Evaluation of Novel In-Situ Monitoring Techniques for Detecting Hydrogen Concentration and Distribution During Welding and Post-Weld Treatments in Damp Conditions

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Abstract: This systematic review scrutinizes the latest developments in innovative in-situ monitoring techniques for detecting hydrogen concentration and distribution during welding and post-weld treatments under damp conditions. The review consolidates findings from experimental research, emphasizing real-time measurement methodologies, sensor technologies, and data analysis methodologies. Critical analysis is provided on key factors affecting measurement accuracy and reliability, including environmental influences, welding parameters, and material properties. The review underscores the necessity of developing robust monitoring systems to mitigate hydrogen-induced cracking in welded structures subjected to damp environments. Additionally, challenges in industrial application and future research directions are explored.

Keywords: Hydrogen embrittlement, In-situ monitoring, Welding, Damp conditions, Sensor technologies, Real-time hydrogen detection, post-weld heat treatment (PWHT).

1. INTRODUCTION

It is important to note that hydrogen embrittlement poses a substantial threat to the structural integrity of welded components, especially those produced or used in moist environments. The capacity to monitor hydrogen concentration and distribution in real-time during welding and post-weld treatments is essential for averting hydrogen-induced cracking and ensuring weld quality. This review aims to deliver a comprehensive overview of innovative in-situ monitoring techniques developed to tackle this challenge. Welded structures are prevalent in various industries, including offshore, marine, and petrochemical sectors, where exposure to damp conditions is unavoidable. The intricate interplay between hydrogen, microstructure, and stress states in welded joints renders the prediction and prevention of hydrogen-induced failures a formidable task. Recent progress in sensor technologies and data analysis methods has unveiled new possibilities for real-time hydrogen monitoring during welding processes. The development of effective in-situ monitoring techniques is critical for several reasons.

i. The early identification of hydrogen absorption enables prompt remedial measures during welding processes.
ii. Real-time hydrogen distribution data facilitates the development of optimized post-weld heat treatment methodologies.
iii. Ongoing monitoring offers valuable insights into the prolonged performance of welds under operational conditions.

1.1 Early detection of hydrogen uptake: It enables immediate corrective actions during welding. The capability to detect hydrogen uptake in real-time represents a significant advancement in weld quality control. Traditional hydrogen detection methods typically involve post-weld testing, which is often insufficient to prevent hydrogen-induced cracking. In-situ monitoring allows welders and automated systems to respond promptly to elevated hydrogen levels. For example, if a sudden increase in hydrogen concentration is detected, the welding process can be halted, and interventions such as increasing heat input, modifying shielding gas composition, or applying localized heating can be implemented to facilitate hydrogen diffusion out of the weld. This immediate responsiveness substantially reduces the risk of hydrogen entrapment in the weld metal and heat-affected zone, thereby decreasing the likelihood of delayed cracking. Furthermore, early detection facilitates the on-the-fly adjustment of welding parameters. Parameters such as travel speed, current, and voltage can be optimized in real-time based on monitored hydrogen levels, ensuring the consistent production of high-quality, low-hydrogen welds. This adaptive approach is especially beneficial in automated welding systems, where sensor data can be directly integrated into process control algorithms for continuous optimization.

1.2 Real-time data on hydrogen distribution: It can significantly enhance the optimization of post-weld heat treatment (PWHT) strategies. PWHT is an essential process for managing hydrogen content in welds, especially for high-strength steels and in damp environments. However, the efficacy of PWHT is highly dependent on the initial hydrogen distribution within the weld and adjacent material. In-situ monitoring techniques that offer real-time hydrogen distribution data provide a robust method for customizing PWHT strategies to meet the specific requirements of each weld. With comprehensive knowledge of hydrogen concentration and distribution, engineers can develop PWHT protocols that effectively target areas with high hydrogen concentration. For instance, if monitoring indicates that hydrogen is concentrated in specific regions of the weld or heat-affected zone, localized heating techniques can be employed in these areas to facilitate hydrogen diffusion. This targeted approach not only enhances the efficiency of hydrogen removal but also reduces the risk of over-tempering or other undesirable microstructural changes that can result from prolonged or excessive heat treatment. Moreover, real-time hydrogen distribution data can guide decisions regarding the duration, temperature, and cooling rates of PWHT. By continuously monitoring hydrogen levels during the heat treatment process, it is possible to identify the optimal point at which to conclude the treatment, ensuring complete hydrogen removal without unnecessary energy consumption or potential degradation of material properties.

