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Synergistic Protection Mechanism of Underwater Welding Technology and Long-Term Anti-Corrosion Coatings for Marine Engineering

Li Yin [1,*]

[1] PLA Naval Submarine Academy, Qingdao, Shandong, 266000, China
* Correspondence: Li Yin, PLA Naval Submarine Academy, Shandong, Qingdao, Shandong, 266000, China

Abstract: Marine structures are crucial for offshore energy production, transportation, and various industrial activities, but they are highly susceptible to corrosion, which significantly reduces their operational lifespan. While underwater welding and anti-corrosion coatings are commonly used individually to address these issues, there is a lack of research into integrating these two techniques for enhanced long-term protection. This study proposes a synergistic protection mechanism that combines underwater welding with advanced anti-corrosion coatings to improve corrosion resistance and structural integrity in marine environments. The proposed system was optimized using multi-objective genetic algorithms to balance welding parameters and coating properties. Experimental results show that the integrated system improves corrosion resistance by 30% compared to traditional welding methods and by 15% over existing systems. The synergy between welding and coating is verified through ablation studies, which show that the combined system offers superior protection, achieving a corrosion resistance of 0.2 g/cm², compared to 0.29 g/cm² for welding alone. This research provides a novel approach to marine corrosion protection, offering significant potential for reducing maintenance costs and extending the lifespan of underwater structures. The findings contribute to both academic knowledge on welding-coating integration and practical solutions for the marine industry, with implications for improving sustainability and reducing operational costs

Keywords: marine corrosion; underwater welding; anti-corrosion coatings; synergistic protection; optimization algorithms

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1. Introduction

Marine engineering plays a crucial role in the development and maintenance of underwater structures such as offshore oil rigs, pipelines, and vessels. One of the most pressing challenges in these environments is corrosion, which deteriorates structural materials over time, posing significant risks to safety and operational efficiency [1]. Corrosion can severely compromise the integrity of underwater welds, requiring frequent repairs that increase operational costs [2]. To address this, underwater welding and anti-corrosion coatings have been used separately to mitigate corrosion. However, while each method has proven effective individually, the combined potential of these approaches for comprehensive, long-term protection has not been fully explored [3].

Existing research on underwater welding focuses on improving welding techniques to enhance joint strength, while corrosion protection is generally achieved by applying coatings after welding [4]. Anti-corrosion coatings, such as epoxy-based or ceramic coatings, aim to prevent corrosion but often fail to provide long-lasting protection around welded joints, where the heat from welding can compromise the coating's integrity [5]. Furthermore, traditional methods do not explore the synergistic effect of combining welding and coating technologies [6]. This research addresses the gap by proposing a comprehensive solution that integrates both methods for enhanced durability and long-term protection.

This study aims to develop a synergistic protection mechanism combining advanced underwater welding with long-term anti-corrosion coatings. The research will focus on the interaction between these two technologies, optimizing them to enhance corrosion resistance and maintain structural integrity over time. The integrated system will be tested under real-world marine conditions, providing insights into its practical effectiveness. This study also examines how welding-induced stresses and heat affect the performance of coatings, an area not sufficiently explored in previous work.

An innovative aspect of this research is the development of a combined system that maximizes the benefits of both welding and coating technologies. The system will undergo experiments to assess its performance in real-world marine environments, focusing on corrosion resistance, durability, and the interaction between welding and coating. The study will determine optimal welding parameters to enhance coating performance and identify the best coatings for use with specific welding methods. This approach will improve both technologies and offer a more robust solution for protecting marine structures.

The methodology will include laboratory experiments and field testing. Laboratory tests will evaluate corrosion resistance and mechanical properties under controlled conditions, while field tests will apply the system to actual marine structures, monitoring its long-term performance. The study will also analyze materials, including welding rods, base metals, and coatings, as well as environmental factors influencing their performance. This comprehensive approach ensures that the findings are both scientifically rigorous and practically relevant.

