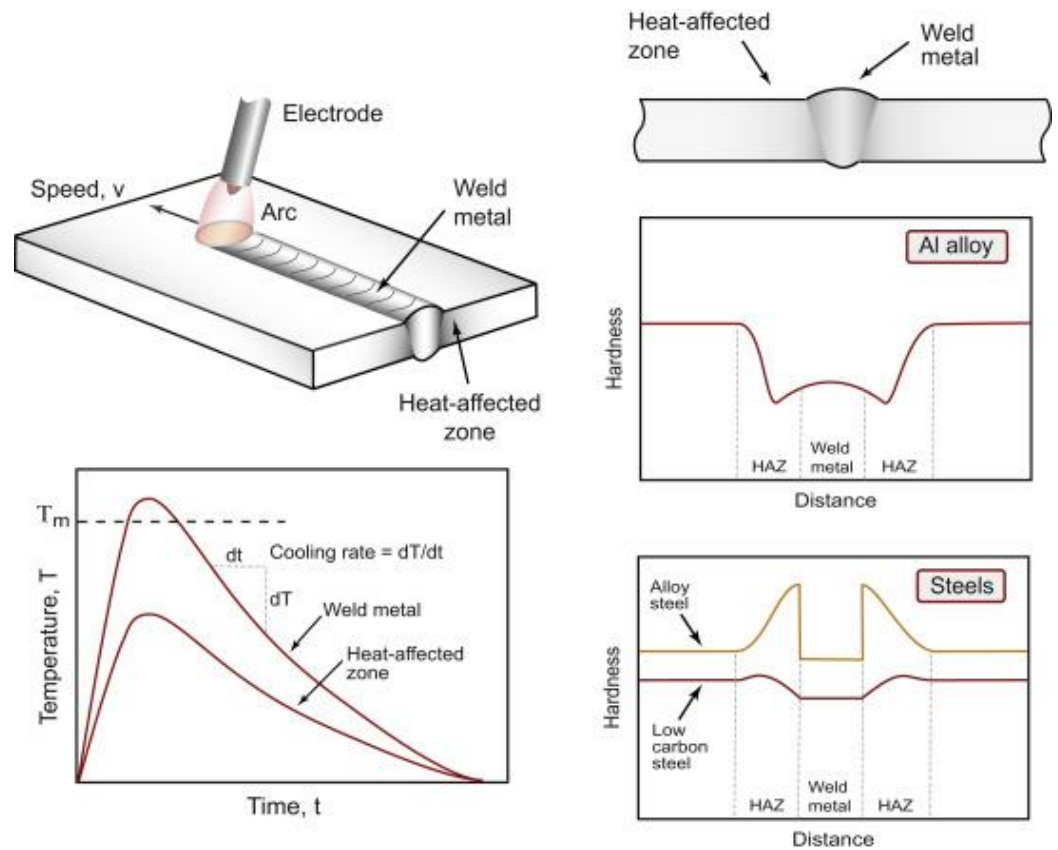


Figure 1. Temperature distribution across the fusion and heat-affected zone (HAZ) during a welding thermal cycle, showing the influence of thermal gradients on microstructural evolution in welded joints [7].

Result oriented performance-based standards deems the welding acceptable if the mechanical and Non-Destructive Test (NDT) are passed without giving attention to the details of the parameters used during the welding, welding procedure qualification, Procedure Qualification Record or consumables qualification. Contrary to this are the

detail oriented prescriptive standards that developed particular input parameters like heat inputs, time between passes, requirements for procedures, consumables and welders' qualification, and mandatory constraints and limits in procedures which must be followed, emphasizing process control and defects' prevention. These differences in prescriptive and result oriented philosophies results in far different technical requirements for welding procedure specifications, welder qualification, quality control, and acceptance criteria, considering the critical implications of Hydrogen Sulfide on the performance of microstructure of HAZ [8].

1.3. Research Objectives

The objectives of this critical review accounted for the following main aims.

1. Analysis of the key international welding standards in context of their effect on HAZ microstructure in API 5L X52 considering their controlling rules for methods and consumables.
2. Collect and analyze public data for establishing quantitative correlations between parameters set by standards and the resulting HAZ properties in sour service.
3. Efficiency and effectiveness evaluation of different standard philosophies in tackling sour service degradation phenomena.
4. Identify contemporary methods, procedures, technologies and research directions for enhancement and assurance of HAZ performance.
5. Establishing the need for development of a comprehensive unified standard especially for sour service which would incorporate the most effective elements from existing standards and the emerging procedures, technologies and research directions, to cater the HAZ performance in a better way in sour service environment.

