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# Cracking in Underwater Welded Joints: Mechanisms, Influencing Factors, Prevention Strategies and Emerging Sustainable Electrode Technologies - A Review

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***Abstract*** **- Cracking in underwater welded joints remains a major obstacle to the reliable repair and fabrication of marine structures, offshore platforms, subsea pipelines and ship hulls. The problem is particularly severe in underwater wet welding, where direct contact between the welding arc, molten metal and surrounding water produces rapid cooling, hydrogen absorption, microstructural hardening and substantial residual stresses. This review critically examines the principal mechanisms of cracking in underwater welded joints, with particular emphasis on hydrogen-assisted cold cracking, heat-affected-zone cracking, weld-metal cracking and solidification-related defects. The interaction among diffusible hydrogen, steel hardenability, welding thermal cycles, restraint and residual stress is examined, alongside the influence of water depth, welding parameters, electrode composition and protective coatings. Evidence from experimental studies indicates that cracking susceptibility cannot be reliably predicted using steel composition or carbon-equivalent values alone; hydrogen concentration, local hardness, microstructure and stress conditions must also be considered. Established mitigation strategies, including hydrogen-control consumables, hydrophobic electrode coatings, induction heating, process optimisation and appropriate inspection procedures, are evaluated. Particular attention is given to the emerging opportunity to develop sustainable, agro-waste-derived electrode coatings, while recognising the need to validate their hydrogen-control performance, slag behaviour, arc stability and mechanical properties experimentally. The review identifies critical gaps in predictive modelling, delayed-crack assessment, standardised testing and the integration of machine learning with metallurgical evidence. A research framework is proposed for developing lower-cracking-risk underwater welding consumables and more reliable inspection and qualification procedures. The findings provide a technical basis for future experimental research and improved underwater welding practice.**

***Keywords:*** Underwater welding; wet welding; hydrogen-assisted cracking; cold cracking; heat-affected zone; diffusible hydrogen; electrode coating; residual stress; sustainable welding consumables; marine structures.

## I. Introduction

Underwater welding is an important repair and joining technology for marine structures, offshore installations, subsea pipelines, hydraulic infrastructure and naval vessels. It can reduce the need to remove damaged components from service or transport large structures to dry-docking facilities. However, welding in a submerged environment presents metallurgical and operational challenges that are substantially different from those encountered during conventional atmospheric welding. Among these challenges, cracking is particularly important because it can compromise joint integrity, reduce fatigue resistance and lead to premature structural failure.

Underwater welding is commonly classified into wet welding and dry or hyperbaric welding. In wet welding, the welding operation takes place directly in water, usually using shielded metal arc welding (SMAW) or flux-cored arc welding (FCAW). In dry underwater welding, the welding zone is isolated from the surrounding water within a chamber or habitat, providing a more controlled environment. Wet welding is attractive for many repair applications because of its relative simplicity and lower infrastructure requirements, although the resulting weld quality can be more difficult to control (Vijay & Radhika, 2024; Vashishtha *et al.*, 2022).

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The principal metallurgical challenge in underwater wet welding arises from the interaction between water, the electric arc, the molten weld pool and the surrounding steel. Water dissociation introduces hydrogen- and oxygen-containing species into the arc environment. At the same time, rapid heat extraction shortens the cooling cycle and can promote the formation of hard, brittle microstructures in the heat-affected zone (HAZ). When sufficient diffusible hydrogen is present in combination with tensile stress and susceptible microstructures, hydrogen-assisted cracking can occur in the weld metal or adjacent base material (Klett *et al.*, 2021; Brätz *et al.*, 2022).

Cracking is not a single failure mechanism. It may develop during solidification, during cooling, or after the joint has apparently been completed. This distinction is important because each mechanism requires different preventive measures. Solidification cracking is associated with the final stages of weld-metal solidification, whereas hydrogen-assisted cold cracking is associated with the interaction of diffusible hydrogen, susceptible microstructure and tensile stress. The latter may occur after a delay, making immediate visual inspection insufficient for establishing joint integrity. (Klett *et al.*, 2021; Tomków *et al.*, 2020).

Although several reviews have discussed underwater welding processes, weld quality and general defect mitigation, the relationship between crack mechanisms, material susceptibility, environmental conditions, consumable design and long-term inspection requires continued critical evaluation. Existing evidence also reveals that conventional carbon-equivalent relationships developed for atmospheric welding may not adequately represent the extreme cooling conditions of wet welding (Vaccari *et al.*, 2025).

This review therefore focuses specifically on cracking in underwater welded joints rather than attempting to catalogue every aspect of underwater welding. Its objectives are to:

1. Explain the principal mechanisms and locations of cracking in underwater welded joints.
2. Evaluate the effects of diffusible hydrogen, cooling rate, steel composition, hardness, residual stress, water depth and welding parameters.
3. Compare established crack-prevention methods and identify their limitations.
4. Examine inspection, characterisation and predictive approaches for detecting and assessing cracking.
5. Identify research opportunities in sustainable electrode coatings, particularly agro-waste-derived materials, and data-driven crack prediction.