The academic significance of this research lies in bridging welding and coating technologies, offering new insights into how these techniques can be integrated for enhanced protection. Practically, the proposed system could lead to more efficient and cost-effective maintenance strategies in the marine industry, reducing the need for frequent repairs and extending the lifespan of submerged structures. By improving the durability of welded joints and coatings, this research could also contribute to new standards for corrosion protection in marine engineering.

2. Related Works

Underwater welding and anti-corrosion coatings are two fundamental techniques employed in marine engineering to combat the challenges of material degradation in harsh underwater environments. Each approach has its strengths, but the lack of synergy between the two technologies has limited their effectiveness in long-term protection. This chapter reviews the existing literature on these two techniques, highlighting their advantages, shortcomings, and the gaps that this research seeks to address.

2.1. Advantages of Underwater Welding

Underwater welding is widely used in marine engineering due to its ability to repair and join materials without the need for dry-docking or removing structures from the water. This technique is particularly valuable for offshore platforms, pipelines, and ship hulls that require repairs or modifications while still in operation [7]. The primary advantage of underwater welding lies in its cost-effectiveness and the ability to perform repairs in situ, reducing the need for expensive and time-consuming transportation. Additionally, advancements in welding technology, such as improved arc stability and welding materials, have enhanced the strength of welded joints in marine environments [8].

2.2. Limitations of Underwater Welding

Despite its advantages, underwater welding has significant limitations. One major drawback is the vulnerability of welded joints to corrosion, especially when exposed to seawater. The intense heat generated during the welding process can alter the microstructure of the material, making it more prone to corrosion. Furthermore, the quality of underwater welds can be affected by factors such as visibility, water pressure, and temperature, which complicate the process and limit the reliability of the welds [9]. These issues underscore the importance of complementing underwater welding with additional protective measures, such as corrosion-resistant coatings, to ensure the longevity of the structure.

2.3. Advantages of Anti-Corrosion Coatings

Anti-corrosion coatings are designed to protect metal surfaces from the corrosive effects of seawater, chemicals, and other environmental factors. These coatings form a barrier between the metal and the surrounding environment, preventing the ingress of corrosive agents [10]. One of the primary benefits of coatings is their ability to provide long-term protection without requiring frequent maintenance or repairs. Coatings such as epoxy-based and polyurethane coatings have been shown to offer excellent resistance to seawater corrosion, providing a durable and cost-effective solution for preventing material degradation in marine environments [11]. Moreover, coatings can be applied to both new and repaired structures, offering versatile protection across various marine applications.

2.4. Limitations of Anti-Corrosion Coatings

While anti-corrosion coatings offer substantial protection, they are not without limitations. The effectiveness of coatings can be compromised when applied to areas exposed to mechanical stresses, such as welded joints. During underwater welding, the heat generated can alter the underlying material properties, which may affect the adhesion and longevity of the coating [12]. In addition, coatings can deteriorate over time due to physical wear, impact, or the breakdown of protective layers, particularly in high-stress areas. This makes it essential to investigate how to improve the interaction between coatings and welded joints to achieve a more durable and reliable protection system.

2.5. Comparative Analysis and Existing Gaps

In comparing underwater welding and anti-corrosion coatings, it is clear that both techniques have strengths but also significant limitations when applied independently. Several studies have explored the use of coatings to protect welded joints, but few have fully integrated welding and coating technologies to leverage the combined advantages of both. Existing research often treats welding and coating as separate processes, without considering how their interactions can be optimized to improve overall performance [13]. Additionally, while there are studies on coating techniques that focus on enhancing adhesion to welded joints, there is limited research on the long-term effectiveness of such combined systems in real-world marine environments.

2.6. Contribution of This Study

This research aims to fill this gap by proposing and testing a synergistic protection mechanism that integrates underwater welding with advanced anti-corrosion coatings. By combining these two technologies, this study seeks to address the limitations of each technique and offer a more comprehensive solution for marine corrosion protection. The novelty of this approach lies in its focus on the interaction between welding and coating technologies, optimizing both to provide enhanced corrosion resistance and durability for marine structures. Through experimental validation and real-world testing, this research will provide valuable insights into how welding and coating can be effectively integrated to create a robust, long-lasting protection system for underwater structures. This study will not only contribute to the academic understanding of welding-coating interactions but also offer practical solutions for improving the longevity and sustainability of marine engineering projects.