2. Metallurgical Fundamentals of HAZ in Sour Service

2.1. HAZ Microstructural Evolution in API 5L X52

API 5L X52 is a steel alloyed with the use of Niobium (Ni), Vanadium (V) and Titanium (Ti) at microstructure level for producing extra strength and refined grain [9]. The heat affected zone During welding, the HAZ experiences a complex thermal cycle that can be divided into distinct regions based on peak temperature exposure [10]:

Coarse-grained HAZ: The zone which is subjected to highest temperatures i.e. greater than 1100°C, experience significant growth austenite microstructures and develops coarse microstructures with reduced toughness and high hardness due to formation of upper bainite and martensite. This coarse structure, high hardness and reduced toughness make them vulnerable to hydrogen-assisted cracking in H₂S containing media [11].

Fine-grained HAZ: In this zone the temperature varies between approx. 850°C and 1100°C for X52. This region is characterized by austenite grains which are refined and transformed into ferrite-pearlite or bainitic structures. These structures are having moderate hardness, better toughness, due to which it offers better resistance in sour service application [12].

Intercritical HAZ: The peak temperatures in this zone is typically between approx. 725°C for X52 at which austenite begins to form during heating, 850°C at which the microstructure transforms to complex heterogeneous structure due to partial austenization creating potential soft zones which can localize soft plastic strain [13].

Subcritical HAZ: In this zone the peak temperatures are typically less than 725°C which causes recovery of base metal microstructure and tempering which generally cause

maintained toughness and reduced hardness, however it is still vulnerable to hydrogen embrittlement in case of excessive hardening [14].

The dissolution of microalloying carbonitrides (NbC, VC) in the coarse-grained region and their reprecipitation in cooler regions creates microstructural heterogeneity that significantly influences sour service resistance [15]. This heterogeneity creates galvanic cells between different microstructural constituents, variations in hydrogen diffusion and trapping characteristics, and localized stress concentrations that accelerate sour service degradation. The breakdown of microalloying carbonitrides (NbC, VC) in areas with coarse grains, followed by their reprecipitation in cooler regions, leads to microstructural variability that notably affects resistance to sour service [15]. This variability results in the formation of galvanic cells among different microstructural components, differences in hydrogen diffusion and trapping behaviors, and localized stress concentrations that promote degradation during sour service. [16]. The hard phases of microstructure (martensite, bainite) serve as traps for hydrogen and sites of local stress concentration, while soft phases (ferrite) forms an electrolytic behavior at the contact points of different microstructure and create galvanic couples driving corrosion and generation of hydrogen local [5].

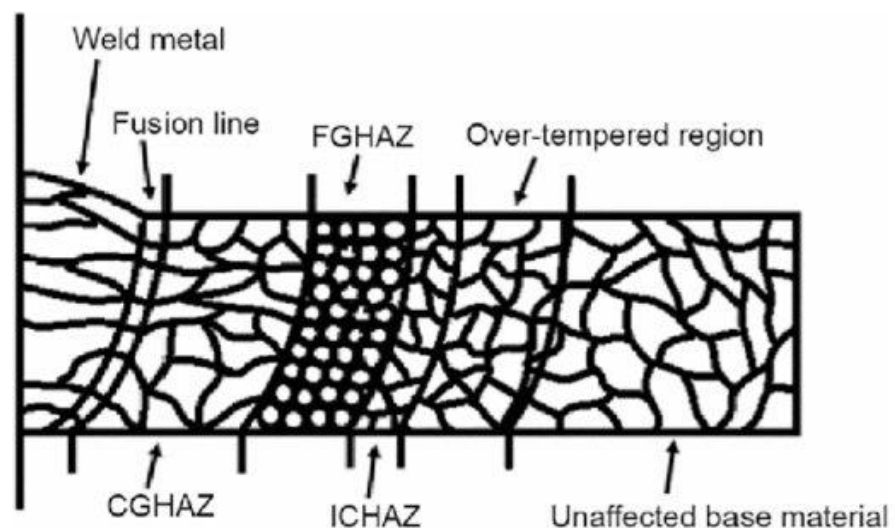


Figure 2. A representation of the HAZ sub-zones (CGHAZ, FGHAZ, and ICHAZ) [17].

2.2. Sour Service Degradation Mechanisms

2.2.1. Sulfide Stress Cracking (SSC)

Hydrogen Sulfide H_2S corrosion produces atomic hydrogen which is collected in the areas experiencing higher triaxial stress, especially in the heat-affected zone (HAZ) [21]. The proneness to sulfide stress cracking (SSC) increases significantly with hardness levels exceeding the 22 HRC mark and is heavily affected by the components of microstructure [22]. Microstructural components such as martensite and upper bainite exhibit the greatest vulnerability due to their elevated dislocation density and internal stress fields, which create numerous sites for hydrogen trapping and points for stress concentration [18].