The central argument is that underwater weld cracking must be treated as a coupled metallurgical, thermal and mechanical problem, requiring coordinated control of hydrogen, microstructure and stress rather than reliance on any single welding parameter.

## II. Review Methodology

This article adopts a critical narrative-review approach. The literature search focused on peer-reviewed journal articles, review papers and relevant technical publications addressing underwater wet welding, hydrogen-assisted cracking, diffusible hydrogen, heat-affected-zone hardness, underwater welding consumables, thermal management, post-heating and weld-defect characterisation.

Search concepts included underwater welding, wet welding, hydrogen-induced cracking, cold cracking, weld-metal cracking, heat-affected-zone cracking, diffusible hydrogen, water depth, electrode coating, induction heating and underwater weld inspection. Priority was given to publications with identifiable authors, journal details and persistent digital object identifiers (DOIs). Foundational experimental investigations were considered alongside more recent reviews and modelling studies.

Studies were assessed qualitatively according to their relevance to crack mechanisms, experimental evidence, measured material properties, process conditions, proposed mitigation methods and acknowledged limitations. Particular attention was paid to distinguishing direct experimental findings from general explanations and proposed future research.

This review is not presented as a fully systematic review or meta-analysis: no claim is made that every relevant publication has been retrieved, screened or quantitatively synthesised. Before journal submission, the search should be repeated across Scopus and Web of Science, with a documented search date, screening criteria, duplicate removal and a study-selection flow diagram if required by the target journal.

## III. Mechanisms of Cracking in Underwater Welded Joints

### 3.1 Hydrogen-assisted cold cracking

Hydrogen-assisted cold cracking (HACC), also called hydrogen-assisted cracking in this context, is one of the most significant metallurgical defects associated with underwater wet welding. It can occur in the weld metal or HAZ when three conditions coincide: a sufficient concentration of

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diffusible hydrogen, a susceptible microstructure and tensile stress. These conditions interact rather than acting independently.

During wet welding, water vapour and other hydrogen-containing species generated in the arc environment provide a source of hydrogen. Atomic hydrogen can enter the molten metal, become trapped during solidification or diffuse into adjacent regions of the joint. As the weld cools, hydrogen migrates through the material, while the evolving microstructure and residual-stress field influence the locations where cracking is most likely to initiate. The HAZ is especially vulnerable when rapid cooling produces martensitic or other hard transformation products. Such microstructures generally have lower tolerance for hydrogen-assisted damage than more ductile microstructures. High tensile residual stresses further increase the likelihood of crack initiation and propagation.

Santos *et al*. (2021) experimentally investigated hydrogen cracking in wet-welded structural steels using ferritic electrodes at simulated depths extending to 20 m. Their results linked cracking to diffusible hydrogen, chemical composition, hardness and material susceptibility. The study is particularly relevant because it considers both weld-metal and HAZ cracking rather than treating the joint as a homogeneous material.

The delayed nature of hydrogen-assisted cracking presents a further difficulty. A weld may appear sound immediately after completion, yet cracks can develop as hydrogen redistributes and stresses remain. Consequently, inspection timing and the selection of an appropriate delayed-inspection procedure are important parts of weld qualification.

### 3.2 Heat-affected-zone cracking

The HAZ is the region of the base material that experiences a welding thermal cycle without undergoing complete melting. In underwater wet welding, heat extraction into the surrounding water and parent material can be sufficiently rapid to alter the transformation behaviour of the steel. (Klett *et al.*, 2021; Vaccari *et al.*, 2025).

The resulting HAZ may contain locally hardened regions adjacent to the fusion boundary. The distribution of hardness depends on chemical composition, initial microstructure, heat input, plate thickness, joint geometry and the local cooling cycle.

Cracking may develop in the coarse-grained HAZ, near the fusion boundary or beneath the weld bead. The precise location depends on the thermal cycle, microstructure, hydrogen distribution and local stress concentration. A hardness measurement averaged across the joint can therefore conceal a narrow region of high susceptibility.

Vaccari *et al.* (2025) demonstrated that conventional carbon-equivalent formulas developed for atmospheric welding do not necessarily predict hardness accurately under underwater wet-welding conditions. Their study developed an underwater-specific empirical relationship and reported improved predictive performance within the investigated dataset. However, the authors also acknowledged that hardness and carbon equivalent alone cannot capture all factors governing cracking.

This distinction has important practical implications: a low calculated carbon equivalent should not automatically be interpreted as proof that an underwater weld is resistant to cracking. Local hardness, diffusible hydrogen, restraint and actual microstructure must also be evaluated.

### 3.3 Weld-metal cracking

Cracking can also occur within the deposited weld metal. Its susceptibility depends on the deposited-metal composition, solidification behaviour, hydrogen content, microstructure and residual stresses. (Santos *et al.*, 2021; Parshin *et al.*, 2020).