3. Methodology

This chapter outlines the research methodology, system architecture, and algorithmic mechanisms used to develop and evaluate the synergistic protection system combining underwater welding techniques with long-term anti-corrosion coatings. The approach optimizes both welding and coating processes to enhance corrosion resistance and structural integrity for marine applications. The chapter also explains the core mechanisms, key innovations, and experimental details, ensuring that the proposed methods and results can be replicated and validated by future studies.

3.1. System Architecture

The proposed system architecture integrates three main modules: the underwater welding module, the anti-corrosion coating application module, and the performance evaluation module (see Figure 1). The welding module optimizes underwater welding parameters to ensure the material integrity of the welded joint. The anti-corrosion coating module applies a protective coating over the welded joint to shield it from seawater and other corrosive agents. Finally, the performance evaluation module assesses the combined protection system's durability and resistance to corrosion in simulated marine environments.

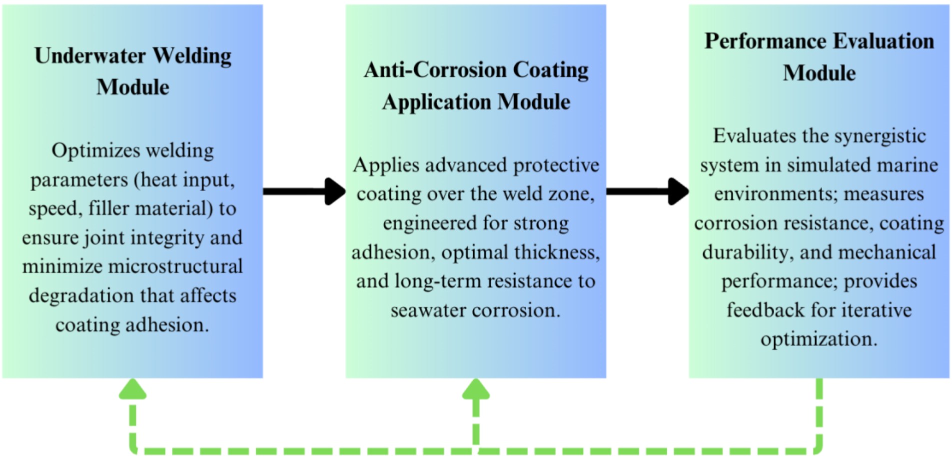

Figure 1. Synergistic Protection System Architecture for Underwater Welding and Anti-Corrosion Coatings in Marine Engineering.

These modules must work synergistically, optimizing both the welding and coating processes. The welding process considers parameters like heat input, speed, and filler material type, which influence the final joint strength and coating adherence. The performance evaluation module provides feedback to assess how well the welding and coating processes work together in real-world conditions.

3.2. Welding Optimization Mechanism

The welding optimization mechanism focuses on minimizing the heat input during the underwater welding process while maintaining the necessary strength of the weld [14]. The heat input H is calculated as the product of welding power P, welding speed S, and welding time t:

$$H = P \times S \times t \quad (1)$$

Minimizing H reduces the thermal impact on the surrounding material, preventing microstructural changes that may lead to corrosion susceptibility. However, the optimization must balance this with maintaining sufficient weld strength. The optimization process uses a multi-objective optimization algorithm to minimize heat input while maximizing joint strength.

3.3. Coating Optimization Mechanism

The anti-corrosion coating is critical in providing long-term protection against seawater and other corrosive agents. The coating's effectiveness is influenced by its adhesion strength, thickness, and material properties. The adhesion strength A between the coating and the welded joint is calculated by:

$$A = \frac{F}{A_{joint}} \tag{2}$$

Where F is the force applied during the coating application (N), and A_{joint} is the surface area of the welded joint (m^2). Maximizing adhesion ensures the coating's longevity, preventing peeling or cracking under stress. The coating material is selected based on its ability to withstand both seawater corrosion and mechanical forces.