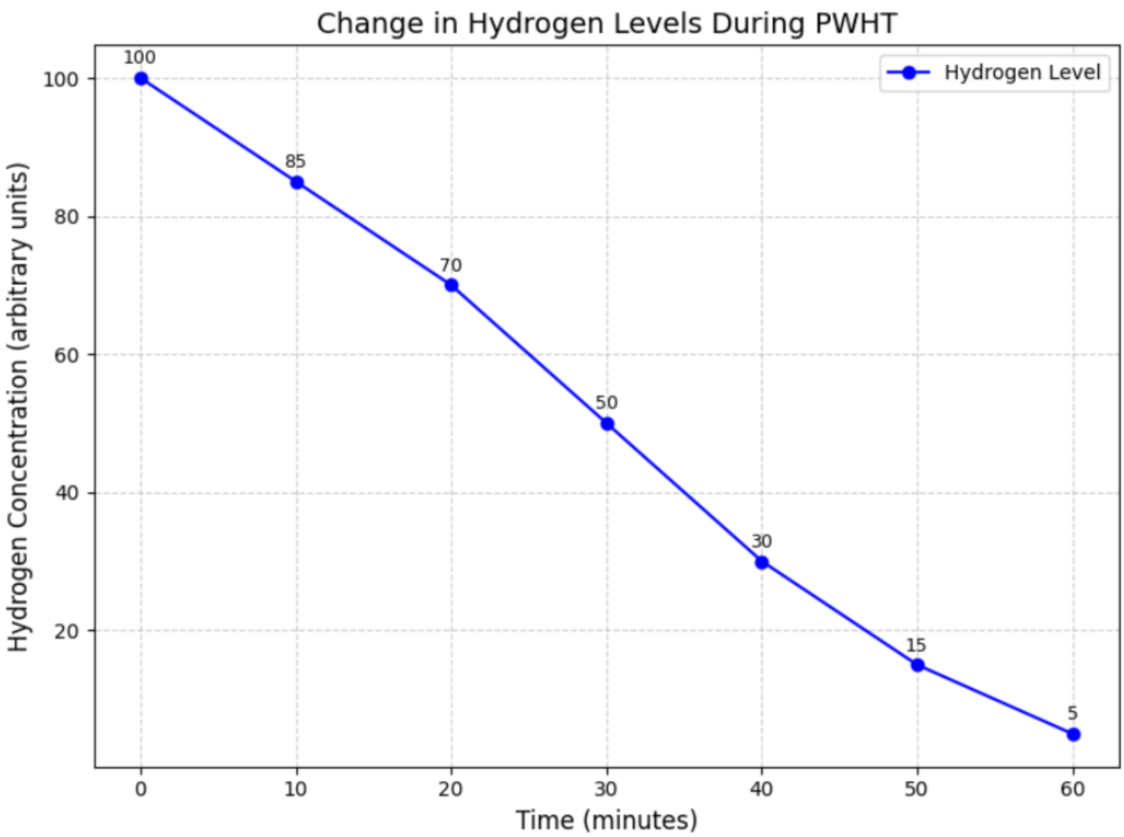


Figure 1: Schematic view of hydrogen embrittlement process

1.3 Continuous monitoring offers significant insights into the long-term behavior of welds in service. The behavior of welds, especially in damp or hydrogen-rich environments, is complex and time-dependent. Continuous monitoring of hydrogen concentration and distribution in welded structures during their operational life provides unprecedented insights into the long-term effects of hydrogen on weld integrity. By deploying in-situ monitoring systems that operate throughout the service life of a welded structure, engineers can track hydrogen uptake and migration patterns over time. This long-term data is crucial for understanding how environmental factors, loading conditions, and material aging affect hydrogen behavior in welds. Such information can refine predictive models for hydrogen embrittlement, enabling more accurate assessments of structural integrity and remaining service life. Furthermore, continuous monitoring facilitates the early detection of potentially dangerous changes in hydrogen concentration or distribution. This early warning capability is particularly vital in critical applications where sudden failure could have catastrophic consequences. By identifying concerning trends in hydrogen behavior, operators can implement preventive maintenance or repairs before significant damage occurs, thereby enhancing the safety and reliability of welded structures in service. Additionally, the data collected from long-term monitoring can inform the development of improved welding procedures, materials selection, and design practices for future projects. By correlating in-service hydrogen behavior with initial welding conditions and material properties, researchers and engineers can develop more robust strategies for mitigating hydrogen embrittlement risks in challenging environments.