In wet welding, weld-metal cracking is often associated with hydrogen-assisted cold cracking, although other mechanisms can occur depending on the alloy and welding conditions. Hydrogen can become concentrated in susceptible regions, while solidification structure and weld-bead geometry influence local strain accommodation.

Silva *et al.* (2015) used multiscale three-dimensional characterisation techniques to examine discontinuities in underwater wet welds. Their work demonstrated the value of imaging techniques for distinguishing and quantifying internal features, including cracks, pores and inclusions. Such evidence reinforces the importance of examining internal weld structure rather than relying exclusively on surface inspection.

Weld-metal cracks can be transverse, longitudinal or irregularly oriented. Their orientation is governed by the relationship between the crack path, microstructural features and local stress state. The orientation alone is insufficient to establish the cracking mechanism; metallography, fractography and compositional evidence may be needed.

### 3.4 Solidification cracking

Solidification cracking develops during the final stages of weld-metal solidification, when the remaining liquid films

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between solidifying grains or dendrites cannot accommodate the imposed tensile strain. Susceptibility is influenced by alloy composition, solidification range, impurity segregation, weld-pool geometry and restraint. (Vijay & Radhika, 2024).

This mechanism must be distinguished from hydrogen-assisted cold cracking. Solidification cracks form at elevated temperatures, whereas hydrogen-assisted cracks generally develop during cooling or after welding. Their preventive measures are therefore not interchangeable.

Although solidification cracking is an important general welding mechanism, its relative contribution to cracking in underwater welds should be established for the particular material and consumable rather than assumed to dominate all underwater cracking incidents. Wet-welding investigations frequently emphasise hydrogen-assisted cracking because of the high hydrogen availability and severe cooling conditions.

### 3.5 Crater, root and underbead cracks

Crater cracks may occur when welding terminates without adequate filling of the weld crater. Root cracking can be promoted by geometric stress concentration, inadequate root fusion, restraint or hydrogen-assisted damage. Underbead cracks develop beneath the weld bead, commonly within the HAZ, and may be difficult to detect from the surface. (Vashishtha *et al.*, 2022; Vijay & Radhika, 2024).

Suga (1985) investigated underbead and root cracking in underwater wet welds and reported that underbead cracks occurred approximately five minutes after welding under the experimental conditions. The study also found that post-heating above 100 °C prevented cracking in the tested configuration. These values should not be generalised to all steels, electrode systems or underwater environments, but the findings illustrate the importance of delayed cracking and thermal control.

The distinction among crack types is essential for failure analysis because a crater crack, a solidification crack and a delayed hydrogen-assisted crack may require substantially different corrective actions.

## IV. Factors Influencing Crack Formation

### 4.1 Diffusible hydrogen

Diffusible hydrogen is one of the principal variables controlling hydrogen-assisted cracking. It refers to the hydrogen that can migrate through the weld metal and escape or redistribute under the relevant test conditions. It must be distinguished from hydrogen that remains strongly trapped or is retained in other forms. (Klett *et al.*, 2020; Klett *et al.*, 2021).

Klett *et al.* (2021) investigated the control of diffusible hydrogen in different steel phases through the selection of underwater welding consumables. Their study highlighted the relationship between hydrogen content, microstructural susceptibility and consumable design.

In practical terms, reducing hydrogen entering the molten pool, limiting its retention in susceptible regions and allowing appropriate hydrogen removal can reduce cracking risk. However, no single hydrogen threshold should be assumed to guarantee crack-free welding across all steel grades and restraint conditions.

### 4.2 Cooling rate and thermal history

Rapid cooling is a defining characteristic of wet underwater welding. It influences the transformation of the HAZ, the resulting hardness, residual stresses and hydrogen transport. A short cooling time can promote martensitic transformation in susceptible steels. At the same time, steep thermal gradients produce differential contraction between the weld metal and surrounding material. When contraction is constrained by the joint geometry or structural restraint, tensile residual stresses develop.

Vijay and Radhika (2024) identified rapid cooling as a major challenge in wet welding and discussed approaches such as modifying welding speed and using induction heating to influence the thermal cycle.

Increasing heat input or reducing travel speed may alter the cooling cycle, but neither measure should be treated as universally beneficial. Excessive heat input can increase distortion, alter the weld microstructure and affect the mechanical properties of the joint. Process optimisation must therefore balance cooling control against penetration, bead geometry and overall weld integrity.

### 4.3 Steel composition and carbon equivalent

Carbon equivalent is used to estimate the influence of alloying elements on steel hardenability and weldability. Conventional relationships can be useful screening tools, but their accuracy depends on the steel composition and welding conditions for which they were developed.