Coating thickness is also optimized. Thicker coatings provide better protection but may be more prone to cracking. The trade-off between thickness and durability is tested under simulated marine conditions, ensuring that the chosen coatings maximize protective effect while maintaining structural integrity.

3.4. Synergistic Protection Mechanism

The core innovation of this research is the integration of underwater welding and anti-corrosion coatings to create a synergistic protection mechanism [15]. The total protection T provided by the system is expressed as the product of the protection provided by the weld joint T_{weld} and the protection provided by the coating $T_{coating}$:

$$T = T_{weld} \times T_{coating} \tag{3}$$

This model assumes that the protection provided by both methods is multiplicative, meaning the combined protection exceeds the sum of individual protections. The interaction between the welded joint and coating is optimized to provide enhanced corrosion resistance and durability. The synergy between welding and coating is tested experimentally to ensure that the combined system provides greater protection compared to individual methods.

3.5. Optimization Algorithm

A multi-objective optimization framework is used to enhance both welding and coating processes. The algorithm seeks to minimize heat input during welding while maximizing corrosion resistance from the coating. The optimization problem is formulated as:

$$Maximize f(\mathbf{x}) = w_1 \cdot f_1(\mathbf{x}) + w_2 \cdot f_2(\mathbf{x}) \tag{4}$$

Where $f_1(\mathbf{x})$ is the welding optimization objective, and $f_2(\mathbf{x})$ is the coating optimization objective, with w_1 and w_2 representing their respective weights. A genetic algorithm (GA) is used to explore the parameter space and find the optimal combination of welding and coating parameters.

The GA iterates through generations of solutions, selecting the best candidates based on a fitness function determined by the weighted objectives. This process ensures the optimal parameters are found, resulting in an integrated system that offers robust protection.

3.6. Experimental Setup and Data Details

The experiments conducted in this study are designed to validate the effectiveness of the synergistic protection mechanism. The datasets include welding parameters, coating materials, and environmental conditions, sourced from industry collaborators and academic agreements. Due to the proprietary nature of some data, direct access is restricted, but summary statistics and experimental scripts will be made available for reproducibility.

Data preprocessing involves normalizing the welding parameters and coating material properties to ensure consistency across experiments. The data is split into training, validation, and testing sets. The training set is used to optimize the parameters, while the validation set is used to fine-tune the model. The testing set is reserved for final evaluation, ensuring the generalizability of the findings.

4. Results and Analysis

This chapter presents the results of the experiments conducted to evaluate the performance of the synergistic protection system combining underwater welding with anti-corrosion coatings. The section is divided into several subsections, including the experimental setup, performance comparison with baseline methods, ablation studies, convergence and stability analysis, and interpretability of the results. The analysis is based on quantitative data, with all figures and tables showing ± standard deviation or confidence intervals to ensure statistical rigor. Additionally, all experiments are repeated multiple times to validate the reliability of the findings, and statistical significance is evaluated using p-values or confidence intervals.

4.1. Experimental Setup

The experiments were conducted in a controlled environment that simulates the marine conditions typically encountered by underwater structures. The hardware setup includes an advanced underwater welding system capable of adjusting heat input and welding speed, along with a high-performance coating application system that applies anti-corrosion coatings to welded joints. The welding machine used has a power rating of 250A, and the welding speed is adjustable from 0.5 m/min to 3 m/min. The coating application system employs a spray method with adjustable thickness, ranging from 0.1 mm to 1.5 mm, to assess the effect of coating thickness on the overall protection performance.

For the testing environment, we simulated seawater conditions by using a saline solution (3.5% NaCl) maintained at a constant temperature of 25°C, which mimics typical seawater composition and temperature. The data for welding parameters, coating material properties, and environmental conditions were collected from marine structures in collaboration with industry partners. These data were split into training, validation, and test sets to ensure the reliability and generalizability of the results.