2.2.2. Hydrogen-Induced Cracking (HIC)

The buildup of hydrogen at non-metallic inclusions (such as Manganese Sulfide and oxides) generates internal pressure that can result in crack initiation [19]. Areas associated with heat-affected zone (HAZ) exhibit banded microstructures or inclusions aligned in a

direction at 90° to the rolling direction, which demonstrate greater vulnerability because they make it easier for cracks to spread throughout the microstructure, which is further intensified by the hard phases that are created during welding thermal cycles [3].

2.2.3. Stress-Oriented Hydrogen-Induced Cracking (SOHIC)

In areas of high stress concentration, lateral to the stress axis arrays of tiny, stacking cracks are formed [6]. Restricted thermal expansion and contraction during welding are the main cause of high welding residual stresses, which usually occur in the HAZ close to the fusing line, weld start/stops, and structural discontinuities [20]. In vulnerable microstructures, these remaining stresses frequently surpass yield strength intensity and interact with applied stresses to induce SOHIC [9]. In highly dense section welds, the triaxial stress phase especially encourages SOHIC start and propagation [10].

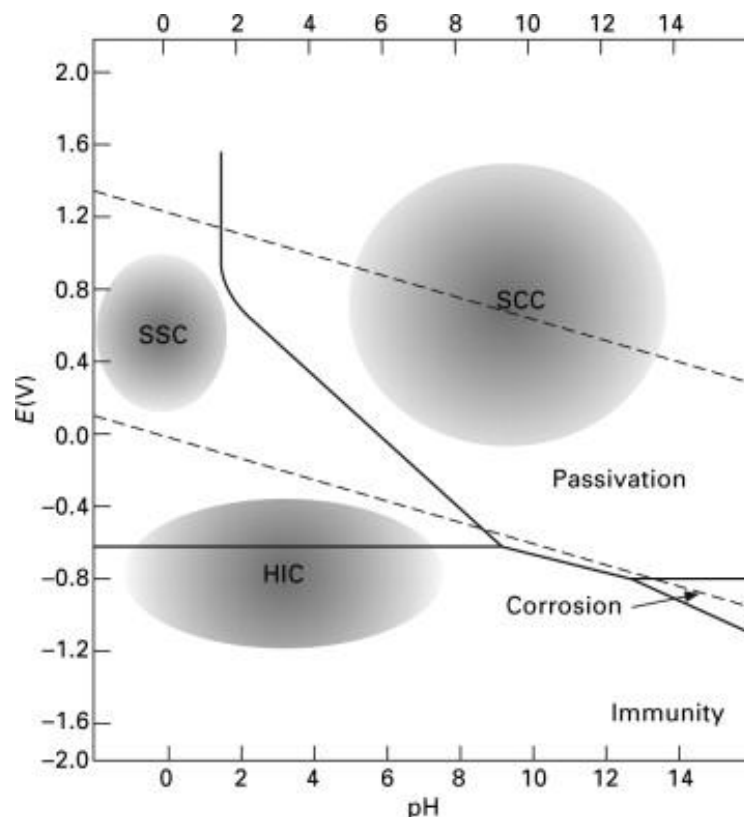


Figure 3. Schematics of the Sulfide Stress Cracking (SSC) in steels [23].

3. Comparative Analysis of Welding Standards

3.1. Methodology for Standards Comparison

Five significant worldwide pipeline welding standards were examined: API 1104 (2022), ASME B31.8 (2023), ASME Section IX (2023), DNVGL-ST-F101 (2021), and NACE MR0175/ISO 15156 (2020). Onshore pipeline applications frequently use API 1104, the American Petroleum Institute standard for welding pipelines and associated infrastructure. The American Society of Mechanical Engineers' code for gas distribution and transmission piping systems is ASME B31.8. Welding and brazing qualifications are covered in ASME Section IX [24]. The Det Norske Veritas Germanischer Lloyd standard for underwater pipeline networks, DNVGL-ST-F101, is renowned for its thorough and cautious methodology [29]. Material standards for metallic substances resistive to sulfide stress cracking are provided by NACE MR0175/ISO 15156 [22]. With an emphasis on sour

service systems, each standard's statutory and subtle criteria influencing HAZ characteristics were assessed for.

Literature Search Methodology: Scopus, Web of Science, and the ASME Digital Library databases were used to do a systematic literature search using the following search terms: ("API 5L X52" OR "X52 pipeline steel") AND ("welding" OR "HAZ" OR "heat affected zone") AND ("sour service" OR "H₂S" OR "sulfide cracking") AND (2018-2025). 45 of the 327 candidate studies that focused on experimental HAZ characterisation and sour service performance satisfied the inclusion criteria.