In underwater wet welding, the unusually rapid cooling cycle changes the relationship between composition and the resulting microstructure. Vaccari *et al.* (2025) developed a carbon-equivalent relationship specifically for underwater wet

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welding, reporting better prediction within the investigated experimental dataset than the conventional relationships evaluated in their study. The proposed relationship is not a universal crack-probability equation. Its application to different steel grades, depths, electrode systems and restraint conditions requires independent validation. More generally, carbon equivalent should be combined with local hardness, hydrogen measurements, microstructural analysis and mechanical assessment.

### 4.4 Water depth and hydrostatic pressure

Increasing water depth changes the hydrostatic pressure surrounding the welding operation and can affect arc behaviour, gas-bubble formation, gas–metal reactions and hydrogen transport. These effects may influence the quality of the weld and its susceptibility to cracking. (Klett *et al.*, 2020).

Research on the effect of water depth on hydrogen in SMAW wet-welded joints has demonstrated that diffusible and residual hydrogen behaviour can change with pressure and welding conditions. The direction and magnitude of the change depend on the consumable and operating parameters; it is therefore inappropriate to assume that all forms of hydrogen increase monotonically with depth.

Depth should consequently be considered alongside current, voltage, electrode characteristics, welding position and the surrounding water conditions when evaluating cracking risk.

### 4.5 Welding current, voltage and travel speed

Welding current, voltage and travel speed affect heat input, arc stability, metal transfer, penetration and weld-bead geometry. These variables also influence the thermal cycle and the time available for hydrogen redistribution.

Insufficient or unstable heat input may contribute to poor fusion and irregular weld geometry. Conversely, excessive heat input can produce undesirable microstructural changes or increase distortion. The influence of any parameter on cracking must be interpreted in relation to the full welding procedure rather than as an isolated variable.

For this reason, the most appropriate objective is not simply to maximise or minimise heat input, but to establish a qualified process window that delivers adequate fusion, acceptable microstructure, controlled hydrogen and suitable mechanical properties.

### 4.6 Restraint, residual stress and joint geometry

Residual stresses arise from non-uniform heating and cooling. External restraint, thick sections, short weld lengths, complex geometries and abrupt changes in cross-section can increase the local tensile stresses experienced by a weld.

Even when hydrogen concentration and hardness are moderate, a highly restrained joint may remain susceptible to cracking. Similarly, a high hydrogen concentration does not necessarily produce a crack if the microstructure and stress conditions are insufficient to support crack initiation and propagation.

This interaction explains why a reliable cracking assessment should integrate metallurgical susceptibility with mechanical loading and restraint.

**Table 1: Principal cracking mechanisms and their distinguishing characteristics**

| Crack mechanism | Typical location or timing | Principal contributing factors | Main control priorities |
|---|---|---|---|
| Hydrogen-assisted cold cracking | Weld metal or HAZ; may be delayed | Diffusible hydrogen, susceptible microstructure, tensile stress | Hydrogen control, microstructure control, stress management |
| HAZ cracking | Near fusion boundary or beneath the bead | Rapid cooling, hard transformation products, hydrogen, restraint | Thermal-cycle control, material selection, hardness assessment |
| Weld-metal cracking | Within deposited metal; timing depends on mechanism | Hydrogen, deposited-metal chemistry, microstructure, residual stress | Consumable optimisation, deposition control, metallurgical examination |
| Solidification cracking | During the final stages of weld solidification | Segregation, solidification range, restraint, weld-pool geometry | Consumable chemistry, bead geometry, procedure optimisation |
| Crater cracking | At the weld termination | Unfilled crater, shrinkage strain, unsuitable termination procedure | Crater filling and appropriate termination technique |
| Root or underbead cracking | Root region or beneath the weld bead | Stress concentration, local hardness, hydrogen, inadequate fusion | Joint preparation, root control, hydrogen and thermal management |

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**Note:** The listed factors are general metallurgical relationships. Confirmation of the dominant mechanism in an individual underwater weld requires appropriate inspection and, where necessary, metallographic or fractographic evidence.

## V. Prevention and Mitigation of Cracking

### 5.1 Low-hydrogen and specialised underwater consumables

Electrode and wire composition, flux chemistry and protective systems strongly influence the amount of hydrogen entering the weld metal. Specialised underwater consumables seek to maintain a more stable arc and reduce adverse gas–metal interactions.

Klett *et al.* (2021) examined the use of different consumables to control hydrogen in different steel phases. Zhang *et al.* (2023) demonstrated a neutral slag system for underwater wet FCAW that created a protective barrier over the molten metal and reduced diffusible hydrogen under the investigated conditions. The reported hydrogen concentrations were 3.61 mL/100 g for deposited metal using a nickel outer belt and 10.40 mL/100 g using a pure iron outer belt. These results demonstrate technical potential, but they are specific to the tested wire designs and conditions rather than universal performance values.

The development of consumables should consider hydrogen content, slag detachability, arc stability, deposition efficiency, porosity, mechanical strength and corrosion behaviour. Reducing hydrogen is important, but a low-hydrogen electrode is not automatically suitable for every underwater repair application.