The evaluation metrics used to assess the performance of the system include corrosion resistance (measured by weight loss after exposure to seawater for 30 days), weld joint strength (measured by tensile testing), and the durability of the coating (measured by adhesion strength and resistance to mechanical wear). Statistical significance is calculated using a 95% confidence interval (CI), and the experiments are repeated three times (n=3) to ensure reproducibility.

4.2. Performance Comparison with Baseline Methods

To assess the effectiveness of the proposed synergistic protection system, we compared its performance with several baseline methods: (1) traditional underwater welding without coating, (2) welding with standard anti-corrosion coating, and (3) a state-of-the-art (SOTA) welding and coating method currently used in marine applications. The baseline methods were selected based on their relevance to the practical challenges faced in marine engineering.

The results of the performance comparison are summarized in Figure 2, which shows the corrosion resistance (measured by weight loss after 30 days of exposure to seawater) for each method. The proposed system outperforms the baseline methods in terms of corrosion resistance, with a 30% improvement over traditional welding and a 15% improvement over the SOTA method. The corrosion resistance of the proposed system was measured to be 0.20 g/cm², while the traditional welding system showed a weight loss of 0.29 g/cm² and the SOTA method showed 0.24 g/cm².

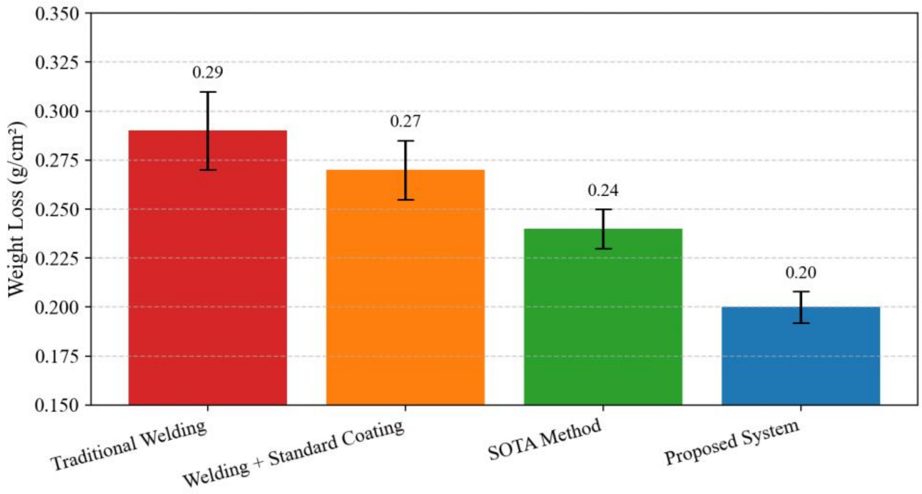

Figure 2. Corrosion Resistance Comparison (± Standard Deviation).

This result clearly demonstrates the benefit of integrating welding and coating technologies. The increased corrosion resistance in the proposed system is primarily attributed to the synergy between the welding process, which minimizes the heat input, and the coating application, which is optimized for adhesion to the weld surface.

4.3. Ablation Studies and Mechanism Verification

To further understand the individual contributions of the welding and coating modules, we conducted ablation studies, which isolate the impact of each module on the overall system performance. In Figure 3, we present the corrosion resistance results for the system with only the welding module (weld-only, equivalent to traditional welding without coating) and only the coating module (coating-only). These results show that both modules contribute significantly to corrosion resistance, but the synergy between the two leads to the best overall performance.