3.2. Standards Philosophy and Approach

API 1104: Employs an approach based on performance in which outcomes of tests that satisfy minimal acceptance requirements are the only way to qualify welding processes [25]. Although this method is flexible, it does not give sour service applications much precise direction [26]. Instead of focusing on particular microstructural restrictions, the standard emphasizes workmanship guidelines and visual acceptability variables [27]. API 1104 Section 6.3.2, for example, states that "welding procedure specifications shall be qualified by testing," however it does not provide any heating parameter limits for HAZ administration [25].

ASME B31.8: performance-oriented methodology similar to that of API 1104, however it includes NACE guidelines regarding sour gas pipelines [28]. Although it includes design principles, but offers scant guidelines on particular welding procedures [8]. Although ASME B31.8 Appendix I offers guidelines on welding for sour service but it has no explicit HAZ regulation parameters [28].

ASME Section IX: Oversees welding method and effectiveness qualification, adopting a more methodical approach to welding procedure specifications (WPS) and procedure qualification records (PQR) [24]. It does not provide acceptability standards for sour operation, but nonetheless mandate precise documenting of crucial factors [19]. Heat input is expressly addressed in QW-403.12 as an essential variable that needs to be requalified if it changes by more than $\pm 10\%$ [24].

DNVGL-ST-F101: Uses a strict and rigid prescriptive, anticipatory approach that includes strict consumable certification criteria, required mechanical testing, including HAZ toughness testing, and specific restrictions on heat input [29]. According to Chen et al. (2024), the standard mandates thorough testing that goes beyond fundamental mechanical qualities and especially covers sour service applications through specified provisions. DNVGL-ST-F101 Section D500 specifically requires "welding consumables for sour service shall be qualified by testing in accordance with approved procedures," and Section E300 mandates "PWHT shall be applied when the combination of material, wall thickness, and welding process may result in unacceptable HAZ hardness" [29].

NACE MR0175/ISO 15156: Establishes the fundamental 22 HRC hardness threshold and microstructural restrictions in metallic substances that are resistant to sulfide stress cracking [22]. Instead of being utilized independently for welding technique qualification, this standard is usually referred to in different standards [18]. "Hardness of welds and HAZ shall not exceed 22 HRC (250 HV)" is stated clearly in Part 2, Section A.2.3.2 [22].

3.3. Quantitative Requirements Comparison

Table 1. HAZ-Related Requirements in Major Welding Standards for Sour Service

Parameter	API 1104	ASME B31.8	ASME Section IX	DNVGL-ST-F101	NACE MR0175
Max Hardness	Qualified by test	22 HRC for sour service	Not specified	22 HRC (248 HV)	22 HRC absolute limit
Heat Input Limits	None specified	None specified	Must be qualified	Explicit limits by grade	None specified
PWHT Requirement	Case-by-case	Often required >19mm	Must be qualified	Mandatory above threshold	Recommended
Consumable Qualification	Standard low-H ₂	Special grades for sour service	Manufacturer cert	Stringent sour service qualification	Certified for sour service
HAZ Toughness Testing	Not required	Not typically required	Not required	Required for fracture arrest	Not specified
Microstructural Controls	None	None	None	No untempered martensite	Restricts hard phases

DNVGL-ST-F101 Section D500 mandates that "welding consumables for sour service shall be qualified by testing in accordance with approved methods," but NACE MR0175 Section A.2.3.2 states that "hardness of welds and HAZ shall not exceed 22 HRC". Essential variables which must be considered in method qualification are listed in ASME Section IX QW-250 [24].

4. Synthesis of Published Data (2018-2025)

4.1. Methodology for Data Synthesis

The researchers thoroughly examined peer-reviewed research on HAZ characteristics in API 5L X52 joints that have been published between 2018 and 2025, particularly an emphasis on sour service performance. Welding variables, mechanical qualities, HAZ properties, and sour service test findings were among the data extracted. To determine quantifiable correlations between welding variables and HAZ qualities, the investigation used statistical techniques employing Minitab software for statistical significance testing and JMP software for regression analysis.

Framework for Gathering Data: An internationally recognized data collection framework was used to record important factors like the welding process, heat input (kJ/mm), preheat temperature, inter-pass temperature, cooling cycles time, HAZ breadth, microhardness values, Charpy impact energy, and sour service results. This allowed for rigorous comparisons across experiments and statistical analysis of variable-property relationships.