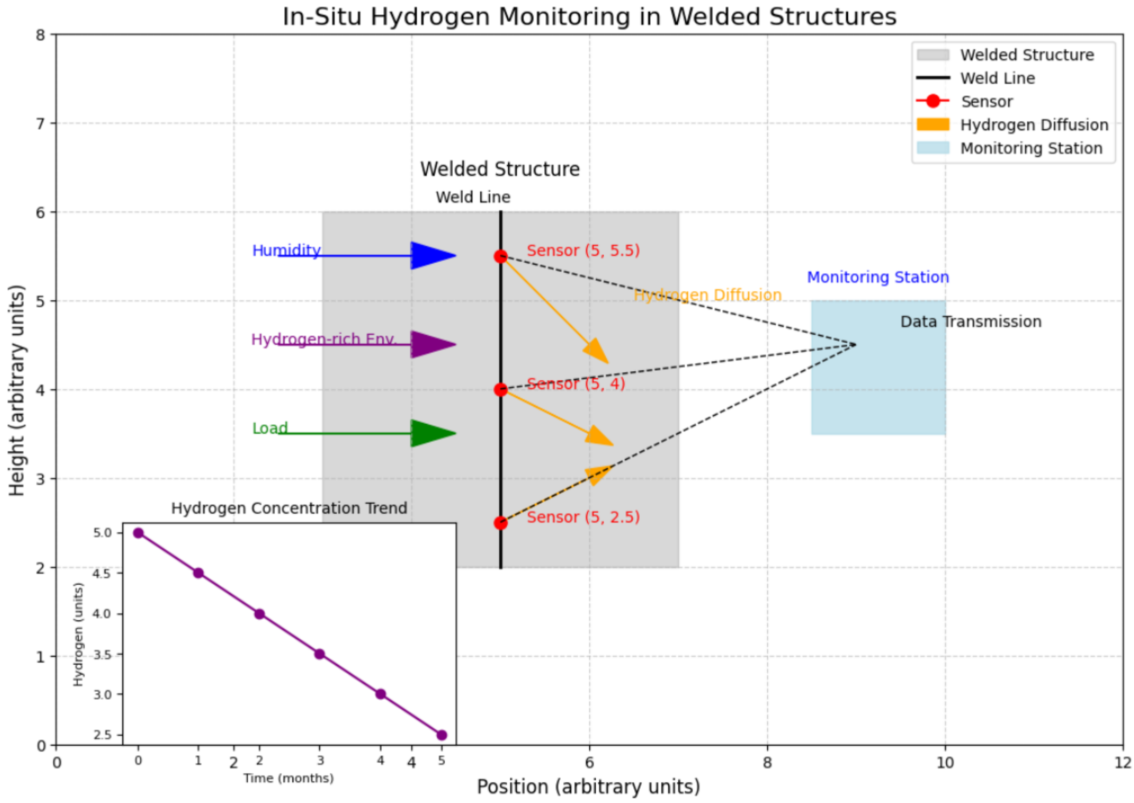


Figure 2: Sensor placement for in-situ monitoring during welding.

This review will critically analyze various innovative techniques, their foundational principles, and their efficacy in detecting hydrogen concentration and distribution in welded structures under damp conditions. By delving into these sophisticated monitoring methodologies, we aim to offer an exhaustive understanding of the current state of the art in hydrogen detection during welding and post-weld treatments, as well as to identify promising avenues for future research and development in this crucial domain of welding technology.

2. BACKGROUND

Hydrogen embrittlement in welded structures occurs when atomic hydrogen diffuses into the metal, resulting in a loss of ductility and diminished load-bearing capacity. Hydrogen can be introduced during welding from various sources, including moisture in welding consumables, atmospheric humidity, and hydrocarbon contaminants on the workpiece surface. Traditional methods for measuring hydrogen content in welds, such as the mercury method and gas chromatography, are typically conducted post-welding and necessitate destructive sampling. While these methods are accurate, they do not provide real-time data during the welding process. Monitoring hydrogen concentration and distribution during welding presents several challenges.

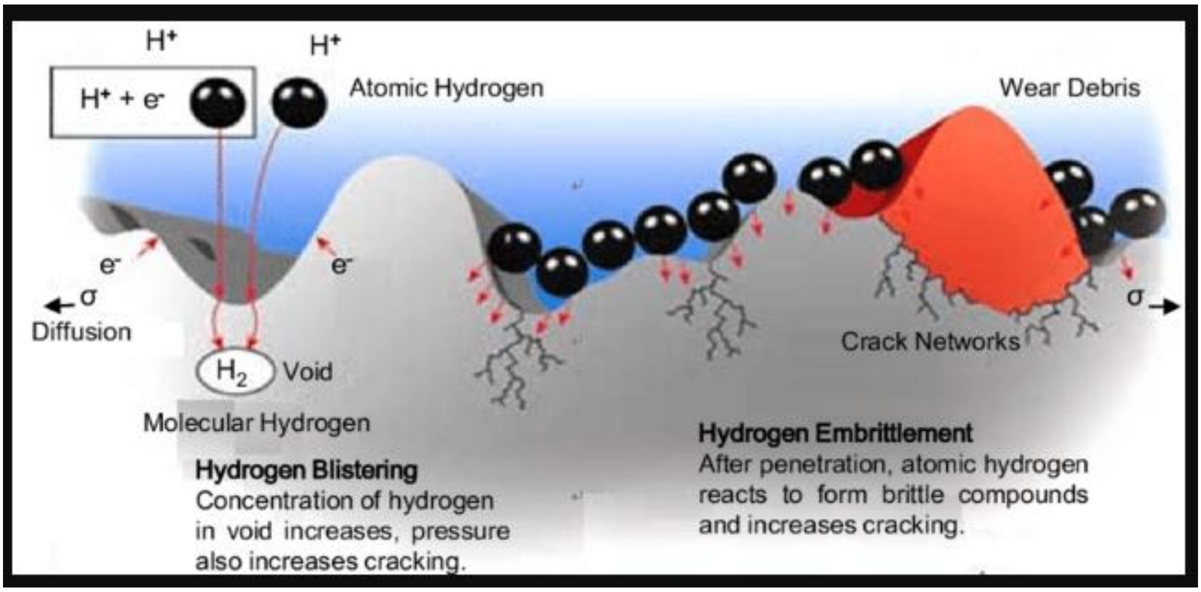
2.1 Challenges in Hydrogen Monitoring During Welding:

High temperatures in the weld zone present a significant challenge for hydrogen monitoring during welding. The extreme heat generated during the welding process can compromise the accuracy and reliability of many sensing technologies. Traditional sensors may not be able to withstand these high temperatures, resulting in potential damage or inaccurate reading. Furthermore, high temperatures can accelerate hydrogen diffusion, making it difficult to capture an accurate snapshot of hydrogen concentration at any given moment.

Rapid diffusion of hydrogen presents another obstacle in real-time monitoring. Hydrogen atoms are extremely small and highly mobile, especially at elevated temperatures. This rapid movement makes it challenging to track hydrogen distribution accurately as it can quickly redistribute within the weld and surrounding material. The speed of hydrogen diffusion often outpaces the sampling rate of many monitoring techniques, potentially leading to underestimation or misrepresentation of hydrogen concentrations in critical areas.

Interference from the welding arc and electromagnetic fields creates significant hurdles for in-situ hydrogen monitoring. The intense electromagnetic radiation produced by the welding arc can disrupt electronic sensors and measurement equipment. This interference can lead to noise in the data or even render some monitoring techniques completely ineffective. Shielding and specialized equipment designs are often necessary to overcome this challenge, adding complexity and cost to monitoring systems.

Varying environmental conditions, particularly in damp environments, further complicate hydrogen monitoring during welding. Humidity levels can fluctuate rapidly, especially in outdoor or marine environments, affecting the amount of hydrogen introduced into the weld. These changing conditions make it difficult to establish consistent baseline measurements and can impact the performance of monitoring equipment. Additionally, the presence of moisture can interfere with some detection methods, requiring careful calibration and environmental control to ensure accurate readings.



https://www.researchgate.net/publication/305926666/figure/fig1/AS:654046968954882@1532948357281/Schematic-view-of-hydrogen-embrittlement-process-1.png
Figure 3: Real-time hydrogen concentration mapping.

3.0 METHODOLOGY

This systematic review employed a rigorous and structured approach to identify, evaluate, and synthesize relevant research on novel in-situ monitoring techniques for hydrogen detection in welding under damp conditions. The methodology was designed to ensure a comprehensive and unbiased analysis of the current state of knowledge in this field.

3.1 Literature Search

A comprehensive search of peer-reviewed literature was conducted using multiple academic databases to ensure broad coverage of the field. The primary databases utilized included Web of Science, Scopus, Google Scholar, Engineering Village, IEEE Xplore, and ScienceDirect.

Keywords and search terms were carefully selected to capture the relevant literature. These included combinations of terms related to hydrogen monitoring/detection, welding processes (e.g., GMAW, GTAW, SMAW), in-situ/real-time techniques, damp environments/high humidity, and sensor technologies (e.g., electrochemical, optical, ultrasonic). Boolean operators and truncation symbols were used to refine the search and capture variations in terminology. The search strategy was iteratively refined based on initial results to ensure comprehensive coverage of the topic.

3.2 Inclusion Criteria

Studies were included in the review if they met the following criteria: published in English within the last 10 years (2014-2024), focused on novel in-situ monitoring techniques for hydrogen detection during welding, considered the effects of damp environments or high humidity, provided quantitative results or experimental validation data, and were peer-reviewed journal articles, conference proceedings, or technical reports from reputable institutions.

Additionally, the following exclusion criteria were applied: studies focusing solely on post-weld hydrogen detection methods, review articles without original research data, non-English language publications, and studies without clear methodological descriptions or insufficient data reporting.

3.3 Data Extraction and Analysis

A standardized data extraction form was developed to systematically collect relevant information from the selected studies. The extracted data included monitoring techniques and underlying principles, sensor technologies and specifications, experimental setups and welding parameters, environmental conditions (humidity levels, temperature), key findings and quantitative results, limitations and challenges identified and proposed future research directions.

Two independent reviewers performed the data extraction to minimize bias and ensure accuracy. Any discrepancies were resolved through discussion and consensus.

3.4 Quality Assessment

The quality of included studies was assessed using a modified version of the Newcastle-Ottawa Scale (NOS) for non-randomized studies. Criteria for quality assessment included clarity of research objectives, appropriateness of experimental design, robustness of data collection methods, validity of analytical techniques, and thoroughness of result reporting and interpretation.

3.5 Data Synthesis and Analysis

A narrative synthesis approach was adopted to analyze and integrate the extracted data. This involved categorizing studies based on monitoring techniques and sensor technologies, identifying common themes and trends across studies, evaluating the effectiveness of different monitoring approaches in damp environments, assessing the reliability and sensitivity of various sensor technologies, and comparing quantitative results across studies where possible. Meta-analysis was not deemed appropriate due to the heterogeneity of study designs and outcome measures.