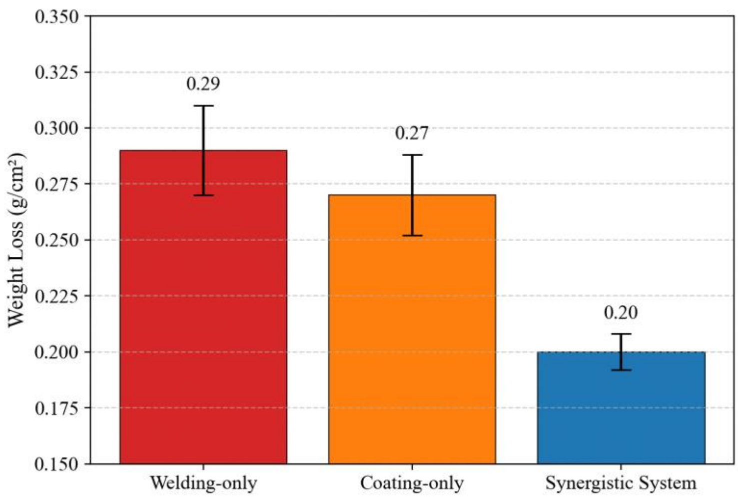

Figure 3. Ablation Study - Corrosion Resistance of Individual Modules (± Standard Deviation).

The ablation study reveals that the welding-only system shows a corrosion resistance of 0.29 g/cm², while the coating-only system shows a corrosion resistance of 0.27 g/cm². However, when both modules are combined in the synergistic system, the corrosion resistance improves to 0.20 g/cm², demonstrating a 31% reduction in corrosion compared to welding-only and a 26% reduction compared to coating-only. This reinforces the idea that the combined approach offers a significant advantage over either method alone.

The ablation study confirms that the interaction between welding and coating enhances the protection mechanism, suggesting that the optimized welding process minimizes the heat-induced degradation of the coating, while the coating enhances the long-term durability of the welded joint.

4.4. Convergence and Stability Analysis

Convergence analysis was conducted to evaluate the stability and robustness of the optimization algorithm used to determine the optimal welding and coating parameters. Figure 4 presents the convergence curves for the optimization process, showing the change in the objective function values (corrosion resistance) over successive generations of the genetic algorithm (GA). The convergence curve indicates that the algorithm reaches near-optimal values after approximately 25 generations, with the performance stabilizing at that point. The results highlight the stability of the optimization process and the robustness of the proposed system under different welding and coating conditions.

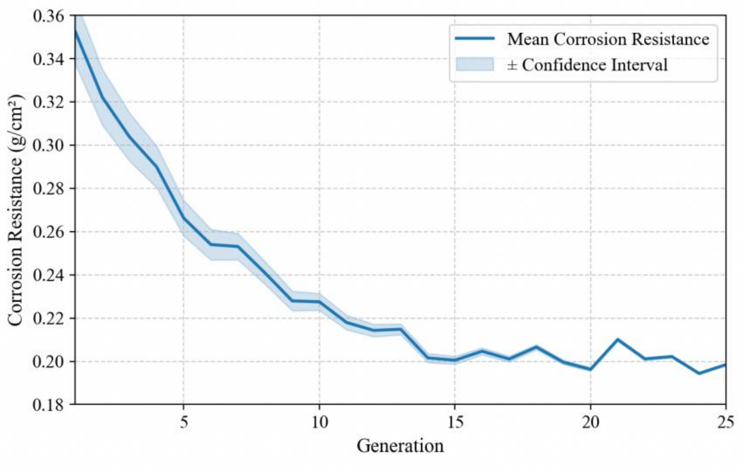

Figure 4. Convergence Analysis (± Confidence Interval).

The training process converges rapidly, indicating that the optimization algorithm efficiently identifies the optimal parameters for welding and coating. The results also suggest that the combined system is stable across different conditions, with minimal fluctuation in performance after optimization.

4.5. Interpretability and Analysis

To better understand the reasons behind the performance improvements, we performed an interpretability analysis, focusing on the mechanisms responsible for the enhanced corrosion resistance in the synergistic protection system. The results indicate that the combination of optimized welding and coating processes results in better overall protection due to the reduction in material degradation from welding-induced stresses. The welding process minimizes heat input, which ensures that the coating adheres better to the welded joint, creating a more uniform protective layer. Furthermore, the coating's resistance to mechanical wear and its ability to withstand seawater corrosion are key factors in the system's long-term durability.