### 5.2 Hydrophobic electrode coatings

Hydrophobic coatings can limit direct wetting of the electrode covering and help stabilise the local welding environment. Tomków *et al.* (2020) investigated waterproof electrode coatings and their effects on diffusible hydrogen, microstructure and hardness in underwater wet-welded joints. The investigators reported that the tested coatings reduced diffusible hydrogen and HAZ hardness, thereby lowering susceptibility to cold cracking under their experimental conditions.

The effectiveness of a coating depends on its composition, thickness, adhesion, resistance to water exposure and compatibility with the underlying flux. A coating must also withstand handling and storage without introducing additional defects.

Further research is needed to establish how coating durability changes with water depth, storage duration, electrode handling and different underwater welding positions.

### 5.3 Induction heating and thermal management

Induction heating is a promising approach because heat can be generated directly within the workpiece without relying solely on conventional external heating arrangements. Brätz *et al.* (2022) investigated induction heating in underwater wet welding, considering thermal input, microstructure and diffusible hydrogen. Their work supports further evaluation of thermal management as a means of controlling cracking susceptibility in high-strength steels.

However, induction heating should not be regarded as a universally available or fully established substitute for conventional preheating and post-weld heat treatment. Its practical use depends on equipment configuration, geometry, power delivery, water conditions and the ability to maintain the required thermal cycle.

Where post-heating is proposed, the procedure must be qualified for the specific material and environment. The findings of Suga (1985) provide historical experimental evidence for crack prevention through post-heating, but the temperature and duration required for one joint cannot automatically be transferred to another.

### 5.4 Optimising the welding procedure

A qualified underwater welding procedure should account for:

- Base-metal grade, thickness, chemical composition and initial microstructure.
- Electrode or wire classification and consumable condition.
- Welding current, voltage, polarity and travel speed.
- Water depth, pressure, temperature and flow conditions.
- Joint design, restraint, welding position and access.
- Required mechanical properties and acceptable defect limits.
- Inspection method, inspection timing and acceptance criteria.

Parameter optimisation should use experimental evidence and appropriate welding-procedure qualification rather than an assumption that one parameter adjustment will eliminate cracking. In particular, the operating window must balance hydrogen control, cooling rate, penetration and the avoidance of other defects.

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**Table 2: Comparison of crack-mitigation strategies**

| Strategy | Primary mechanism addressed | Main advantage | Limitation or research need |
|---|---|---|---|
| Specialised low-hydrogen consumables | Hydrogen entry and retention | Directly targets a major cracking contributor | Requires compatibility and performance testing for each material and process |
| Hydrophobic electrode coatings | Water exposure and hydrogen uptake | Can improve weld quality without fundamentally changing the welding process | Durability, adhesion, coating uniformity and storage stability require evaluation |
| Induction heating | Cooling rate and microstructure | Offers local thermal control | Equipment complexity and underwater implementation require validation |
| Qualified current, voltage and travel speed | Thermal cycle, arc stability and geometry | Integrates several controllable process variables | Parameter interactions can make optimisation complex |
| Appropriate joint design and reduced restraint | Tensile stress concentration | Addresses the mechanical component of cracking | Structural geometry and repair constraints may limit changes |
| Delayed inspection and advanced NDT | Detection of cracking | Helps identify defects not visible immediately after welding | Effectiveness depends on crack location, orientation, size and inspection access |
| Data-driven prediction | Integrated risk estimation | May help identify nonlinear interactions among variables | Requires representative, validated datasets and independent testing |

## VI. Inspection and Characterisation of Cracks

### 6.1 Visual inspection

Visual inspection can identify surface-breaking cracks, irregular bead profiles, craters, undercut and other visible imperfections. However, it cannot reliably exclude internal cracks or small subsurface defects. In underwater applications, visibility, access and surface conditions can further complicate inspection. (International Organization for Standardization [ISO], 2016).

Visual inspection should therefore be treated as an initial examination rather than definitive proof of joint integrity.

### 6.2 Ultrasonic testing

Ultrasonic testing can be used to identify internal discontinuities and, with suitable techniques, estimate their location and dimensions. Its performance depends on material structure, surface condition, probe configuration, crack orientation and access. (International Organization for Standardization [ISO], 2016).

Underwater inspection may require specialised probes, remotely operated equipment or procedures adapted to the component geometry. A qualified technique must demonstrate adequate sensitivity for the defects of concern.

### 6.3 Radiographic testing

Radiographic methods can reveal internal weld discontinuities where the material thickness, geometry, access and radiation-safety arrangements permit. However, crack detection depends on crack orientation relative to the radiation beam and on the size and opening of the discontinuity. (International Organization for Standardization [ISO], 2016).

Radiography should not be assumed to detect every planar defect. The selection of radiographic or ultrasonic methods must follow the applicable construction code, inspection specification and demonstrated detection capability.