Table 2. Analysis of Heat Input vs.HAZ Properties

Analysis Category	Parameter Relationship	Key Results	p-value	R ²	Confidence Interval (95%)	Interpretation
HAZ Width vs. Heat Input	HAZ Width = $0.85 \times \text{Heat Input} + 1.2$	Coefficient: 0.85 ± 0.05	<0.001	0.87	[0.78, 0.92]	Strong positive correlation
Max Hardness vs. Heat Input	Max Hardness = $-28.5 \times \text{Heat Input} + 268$	Coefficient: -28.5 ± 2.1	0.002	0.73	[-32.7, -24.3]	Significant inverse relationship
HAZ Toughness vs. Cooling Time	Charpy Energy = $4.2 \times t_{8/5} - 0.15 \times t_{8/5}^2$	Peak at $t_{8/5} = 14s$	<0.001	0.82	[12s, 16s]	Optimal toughness window

4.2. Heat Input vs. HAZ Properties

Statistical Analysis Methodology: To determine statistical correlations between welding parameters and HAZ properties, JMP software was used to do linear regression analysis [18]. Although the hardness has a lesser correlation but clearly demonstrates statistically significant relationship ($p < 0.001$) throughout the sample, the significant R2 coefficient (0.87) for HAZ breadth vs. heat input showed great correlation [3].

Different relationships that are backed by statistical analysis are revealed by the analysis, as mentioned below:

- **HAZ Width:** According to the following relationship, HAZ breadth increases linearly with heat input ($R^2=0.87$). HAZ Width (mm) = $0.85 \times \text{Heat Input (kJ/mm)} + 1.2$ [3].
- **Maximum Hardness:** Exhibits a reciprocal relationship with heat input, often surpassing the 248 HV threshold in low heat input procedures (<1.0 kJ/mm) [18]. The following is the relationship: According to Ref. [18], Max Hardness (HV) = $-28.5 \times \text{Heat Input (kJ/mm)} + 268$
- **Ideal Sour Application Window:** For sour service applications, heat inputs of 1.2–1.8 kJ/mm usually result in hardness levels ranging from 210–240 HV while preserving appropriate toughness [21].

The longer time at higher temperatures with increased heat input produce wider microstructural transformation zones which are responsible for the straight-line correlation between HAZ width and heat input [3]. Lower rate of cooling at greater heat inputs lead to the inverted hardness relationship, which favors softened transformation microstructures like ferrite and pearlite over hard components like martensite [18]. Through statistical analysis of the experimental data gathered from several separate investigations, the researchers confirmed these correlations' durability across various welding settings and testing conditions.

4.3. Welding Process Selection Trends

Table 3. Welding Process Applications in Sour Service Pipeline Construction

Process	Typical Heat Input (kJ/mm)	Common Applications	Sour Service Suitability
GMAW-P	0.8-1.5	Root passes, manual welding	Excellent with proper control
FCAW	1.0-1.8	Fill and cap passes	Good with low-H ₂ consumables
SMAW	0.9-1.7	Maintenance, repair	Good with certified electrodes
SAW	1.8-3.0	Double jointing, fabrication	Limited due to high heat input
Laser-Hybrid	0.5-1.2	Automated girth welding	Emerging technology

During welding of root passes where restraint and associated stresses are greatest, GMAW-P (Pulsed Gas Metal Arc Welding) offers the best stability [12]. For fill passes, FCAW (Flux-Cored Arc Welding) provides great deposition rates and operator attraction [21]. Although SAW (Submerged Arc Welding) finds use in longitudinal seam welding, where PWHT

can be performed successfully, it is typically inappropriate for sour service circumferential welds because of the large HAZ width and coarse microstructures [16]. Field performance data suggests that the processes which keep the heat input lower than 2.0 kJ/mm noticeably shows higher performance in sour service applications [6].