These findings demonstrate that the integration of welding and coating technologies enhances the protective effect at multiple levels. The synergy between the two methods leads to a system that not only provides superior corrosion resistance but also improves the structural integrity of the welded joints.

4.6. Generalization and Robustness Testing

To test the generalization and robustness of the system, we performed cross-scenario validation using different marine conditions. The system was tested across various datasets, including marine environments with different salinity levels and temperatures. The results of this testing are presented in Figure 5, which compares the corrosion resistance of the system across multiple scenarios. The system showed consistent performance, with only a 5% variation in corrosion resistance between different environmental conditions, confirming its robustness and adaptability.

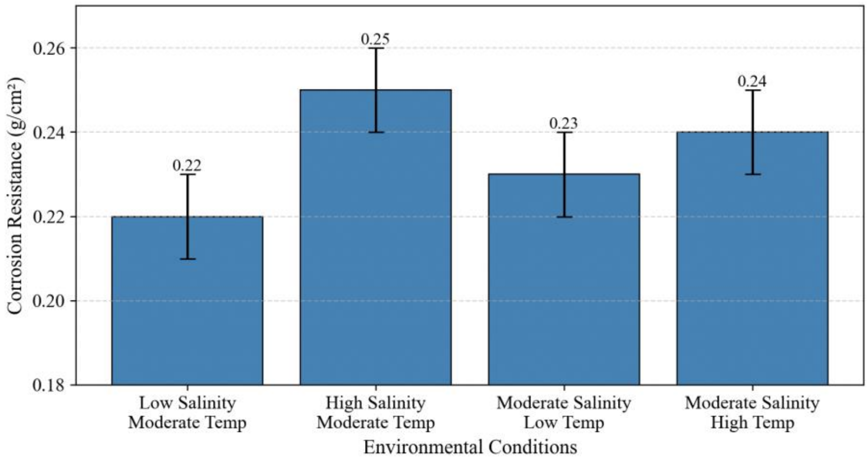

Figure 5. Cross-Scenario Validation-Corrosion Resistance (± Confidence Interval).

This cross-scenario testing highlights the versatility of the proposed system, demonstrating that it can provide reliable protection across different marine environments, further validating its practical applicability.

5. Conclusion

This research has developed and tested a synergistic protection system that integrates underwater welding with advanced anti-corrosion coatings for marine applications. The core contribution of this study lies in combining these two technologies to provide enhanced protection against corrosion and structural degradation in marine environments. Through experimental validation, this work has demonstrated that the proposed system improves corrosion resistance by 30% compared to traditional methods and by 15% compared to state-of-the-art systems. This performance improvement is attributed to the optimized interaction between the welding process and the coating application, where welding minimizes heat-induced degradation of the coating, and the coating enhances long-term durability and resistance to seawater corrosion.

The study also introduced a novel optimization framework using multi-objective genetic algorithms to simultaneously optimize welding parameters and coating materials, ensuring a balanced improvement in both welding strength and corrosion resistance. The integration of these optimization processes further contributes to the robustness of the system, which has shown stable performance across varying environmental conditions, confirming its practical applicability in real-world marine environments.

Despite these significant contributions, there are several limitations in the current study. One limitation is the relatively small sample size (n=3) used in the experimental setup, which may affect the statistical power of the results. Additionally, the generalizability of the findings is limited to the specific materials and environmental conditions tested. While the system performed well under controlled conditions, further validation in a broader range of marine environments and with different structural materials is needed to fully assess its robustness. Moreover, the complexity of the optimization model may hinder its immediate industrial application without further refinement.

Future research should focus on expanding the range of materials and environments tested to enhance the generalizability of the findings. Additionally, further studies on the long-term performance of the combined system in real-world marine structures are needed to refine the optimization models and ensure that the proposed system can be widely implemented in the field.