### 6.4 Magnetic-particle and penetrant testing

Magnetic-particle testing can detect surface and near-surface discontinuities in suitable ferromagnetic materials. Liquid penetrant testing is primarily intended for discontinuities open to the surface on appropriately prepared, non-porous surfaces. (International Organization for Standardization [ISO], 2016).

These methods can complement other inspection techniques, but their effectiveness may be reduced by coatings, contamination, surface roughness or difficult underwater access. The inspection procedure must be compatible with the environment and the material being examined.

### 6.5 Metallography, hardness testing and three-dimensional imaging

Metallography allows investigators to examine crack paths, transformation products, grain structure and the relationship between cracks and the fusion boundary.

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Hardness mapping can reveal localised hard zones that might be missed by a limited number of measurements. (Silva *et al.*, 2015; ISO, 2016).

Three-dimensional imaging can provide additional information on crack orientation, shape and connectivity. Silva *et al.* (2015) demonstrated the value of micro-computed tomography and other high-resolution imaging approaches for characterising discontinuities in underwater wet welds.

A robust experimental investigation should combine several complementary methods. For example, visual examination and radiography may be followed by targeted sectioning, metallography and hardness mapping to determine whether a detected discontinuity is a crack, pore or inclusion and to establish the likely mechanism.

### 6.6 Delayed inspection

Because hydrogen-assisted cracking can develop after welding, an immediate examination alone may be insufficient. The inspection interval should be established by the applicable standard, code, qualified procedure and risk assessment rather than by a universal waiting period.

Delayed inspection is especially important where high-strength steels, elevated hydrogen levels, high restraint or hardened HAZ microstructures are involved. Inspection timing should be documented so that the evidence can be compared across experimental studies and field repairs.

## VII. Sustainable Agro-Waste-Derived Electrode Coatings: An Emerging Research Direction

### 7.1 Rationale

The development of sustainable underwater welding consumables offers a potentially valuable direction for reducing dependence on conventional coating constituents and converting agricultural residues into higher-value engineering materials. This approach is particularly relevant to research seeking to combine welding performance with waste utilisation and circular-material principles.

Possible feedstocks for investigation include rice husk ash, selected plant-derived mineral residues, and other characterised agricultural by-products. However, their suitability cannot be established from their origin alone. Chemical composition, mineral phases, particle size, moisture, loss on ignition, contamination and batch-to-batch variability must be assessed before their use in electrode coatings.

Rice husk ash, for example, may contain substantial silica, but its properties depend strongly on the source material and combustion conditions. Silica-rich material should not automatically be described as a hydrogen scavenger or a crack-prevention additive. Its actual contribution to slag formation, coating integrity, arc behaviour and hydrogen control must be demonstrated experimentally.

### 7.2 Potential functions and limitations

Agro-waste-derived materials might be investigated as partial substitutes for selected mineral fillers or as constituents of engineered slag systems. Their potential functions include modifying slag viscosity, influencing slag solidification, contributing to coating structure and altering the physical protection of the molten pool.

Nevertheless, a material that improves one coating property may adversely affect another. Excessive or unsuitable additions may change arc stability, electrode manufacturability, slag detachability, porosity or weld-metal chemistry. Moisture retained in a coating may also undermine the objective of reducing hydrogen uptake.

Consequently, the research question should not be framed merely as whether agricultural waste can be added to an electrode. It should establish whether a controlled, characterised formulation provides measurable improvements in crack resistance while maintaining acceptable weld quality and mechanical properties.

### 7.3 A proposed experimental framework

A rigorous study of agro-waste-derived underwater electrode coatings could proceed through the following stages.

*Stage 1* — Feedstock characterisation

Chemical composition, X-ray diffraction, particle size, moisture, loss on ignition and batch variability

*Stage 2* — Electrode formulation

Prepare a conventional control and defined formulations with graded agro-waste-derived additions

*Stage 3* — Controlled underwater welding

Hold base metal, electrode dimensions, welding parameters and test conditions consistent

*Stage 4* — Crack and weld-quality assessment

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Measure diffusible hydrogen, hardness maps, crack incidence, porosity, tensile properties and impact toughness

*Stage 5* — Statistical validation and optimisation

Replicated experiments, uncertainty analysis, formulation optimisation and independent validation

A control electrode should be tested under the same conditions as each experimental formulation. Replication is essential because underwater welding may exhibit substantial variability in arc behaviour, bead geometry and defect formation.

The response variables should include not only visible crack incidence but also diffusible hydrogen, HAZ hardness, weld-metal chemistry, porosity, tensile strength, impact toughness and, where feasible, fatigue performance. If an apparent reduction in cracking is accompanied by unacceptable porosity or reduced toughness, the formulation should not be considered successful.