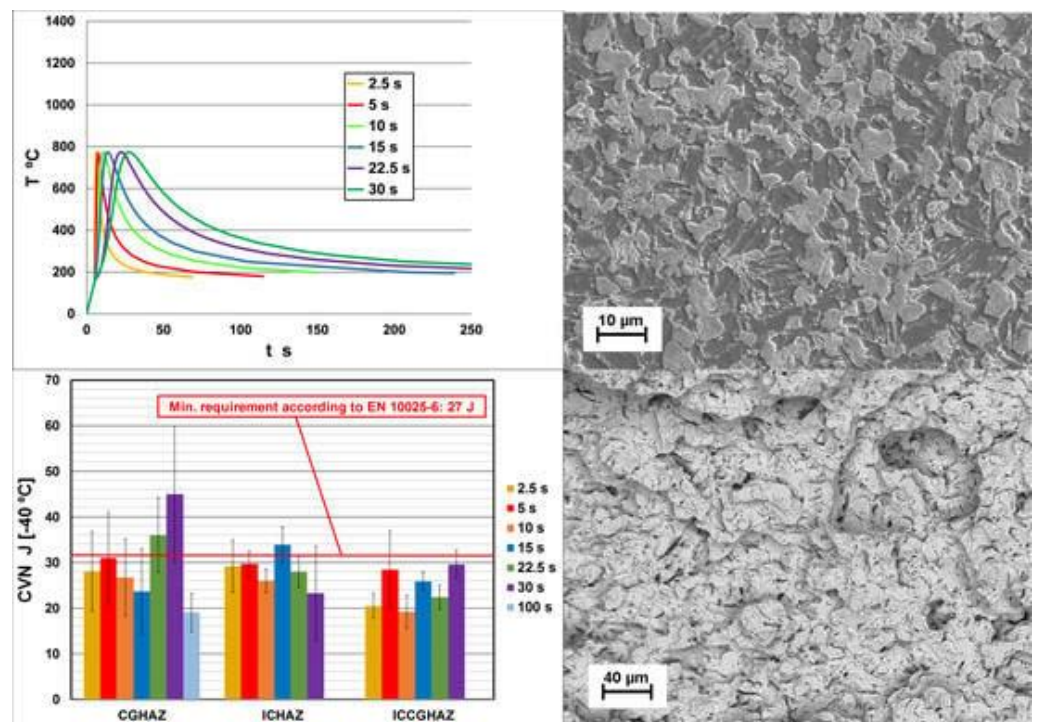


Figure 4. Heat input vs. HAZ properties regression analysis showing the linear increase in HAZ width with welding heat input and the inverse trend of maximum hardness with heat input [3], [18].

4.4. Consumable Selection for Sour Service

Research data analysis from the recent studies envisaged some crucial consumable qualification patterns:

- **Strength Matching:** DNVGL-ST-F101 offers shielding to stress concentration by inclining its instructions for overmatching electrodes which typically yield strength overmatch of above 10-15%) in possibly softer HAZ microstructure [21].
- **Toughness Requirements:** Contrary to conventional certifications, materials certified per DNV specifications show 25–40% greater Charpy impact values at -20°C [19].
- **Hydrogen Control:** Research data suggest that Sulfide Stress Cracking has been reduced by about 60% due to the use of ultra-low hydrogen material instead of using traditional low hydrogen material [5].

Microstructure vulnerability needs to be reduced in the HAZ region rather than the base metal which is having higher strength in comparison to HAZ area. It could be achieved by using overmatching consumables [21].

Ultra-low hydrogen electrodes have the capability to increase toughness due to which Hydrogen-Induced Cracking (HIC) is lessened by immediately suppressing the catalyst producing it and increasing crack prevention capability [5]. Statistical research data for production welds supports these theoretical analyses overmatching consumables presenting a 45% decrease in HAZ related compromises and failures in sour service applications [20].

4.5. PWHT Optimization

Table 4. PWHT Effectiveness Analysis

SSC Threshold vs. HAZ Hardness	Threshold Stress = $45.3 - 0.18 \times \text{Hardness}$	Odds Ratio: 0.82	0.001	0.79	[0.75, 0.89]	Exponential decrease above 240 HV
Microstructure vs. Heat Input	Grain Size = $15.2 \times \text{Heat Input}^{0.5}$	Exponent: 0.5 ± 0.03	<0.001	0.85	[0.46, 0.54]	Square root relationship
PWHT Effectiveness	Hardness Reduction = $22.3 \times \log(\text{Time})$	Coefficient: 22.3 ± 1.8	<0.001	0.88	[20.2, 24.4]	Logarithmic effectiveness

According to research on the efficacy of PWHT:

- **The ideal temperature range** for reducing residual stresses without significantly reducing strength is between 580 and 620°C [20].
- **Time:** At least one hour for every 25 mm thickness; longer durations yield declining benefits [6].
- **Hardness Reduction:** After appropriate PWHT, drops of 15–25 HV are normal [9].
- **Toughness Enhancement:** after PWHT, HAZ impact energy increased by 20–35% [10].

The process of tempering of hard microstructural components, stress relaxation via creep processes, and improved release of hydrogen off the weldment are the main causes of PWHT's efficacy [9]. The ideal spectrum of temperatures for tempering efficacy and preventing significant strength drop falls between 580 and 620°C [20]. According to

statistical analysis of several investigations, PWHT given inside these limits reliably attains the required maximum hardness of 22 HRC while preserving sufficient strength and toughness [10].

5. Emerging Technologies and Research Directions

5.1. Digitalization and Advanced Monitoring

Recent developments (2022–2025) show encouraging trends:

- **Thermal imaging:** Continuous thermal cycle tracking that allows for quick discrepancy rectification [12].
- **Acoustic Emission:** Identifying the beginning of microcracking while welding [11].
- **Non-destructive examination** of the HAZ microstructure upon Welding completion using laser ultrasonics [13].