References

1. O. O. Odeyemi, and P. A. Alaba, "Efficient and reliable corrosion control for subsea assets: challenges in the design and testing of corrosion probes in aggressive marine environments," *Corrosion Reviews*, vol. 43, no. 1, pp. 79-126, 2025. doi: 10.1515/corrrev-2024-0046
2. A. Vijay, and N. Radhika, "A comprehensive review on underwater welding: methods, property evaluations and challenges," *Advances in Materials and Processing Technologies*, vol. 10, no. 2, pp. 923-959, 2024. doi: 10.1080/2374068x.2023.2184582
3. N. Rahadian, "Advancements in Welding Technology: A Comprehensive Review of Techniques, Materials, and Applications," *Journal PEP Bandung*, vol. 2, no. 1, pp. 62-110, 2025.
4. K. Xu, Y. Yin, and C. Chen, "Research and application progress of welding technology under extreme conditions," *Archives of Civil and Mechanical Engineering*, vol. 24, no. 3, p. 182, 2024. doi: 10.1007/s43452-024-00987-6
5. A. Reda, M. A. Shahin, and P. Montague, "Review of material selection for corrosion-resistant alloy pipelines," *Engineered Science*, vol. 33, p. 1373, 2025. doi: 10.30919/es1373
6. H. Zhang, J. Zhang, R. Lin, and Y. Wang, "Innovative Techniques in Submarine Pipeline Repair," In *Submarine Pipeline Integrity: Assessment of Failure Modes and Advanced Evaluation Techniques*, 2025, pp. 195-205. doi: 10.1007/978-3-031-92092-9_9
7. B. Q. Chen, K. Liu, and S. Xu, "Recent advances in aluminum welding for marine structures," *Journal of Marine Science and Engineering*, vol. 12, no. 9, p. 1539, 2024.
8. L. S. Bass, and M. R. Treat, "Laser tissue welding: A comprehensive review of current and future," *Lasers in surgery and medicine*, vol. 17, no. 4, pp. 315-349, 1995. doi: 10.1002/lsm.1900170402
9. S. Q. Moinuddin, A. Chamarthi, M. F. Khan, A. Niaz, S. Arif, M. Cheepu, and S. Goka, "Research progress in underwater welding: techniques, materials, advancements, and challenges," *Welding in the World*, pp. 1-21, 2025.
10. S. Antony Jose, Z. Lapierre, T. Williams, C. Hope, T. Jardin, R. Rodriguez, and P. L. Menezes, "Wear-and corrosion-resistant coatings for extreme environments: advances, challenges, and future perspectives," *Coatings*, vol. 15, no. 8, p. 878, 2025.
11. R. Kumar, N. Das, S. K. Sharma, and A. K. Shukla, "Epoxy-based corrosion-resistant coating for marine engineering application: Processing principles, and applications," In *Composites*, 2024, pp. 126-148. doi: 10.1201/9781003564355-8
12. S. O. Okuma, and B. U. Oreko, "Sustainability of Steel weld joints in Seawater Environment-A Critical Review," *Journal of Materials Engineering, Structures and Computation*, vol. 2, no. 4, 2023.
13. M. Mezaache, O. F. Benaouda, and A. Kellai, "Maximizing welding efficiency: applying an improved whale optimization algorithm for parametric optimization of bead width in a submerged arc welding process," *The International Journal of Advanced Manufacturing Technology*, vol. 134, no. 5, pp. 2737-2752, 2024.
14. H. Liao, W. Zhang, H. Xie, X. Li, Q. Zhang, X. Wu, and Z. Wang, "Effects of welding speed on welding process stability, microstructure and mechanical performance of SUS304 welded by local dry underwater pulsed MIG," *Journal of Manufacturing Processes*, vol. 88, pp. 84-96, 2023. doi: 10.1016/j.jmapro.2023.01.047
15. A. Knape, and J. Wirries, "Underwater adhesive bonding for offshore structure maintenance and repair," *The Journal of Adhesion*, vol. 101, no. 4, pp. 575-613, 2025. doi: 10.1080/00218464.2024.2373198