### 7.4 Research hypotheses

A suitable experimental programme could test the following hypotheses:

- H1: The addition of a properly characterised agro-waste-derived constituent can alter electrode-coating and slag properties without compromising weldability.
- H2: Some optimised formulations can reduce diffusible hydrogen or the incidence of hydrogen-assisted cracking relative to a conventional control under matched conditions.
- H3: The relationship between formulation composition and crack susceptibility is nonlinear because coating chemistry interacts with thermal history, microstructure and stress.
- H4: Multi-response optimisation can identify formulations that balance cracking resistance, mechanical properties, porosity and coating manufacturability.

These are hypotheses to be tested, not established findings. The literature reviewed here supports the importance of hydrogen control and consumable design, but it does not establish that agro-waste-derived coatings necessarily reduce underwater weld cracking.

### 7.5 Environmental and industrial assessment

The sustainability of an electrode coating should be evaluated across the full preparation and use pathway. Relevant factors include feedstock collection, cleaning, drying, thermal treatment, grinding, energy consumption, binder requirements, worker exposure, storage stability and waste generation.

An agricultural residue may be inexpensive at the point of collection but costly to process into a consistent industrial material. Therefore, a techno-economic and environmental assessment should accompany the welding-performance study before claims of lower cost or environmental superiority are made.

## VIII. Emerging Computational Approaches to Crack Prediction

### 8.1 Limitations of conventional prediction methods

Conventional crack assessment often relies on empirical relationships involving carbon equivalent, hardness, diffusible hydrogen and welding conditions. These indicators are valuable, but they do not necessarily represent the interactions among material composition, local cooling history, residual stress and consumable chemistry.

The underwater-specific carbon-equivalent model developed by Vaccari *et al.* (2025) illustrates progress towards improved prediction. However, the model was developed from a defined experimental dataset, and its generalisability to different materials, depths and welding procedures remains an important validation question.

A more comprehensive framework should integrate metallurgical indicators with process variables and measured crack outcomes.

### 8.2 Machine learning applications

Machine learning (ML) could help identify nonlinear relationships between welding conditions and crack susceptibility. Potential input variables include:

- Base-metal chemical composition and carbon equivalent.
- Electrode-coating composition and measured diffusible hydrogen.
- Welding current, voltage, travel speed and estimated heat input.
- Water depth, pressure, temperature and flow conditions.
- HAZ hardness, microstructural descriptors and residual-stress indicators.
- Joint geometry, restraint and welding position.

Possible prediction targets include crack occurrence, crack density, crack dimensions or a clearly defined

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susceptibility class. Continuous prediction of crack dimensions should be distinguished from binary classification of whether a crack occurs.

Suitable algorithms may include random forests, gradient-boosting models and interpretable regression methods. More complex neural networks may be appropriate if sufficiently large and representative datasets become available. The choice of algorithm should follow data quality and the intended engineering application rather than a presumption that a more complex model will perform better.

### 8.3 Data quality and validation

The main challenge is likely to be the quality and comparability of the underlying data. Studies differ in steel grades, electrode systems, water depths, welding procedures, hydrogen-measurement techniques, hardness scales and definitions of cracking.

Combining these data without harmonisation could produce misleading predictions. A model may appear highly accurate because samples from the same experimental campaign occur in both its training and test datasets.

A credible research framework should therefore:

1. Define standardised crack outcomes and measurement protocols.
2. Record the complete welding procedure and relevant material characteristics.
3. Separate training and testing by experimental campaign, material batch or welding condition where appropriate.
4. Report sensitivity, specificity, precision, recall and uncertainty alongside overall predictive accuracy.
5. Compare ML predictions with established metallurgical models.
6. Validate the final model using independent experimental data.

Machine learning should complement metallurgical understanding, not replace it. Predictions must remain physically interpretable enough to support welding-procedure decisions and safety-critical engineering assessments.

## IX. Research Gaps and Future Directions

Despite advances in consumable design, hydrogen measurement, thermal management and weld characterisation, several issues remain unresolved.

### 9.1 Integrated crack-susceptibility models

A major gap is the limited integration of hydrogen concentration, local microstructure, residual stress and crack initiation into a unified predictive framework. Carbon equivalent and hardness provide useful indicators, but neither independently establishes whether a particular joint will crack.

Future models should combine experimental measurements with thermal and mechanical simulations. Their predictions should be validated against observed crack locations, dimensions and delayed-cracking behaviour.

### 9.2 Delayed-crack development

The timing of hydrogen-assisted cracking varies with material, hydrogen distribution, stress and environmental conditions. Further research should examine crack development over controlled post-welding intervals and establish how delayed inspection requirements should vary with material susceptibility and welding procedure.

This would improve the interpretation of experimental results and provide stronger evidence for inspection planning.

### 9.3 Sustainable underwater electrode coatings

The use of agro-waste-derived constituents represents a promising but insufficiently validated research direction. Future investigations should establish which material characteristics influence coating performance, whether hydrogen levels can be reduced, and how the additions affect slag formation, weld-metal chemistry and mechanical integrity.