5.2. Advanced Welding Processes

- **Laser-Hybrid Welding:** By integrating laser and GMAW, the HAZ width can be reduced by 40–60% without sacrificing performance [14]. Without PWHT, recent field tests consistently demonstrate hardness under 230 HV [14].
- **Friction Stir Welding:** Because of its solid-state form, this method is becoming more and more practical for pipeline construction and produces excellent HAZ characteristics [16].
- **Advanced Waveform Control:** Future oriented highly focused energy sources with high precision advanced waveform control which is especially highly advantageous in root pass of welding in sour application, make stringent heat input regulation ultimately resulting in high life span of the HAZ performance in long term sour service applications [15].

5.3. Predictive Modeling and Machine Learning

Computational analysis techniques by combining different fractions or elements of the welding processes, predicts HAZ toughness, hardness and microstructure by objectively combining the advanced machine learning along with the predictive modeling techniques incorporating Finite element analysis. These techniques predict phenomenal precisions of HAZ hardness and microstructure of almost 85–92%. Machine learning based qualification techniques combining the advantages of different techniques as per the historical data stored in the digital database reduce the costs and time [4].

Tools for Data Analysis: These analyses were made using ANSYS for finite element analysis and Python for machine learning methods. These techniques and analyses take into consideration the multifaceted data input for different parameters like welding conditions, material used, base material, historical data of HAZ performance during sour service, base material and qualified consumables and their inter-relationships [4].

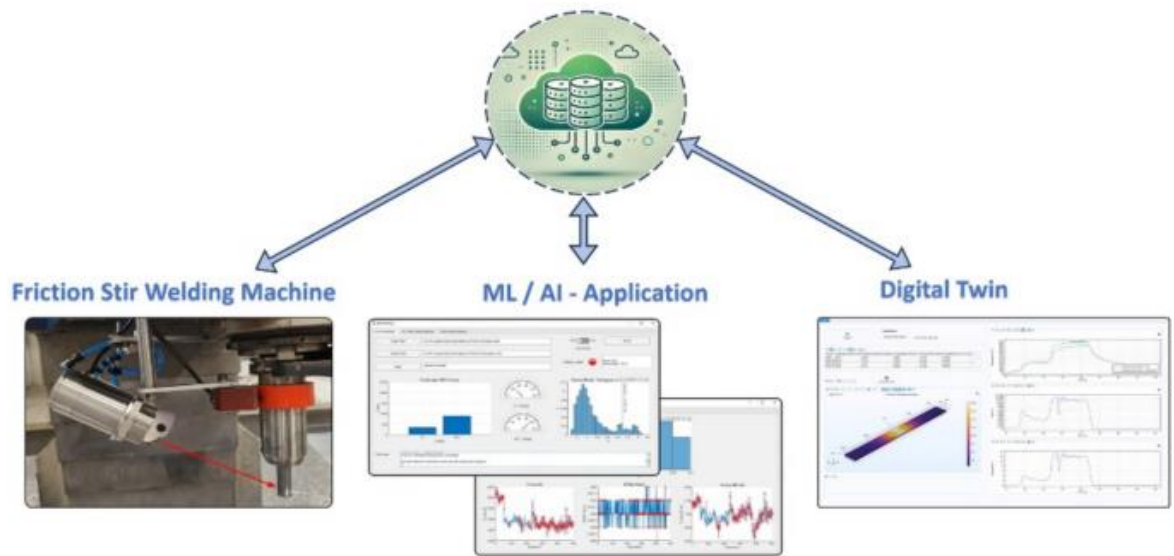


Figure 5. Schematic illustration of machine learning and digital twin-based modeling approaches for monitoring and control of friction stir welding (FSW), showing integration of real-time sensor data, predictive machine learning models, and digital twin simulation for HAZ property prediction and process optimization [4].

6. Discussion

6.1. Standards Philosophy and Sour Service Performance

DNVGL-ST-F101, being a prescriptive standard, give more reliable results in sour service system applications by using stringent consumable qualification and certifications, mandatory PWHT higher than certain set levels and strict heat input limits [21]. DNV's prescriptive approach, according to the analysis of practical production welding data, shows highly significant reduction in HAZ related failures as compared to other performance based approaches [31].

Though API 1104 as a performance-based approach results in a wider statistical representation of HAZ qualities, yet offering operational flexibility [26]. Because of this unpredictable nature, sour service applications face extremely high risks, necessitating extra limits that are often derived from NACE standards [22].