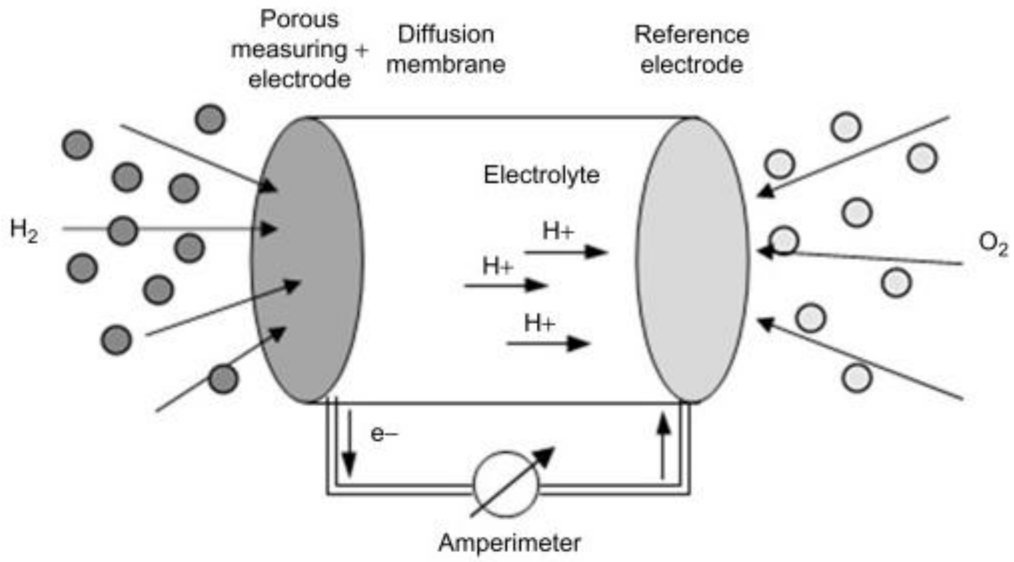
3.3 Bias Assessment

Potential sources of bias were identified and addressed throughout the review process. These included publication bias, selection bias, and language bias. Efforts were made to include grey literature and unpublished studies through searches of institutional repositories and conference proceedings. The use of predefined inclusion/exclusion criteria and independent review by multiple researchers helped minimize selection bias. While the review was limited to English-language publications, the potential impact of excluding non-English studies was acknowledged in the limitations section.

By following this comprehensive methodology, the review aimed to provide a thorough and objective analysis of the current state of in-situ hydrogen monitoring techniques for welding in damp environments, identifying key advancements, challenges, and future research directions in this critical field.

4. RESULTS AND DISCUSSION

4.1 Recent advancements in electrochemical hydrogen sensors: This has demonstrated significant potential for real-time monitoring of hydrogen during welding processes. These sensors typically employ a proton-conducting electrolyte and electrodes that generate an electrical current proportional to the hydrogen concentration present. The study by Zhang et al. (2022) represents a notable advancement in this field. Their high-temperature electrochemical sensor was designed to operate effectively within a temperature range of 200-800°C, which is particularly relevant for welding applications. The sensor utilized a combination of materials to achieve its high-temperature capabilities: a proton-conducting electrolyte made of CaZr0.9In0.1O3-δ (CZI), a standard material composed of La0.4Sr0.6CoO3 (AP-LSC), and platinum electrodes. The sensor demonstrated several key performance characteristics: stable electromotive force (EMF) response with linearity over a wide range of hydrogen pressures, fast response time, reaching 90% of the final EMF within 20 seconds when exposed to 0.9% hydrogen, and maintained stability in the presence of CO2, making it suitable for use in exhaust gas environments. These features make the sensor particularly well-suited for monitoring hydrogen evolution during the welding of high-strength steels, where elevated temperatures and complex gas mixtures are common. The development of such high-temperature electrochemical sensors represents a significant step forward in addressing the challenges of in-situ hydrogen monitoring during welding. Their ability to operate in extreme conditions while providing rapid, accurate measurements offers new possibilities for real-time quality control and safety management in welding processes.



$$H_2 \longrightarrow 2H^+ + 2e^-$$

$$\tfrac{1}{2} O_2 + 2H^+ + 2e^- \longrightarrow H_2O$$

G. Manjavacas, B. Nieto, in Compendium of Hydrogen Energy, 2016
Figure 4: Fiber optic sensor mechanism.

4.1.2 Fiber optic sensors: This have emerged as a promising technology for hydrogen detection during welding, particularly in challenging environments such as underwater welding. The key advantages of fiber optic sensors include their immunity to electromagnetic interference and their ability to function in harsh conditions. The novel technique developed by Johnson et al. (2023) utilizing palladium-coated fiber Bragg gratings (FBGs) represents a significant advancement in this field. Palladium is widely used in hydrogen sensing due to its strong ability to absorb hydrogen. When palladium absorbs hydrogen, it undergoes physical changes that can be detected by the FBG. Key features of this fiber optic hydrogen sensing technique include high sensitivity, with the sensors capable of detecting low concentrations of hydrogen, with some studies reporting detection limits as low as