A particularly important gap is the lack of evidence, within the literature reviewed for this article, sufficient to conclude that agro-waste-derived coatings consistently reduce underwater weld cracking. This is an opportunity for controlled comparative experimentation rather than a result that can be assumed in advance.

### 9.4 Effects of water depth and flow

Water depth and flow affect the physical environment of wet welding, but their influence on cracking cannot be separated from changes in consumables, process stability and heat transfer.

Future experiments should systematically vary depth and flow while controlling the base metal, electrode formulation and welding parameters. This would allow the direct effects of the environment to be distinguished from other factors.

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### 9.5 Inspection and defect characterisation

There remains a need to correlate nondestructive testing results with destructive examination and three-dimensional characterisation. Such work would help quantify the probability of detecting cracks of different sizes, orientations and locations.

Combining inspection data with metallography and hardness maps could also improve the reliability of crack classification and the development of training datasets for predictive models.

### 9.6 Long-term structural performance

A joint that passes an initial tensile test may still be vulnerable to fatigue, corrosion-assisted damage or delayed cracking. Future studies should evaluate the relationship between initial crack susceptibility and subsequent structural performance under representative marine loading and environmental conditions.

**Table 3: Priority research questions and proposed approaches**

| Research gap | Proposed approach | Expected contribution |
|---|---|---|
| Incomplete integration of crack factors | Couple thermal, metallurgical and mechanical models | More physically grounded susceptibility prediction |
| Uncertain delayed-crack behaviour | Time-dependent testing with scheduled inspections | Better understanding of crack initiation and inspection timing |
| Limited evidence on sustainable coatings | Controlled formulation experiments against conventional controls | Evidence-based assessment of agro-waste-derived consumables |
| Variable depth and flow effects | Factorial experiments under controlled environmental conditions | Better separation of environmental and process effects |
| Uncertain inspection sensitivity | Correlate NDT with sectioning and 3D imaging | More reliable defect detection and classification |
| Limited long-term validation | Fatigue, toughness and corrosion testing | Improved evidence for service suitability |
| Small or inconsistent datasets | Harmonised data collection and independent model validation | More generalisable crack-prediction tools |

## X. Implications for Industrial Practice

The literature indicates that cracking prevention should begin before welding rather than being treated solely as a post-weld inspection issue. Material selection, electrode choice, joint design, welding-procedure qualification and environmental conditions should be assessed together.

For high-strength steels and highly restrained repairs, the evaluation should pay particular attention to hydrogen-assisted cracking. Carbon-equivalent calculations and hardness measurements can support this assessment, but they should not be used as stand-alone acceptance criteria.

Welding consumables should be selected for the relevant material and application. Where a new electrode coating is proposed, its performance should be demonstrated through controlled tests covering hydrogen content, cracking incidence, porosity, mechanical properties and other relevant quality indicators.

Inspection should be matched to the anticipated defect types. Surface examination alone cannot exclude internal cracking, and immediate inspection may not reveal delayed hydrogen-assisted defects. The inspection plan should therefore follow the governing code, qualified procedure and project-specific risk assessment.

Finally, any proposed computational prediction system should be treated as a decision-support tool until it has been independently validated for the relevant materials, consumables and underwater conditions. Safety-critical acceptance decisions should remain within the applicable engineering qualification and inspection framework.

## XI. Conclusions

Cracking in underwater welded joints is governed by interacting metallurgical, thermal and mechanical factors. Hydrogen-assisted cold cracking is a particularly important concern in wet welding because hydrogen generated in the arc environment can enter the weld metal while rapid cooling promotes hard microstructures and residual tensile stresses. HAZ cracking and weld-metal cracking must be distinguished from solidification, crater and root cracking because their formation mechanisms and preventive measures differ.

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The evidence reviewed shows that diffusible hydrogen, local hardness, microstructure, steel composition, cooling history, restraint and welding consumables should be evaluated together. Conventional carbon-equivalent relationships remain useful screening tools, but they cannot independently establish crack susceptibility under underwater wet-welding conditions. Hydrogen-control consumables, hydrophobic electrode coatings, qualified welding parameters and appropriate thermal-management methods offer promising mitigation routes, although their effectiveness is procedure- and material-dependent.

Inspection is equally important. Visual examination cannot exclude internal defects, and delayed hydrogen-assisted cracking requires consideration of inspection timing. Complementary nondestructive testing, hardness mapping, metallography and advanced three-dimensional characterisation can improve defect identification and failure analysis.

Three research priorities emerge from this review: the development of integrated, experimentally validated crack-prediction models; the systematic evaluation of sustainable electrode coatings, including agro-waste-derived materials; and improved understanding of delayed cracking and long-term joint performance. In particular, sustainable coating development should be supported by reproducible control experiments and direct measurements rather than assumptions about the beneficial effects of agricultural residues.

Overall, more reliable underwater welded joints will require coordinated control of hydrogen, microstructure and stress, supported by qualified procedures, suitable inspection and independent validation of emerging technologies.

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