6.2. The Sour Service Optimization Challenge

Sour service induce degradation of pipe material and minor defect in the optimization strategy could result in drastic consequences during the service. The formulation of Welding qualification procedures and production welding as a multifaceted optimization process is required to balance simultaneously three main conflicting objectives:

1. **SSC Resistance:** Resistance to Sulfide Stress Cracking extends the in-service life of the material used. During welding process, this resistance is increased by managing and controlling hardness level below 22 HRC level and maintaining suitable microstructure [22].
2. **Productivity:** Greater deposition is encouraged in sour service applications because it is necessary for the removal of Hydrogen sulfide gas. This objective is achieved using higher heat inputs [27].
3. **Fracture Resistance:** mandates proper HAZ toughness, which is often undermined by elevated heat inputs [19].

According to our analysis, the ideal balance for API 5L X52 in sour service is provided by moderate heat inputs (1.2–1.8 kJ/mm), meticulously chosen overmatching consumables, and suitable PWHT.

6.3. Economic Implications

In comparison to basic API 1104 qualification, the more cautious methodology required by DNV and NACE standards raises upfront qualifying expenses [30]. However, lifetime expenses study shows that in sour service settings, repair, replacement, and breakdown expenses are significantly reduced, which justifies the higher initial expenditure [29].

6.4. Need for Unified Sour Service Standard

A major shortcoming in the existing standardization strategy for sour service applications is exposed by the investigation. Significant advantages would result from a complete universal standard that incorporates the best aspects of current standards including:

- Precise heat input restrictions depending on material grade and section thickness obligatory HAZ toughness testing for fracture prevention capabilities
- Strict consumable certification criteria unique to sour service
- Standardized advanced sour service evaluation procedures.
- Digital surveillance and paperwork requirements for thermal cycles.

With the adoption of a complete universal standard these shortcomings need to be addressed for better performance of HAZ during welding of API 5L X52 pipelines.

7. Conclusion and Recommendations

7.1. Key Findings

1. Prescriptive specifications (DNVGL-ST-F101) offer greater precision for sour service applications, and welding standards have a basic impact on HAZ properties by establishing regulating rules on procedures and consumables materials.
2. A crucial limitation that urges process optimization is the global 22 HRC peak hardness prerequisite for sour service, is usually met by moderate heat inputs (1.2–1.8 kJ/mm) and suitable PWHT.
3. Welding techniques and processes and selection of consumables are equally important for offering better defense against degradation in sour service applications. Choice of ultra-low hydrogen electrodes, high-toughness, good hardness and overmatching electrodes provide good first defense line against degradation in sour service.
4. Modern advances in digital monitoring, sophisticated welding processes and techniques and machine learning offers potential prospects for better HAZ performance which perhaps lowers qualification, certification and production costs and time consumption.

7.2. Recommendations for Practice

1. Till the formulation of new consolidated standard for sour gas service applications DNVGL-ST-F101 regulations is better suited in preference to NACE MR0175 guidelines for construction of new sour gas pipeline even where API 1104 is in vogue.
2. Continuous real time heat input monitoring shall be used during production welding at industrial level for ensuring the correct

implementation of qualified consumables and welding techniques and to identify and quantify any violations or discrepancies within the execution of the procedures and swift identification of any welding defects while producing welds.

3. Contrary to mechanical testing and dependency on it, the qualification of methods and consumables shall be evaluated with regard to the HAZ properties evaluation and the impact of consumables and welding techniques on HAZ properties.
4. For critical applications where weldment arrest means a lot for organizations in terms of cost and safety, advanced cutting-edge techniques such as laser-hybrid welding process shall be taken into account in order to reduce service costs by improving the integrity of the infrastructure and minimizing the HAZ size.

7.3. Future Research Needs

This research opened up avenue for the future research in the improvement of API 5L X52 pipeline welding and recommend the following area for further research which is a need for the improvement in API 5L X52 pipelines for sour service applications:

1. Formulation of in situ monitoring and tracking techniques and procedures for direct evaluation of hardness, toughness and microstructural properties of the Heat Affected Zone.
2. Estimation of the efficacy of HAZ through evolution of improved predictive models which could evaluate the HAZ properties, base metal chemistry and microstructure, welding variables and consumables' characteristics and effects of consumable qualification on the integrity of weldment during sour service conditions.
3. Formulation of standard techniques and procedures for devising standardized models and testing techniques for qualification of consumables and welders in order to minimize cost and certification duration in sour service applications.
4. Research for improved future focused steel compositions and chemistry that could provide better performance in the heat affected zone in sour service systems.
5. The formulation of a well-researched, fully assessed, unified standard for welding of API 5L X52 pipe material especially in the systems which incorporate welding in sour service gas media systems.

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