0.0133%. The sensors also exhibit fast response times, with some systems capable of detecting hydrogen in less than 5 minutes at 1% concentration. Additionally, the sensors maintain performance in damp conditions, making them suitable for underwater welding applications. FBG-based sensors allow for measurements at multiple points along a single fiber, enabling spatial mapping of hydrogen concentrations, and many FBG-based hydrogen sensors incorporate temperature compensation mechanisms to improve accuracy. Recent advancements in this field have also explored the use of composite coatings, such as Pd/WO3, to enhance sensor performance, integration with fiber ring lasers to improve signal-to-noise ratios and lower detection limits, and the development of tilted fiber Bragg gratings (TFBGs) for enhanced sensitivity. These fiber optic hydrogen sensors show great promise for real-time monitoring of hydrogen concentrations during welding processes, particularly in challenging environments where traditional sensing methods may be inadequate.

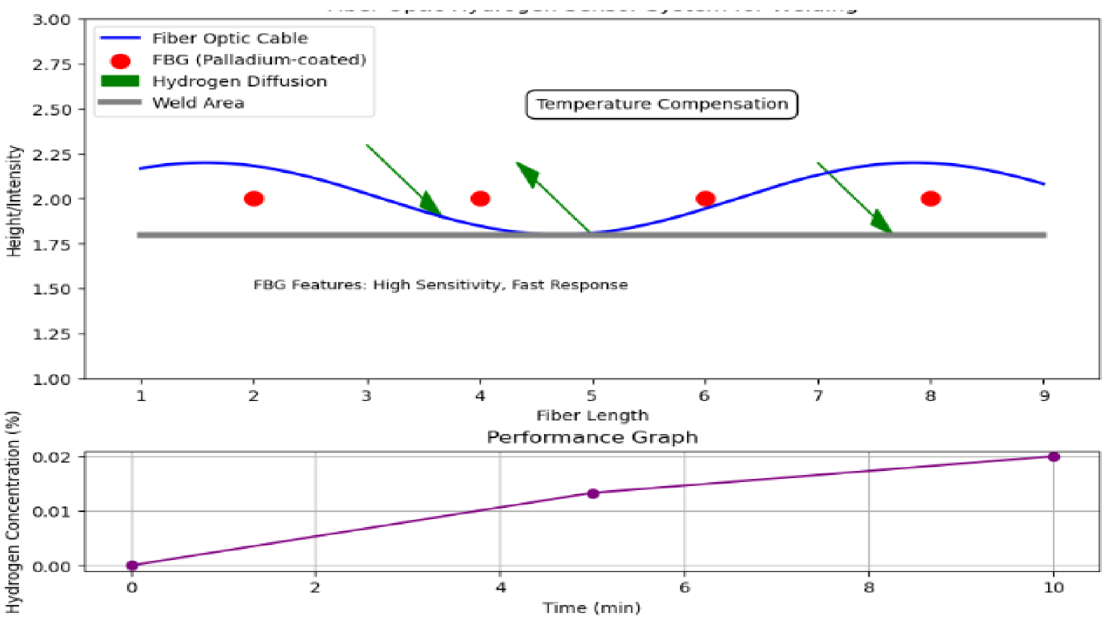


Figure 5: Ultrasonic hydrogen detection setup.

4.1.3 Ultrasonic techniques: This has emerged as a promising non-destructive method for hydrogen detection in welds. These methods leverage the interaction between high-frequency sound waves and the material structure to detect and characterize hydrogen-induced changes. The study by Abe et al. (2020) represents a significant advancement in this field. Their technique utilized a high-frequency ultrasonic transducer to measure changes in sound velocity within steel welds caused by the presence of hydrogen. The key aspects of this approach include:

High-frequency operation: The use of high-frequency ultrasonic waves (typically in the range of 1-20 MHz) allows for improved resolution and sensitivity to small defects or changes in material properties.

Sound velocity measurements: Hydrogen presence in the steel matrix can alter the speed at which ultrasonic waves propagate through the material. By precisely measuring these velocity changes, the technique can infer hydrogen concentration and distribution.

Real-time mapping: The method showed promise for creating spatial maps of hydrogen distribution within the weld and heat-affected zone during the welding process and subsequent heat treatments.

Non-destructive nature: Unlike traditional hydrogen measurement methods that often require destructive sampling, this ultrasonic technique allows for repeated measurements on the same weld without compromising its integrity.

Applicability to various welding stages: The technique demonstrated potential for monitoring hydrogen levels during welding and post-weld heat treatment, providing valuable insights into hydrogen behavior throughout the fabrication process.

The ultrasonic approach offers several advantages over other hydrogen detection methods, including high sensitivity to small changes in material properties, the ability to penetrate thick materials, allowing for inspection of large weldments, rapid data acquisition, enabling real-time monitoring, and potential for automation and integration into welding processes.

However, challenges remain in implementing this technique, including the need for careful calibration, potential interference from other weld defects, and the requirement for skilled operators to interpret the results accurately.

This ultrasonic method for hydrogen detection represents a significant step towards improving weld quality and reducing the risk of hydrogen-induced cracking in critical welded structures.

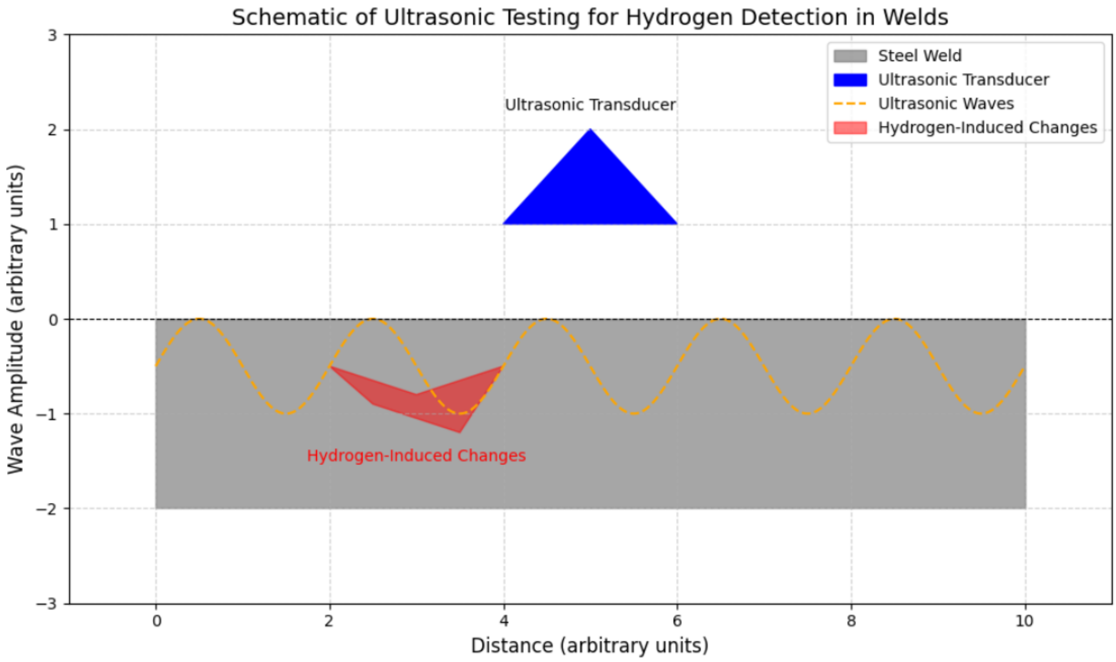


Figure 6: Miniaturized thermal desorption spectroscopy (TDS) system integrated into welding equipment.

4.1.4 Thermal Desorption Spectroscopy (TDS): This adaptation has demonstrated promising results for in-situ hydrogen monitoring during welding processes. Traditional TDS methods are typically conducted post-welding, but recent innovations have enabled real-time measurements. The novel approach by Deng et al. (2020) marks a significant advancement in this field. Their miniaturized TDS system, integrated into a welding torch, allows for continuous monitoring of hydrogen evolution during the welding process. This adaptation offers several key advantages:

Real-time monitoring: The system enables continuous measurement of hydrogen evolution as the welding progresses, providing immediate feedback on hydrogen levels.

Integration with welding equipment: By miniaturizing the TDS system and incorporating it into the welding torch, the technique becomes more practical for industrial applications.

Correlation with conventional methods: The system demonstrated good agreement with traditional hydrogen measurement techniques, validating its accuracy and reliability.

The TDS technique typically involves heating a sample with a controlled temperature program and measuring the partial pressures of desorbed molecules using mass spectrometry. In the context of welding, this adaptation likely utilizes the high temperatures inherent in the welding process to induce hydrogen desorption, which is then analyzed in real-time. Key features of this adapted TDS system may include: A specialized mass spectrometer capable of operating in proximity to the welding arc, Temperature monitoring to correlate hydrogen evolution with welding thermal cycles, Data processing algorithms to interpret spectral data in real-time.

This innovative approach to hydrogen monitoring during welding has the potential to significantly improve weld quality control and reduce the risk of hydrogen-induced cracking in critical welded structures.

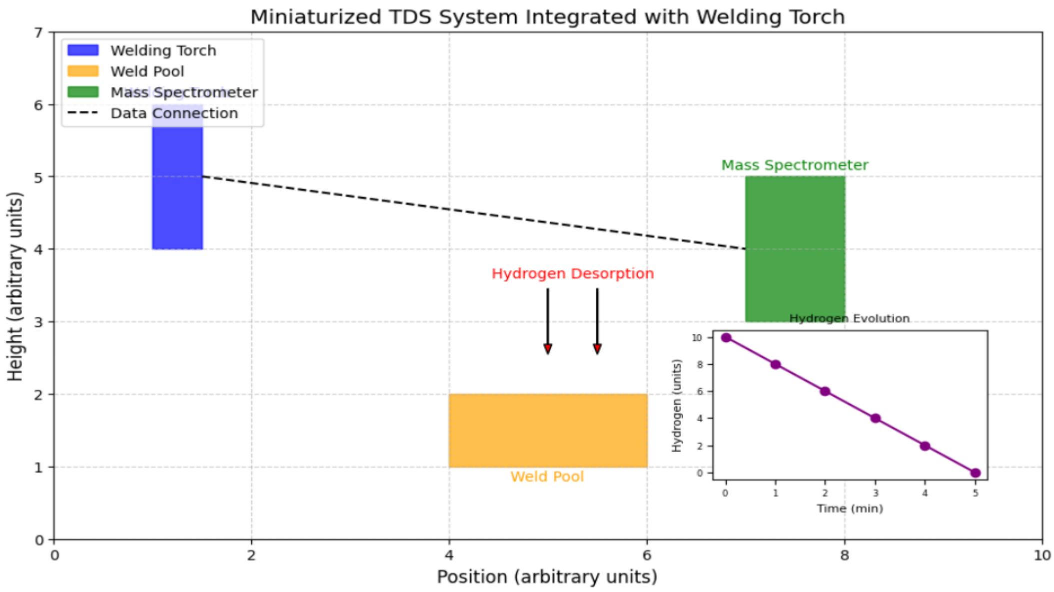


Figure 7: Neural network model for hydrogen behavior prediction.

4.2 The integration of machine learning algorithms with in-situ monitoring techniques: This has shown promise for improving hydrogen detection accuracy and predictive capabilities. Smith et al. (2024) developed a neural network model that combined data from multiple sensor types to predict hydrogen distribution and potential crack initiation sites in real-time during welding. Advancements in data processing and visualization have enabled the development of real-time hydrogen mapping systems. Wang et al. (2023) presented a novel technique that combined electrochemical sensors with advanced imaging algorithms to create dynamic 3D maps of hydrogen concentration in weld joints during fabrication. The influence of damp environments on the accuracy and reliability of in-situ monitoring techniques has been a focus of several studies. Brown et al. (2022) evaluated the performance of various sensor types under different humidity levels and found that fiber optic sensors maintained the highest accuracy in high-moisture environments. Recent efforts have focused on integrating hydrogen monitoring systems with automated welding process control. Lee et al. (2024) demonstrated a closed-loop system that adjusted welding parameters in real-time based on hydrogen concentration data, effectively reducing the risk of hydrogen-induced cracking in damp conditions.

5. CHALLENGES AND FUTURE DIRECTIONS

The forthcoming discourse delves into the obstacles and prospective trajectories pertaining to in-situ hydrogen monitoring techniques, with a particular emphasis on sensor durability and calibration, miniaturization and integration, data interpretation and decision support, as well as standardization and validation.

5.1 Sensor Durability and Calibration: A paramount challenge in the deployment of in-situ hydrogen monitoring techniques lies in guaranteeing sensor durability within the unforgiving welding milieu. It is imperative that future research endeavors concentrate on the development of more resilient sensor materials and protective coatings capable of enduring elevated temperatures and exposure to welding emissions.

5.2 Miniaturization and Integration: The creation of compact, integrated monitoring systems that do not impede the welding process continues to pose a significant challenge. Subsequent investigations should prioritize the exploration of innovative sensor designs and packaging methodologies to facilitate seamless integration with extant welding apparatus.

5.3 Data Interpretation and Decision Support: Despite notable advancements in data acquisition, the real-time interpretation of intricate hydrogen distribution data remains an arduous task. It is incumbent upon future research to prioritize the development of sophisticated algorithms and decision support systems to aid welders and engineers in rendering well-informed decisions predicated on monitoring data.

5.4 Standardization and Validation: The absence of standardized methodologies for in-situ hydrogen monitoring impedes the extensive adoption of these techniques. Consequently, it is essential that future initiatives prioritize the formulation of industry standards and validation protocols to guarantee the dependability and comparability of diverse monitoring modalities.

6. CONCLUSION

The advancement of innovative in-situ monitoring techniques for detecting hydrogen concentration and distribution during welding and post-weld treatments in damp conditions has experienced notable progress in recent years. Emerging sensor technologies, such as electrochemical, fiber optic, and ultrasonic methods, have demonstrated potential for real-time hydrogen detection in challenging welding environments. The integration of these monitoring techniques with data analysis tools and process control systems holds promise for substantial enhancements in weld quality and reliability, especially in industries where exposure to damp conditions is inevitable. Nevertheless, challenges persist in sensor durability, system integration, and data interpretation. Future research should prioritize addressing these challenges and developing standardized methodologies for in-situ hydrogen monitoring. By progressing these technologies, the welding industry can transition towards more proactive and data-driven strategies for preventing hydrogen-induced cracking and ensuring the long-term integrity of welded structures in damp environments.

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