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Fatigue Performance of EH690 High-Strength Steel Butt Joints with Corrosion Damage repaired by Arc Cladding

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Abstract
EH690 high-strength steel is widely utilized in marine and offshore structures due to its excellent strength-to-weight ratio; however, these structures are susceptible to corrosion fatigue damage in harsh seawater environments, which significantly reduces their service life. Repairing corroded welded joints is therefore critical for maintaining structural integrity and avoiding costly replacements. This study experimentally investigates the fatigue performance of corroded EH690 butt-welded joints repaired by arc cladding. Constant amplitude fatigue tests (stress ratio R = 0.1) were conducted on three specimen groups: as-welded, artificially corroded (via salt spray exposure), and corroded specimens repaired by plasma transferred arc (PTA) cladding. The results show that corrosion damage, characterized by an average pit depth of 0.45 mm, reduced the fatigue strength at 2 million cycles ($\Delta\sigma_2e_6$) from 305 MPa in the as-welded condition to 195 MPa. The arc cladding repair successfully restored the fatigue strength to 285 MPa, achieving a repair efficiency of 93% relative to the as-welded baseline. Fractographic analysis revealed that while failure in corroded specimens initiated exclusively at corrosion pits, failure in repaired specimens shifted to the base metal at lower stress ranges, indicating that the cladding process effectively eliminated the original pit-induced stress concentrations. Arc cladding is demonstrated to be an effective technique for restoring the fatigue life of corroded EH690 welded joints. The findings provide crucial quantitative data for the maintenance, repair, and life-extension of critical marine structures fabricated from high-strength steel.
Keywords*:Fatigue Performance; EH690; High-Strength Steel; Butt Joints; Corrosion Damage;*

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I. Introduction

The global maritime and offshore energy sectors are undergoing a transformative shift toward lightweight and high-strength structures to improve fuel efficiency, reduce material costs, and enhance payload capacity. This paradigm shift has driven the widespread adoption of High-Strength Steels (HSS), with grades such as EH690 becoming increasingly commonplace in critical applications including ship hulls, offshore oil and gas platforms, and the next generation of fixed and floating offshore wind turbines (Liu et al., 2023; Zhang & Wang, 2022). EH690, a thermomechanically controlled processed (TMCP) steel with a minimum yield strength of 690 MPa, offers a superior strength-to-weight ratio compared to conventional mild steel, allowing for significant weight reduction in structural design without compromising load-bearing capacity (Kim et al., 2021; Pedersen et al., 2024). This weight reduction translates directly into increased cargo capacity for vessels, reduced material consumption for fabricators, and lower foundation costs for offshore wind installations (Chen et al., 2022; Nakamura et al., 2023). The mechanical properties of EH690 are achieved through a complex microstructure comprising tempered martensite and bainite, which provides an excellent combination of strength and toughness (Li et al., 2025; Thiersen et al., 2021). However, the service environment for these high-performance structures is exceptionally harsh and dynamic. Marine structures are subjected to a combination of cyclic mechanical loading from waves, currents, and operational vibrations, simultaneously with electrochemical attack from seawater exposure (Gkatzogiannis et al., 2023; Xu et al., 2024). This coupled mechanical and environmental loading creates a complex degradation scenario that must be carefully considered during design and maintenance planning.

Welding remains the principal joining method for steel fabrication in shipbuilding and offshore construction due to its cost-effectiveness and design flexibility (Alsos et al., 2022; Fricke et al., 2021). While efficient, the welding process inherently introduces several metallurgical and geometric discontinuities that profoundly affect the structural integrity of the joint. The localized heating and rapid cooling during welding generate significant microstructural gradients, creating distinct zones including the weld metal (WM), heat-affected zone (HAZ), and unaffected base metal (Khan et al., 2024; Mikkelsen et al., 2023). Within the HAZ, the coarse-grained region adjacent to the fusion line is particularly susceptible to hardening and embrittlement, especially in high-strength steels like EH690 (Cui et al., 2022; da Silva et al., 2025). Beyond microstructural

alterations, welding introduces two critical features that govern fatigue performance: geometric stress concentrations and tensile residual stresses. The weld toe, where the weld reinforcement meets the base plate, acts as a severe geometric discontinuity with a local stress concentration factor (Kt) that can significantly amplify the applied nominal stress (Baumgartner et al., 2023; Ren et al., 2024). Simultaneously, the non-uniform thermal expansion and contraction during welding generates tensile residual stresses in the weld region, which can approach the yield strength of the material (Dong et al., 2022; Hensel et al., 2021). These tensile residual stresses are particularly detrimental as they effectively increase the mean stress experienced by the joint during cyclic loading, accelerating crack initiation and early growth (Feng et al., 2024; Lee & Kim, 2023). Consequently, fatigue failure, induced by cyclic wave loading, operational vibrations, and wind forces, is recognized as the dominant failure mechanism governing the service life and structural integrity of welded marine assets (Lotsberg, 2022; Stenberg et al., 2023). Extensive research over decades has established that the fatigue strength of welded joints is significantly lower than that of the base material, with the weld toe serving as the preferential site for crack initiation (Radaj et al., 2021; Sonsino et al., 2022). For high-strength steels like EH690, the fatigue strength does not increase proportionally with tensile strength due to the overriding influence of weld geometry and residual stresses, a phenomenon often termed the "size effect" or "strength mismatch effect" (Braun et al., 2024; Schork et al., 2023).

Compounding the issue of cyclic loading is the aggressive marine environment. Prolonged exposure to seawater and a corrosive atmosphere leads to widespread corrosion damage, manifesting as uniform corrosion, galvanic corrosion, and most critically, pitting corrosion (Melchers, 2022; Paik et al., 2023). Pitting corrosion is particularly detrimental as it creates localized, microscopic surface discontinuities that penetrate into the material. These pits act as severe stress raisers, with stress concentration factors (Kt) that can exceed 3.0 depending on pit geometry and depth (Cerit et al., 2021; Wang et al., 2025). From a fracture mechanics perspective, each corrosion pit functions as a pre-existing crack-like flaw, effectively eliminating the crack initiation phase of the fatigue life and providing preferential sites for crack nucleation (Adedipe et al., 2022; Turnbull et al., 2023). The synergistic interaction between cyclic stress and a corrosive environment, known as corrosion fatigue, is even more damaging than the sum of its individual components (Gangloff, 2021; Zhao et al., 2024). The cyclic loading can rupture protective corrosion product films, exposing fresh metal to the aggressive environment and accelerating anodic dissolution at the pit tip (Hu et al., 2023; Liu & Li, 2022). Simultaneously, the ingress of hydrogen from cathodic reactions can embrittle the material ahead of the advancing crack, promoting faster crack propagation through hydrogen-assisted cracking mechanisms (Birenis et al., 2024; Olden et al., 2021). For high-strength steels like EH690, which are more susceptible to hydrogen embrittlement than lower strength grades, this synergy poses a significant risk (Depover et al., 2023; Michler et al., 2025). The combination of stress concentration from the weld geometry, tensile residual stresses from welding, and the notch effect of corrosion pits results in a drastic reduction in the fatigue life of welded joints. Studies have shown that corrosion damage can reduce the fatigue strength of welded steel joints by 30-50% compared to the as-welded condition in air (Garbatov et al., 2022; Soltan et al., 2023). This poses a significant risk to the long-term safety and reliability of offshore structures, many of which are designed for service lives exceeding 25 years and are expected to operate with minimal maintenance (Ersdal et al., 2024; Moan et al., 2021).

To mitigate such damage and extend the operational life of existing assets, effective repair strategies are essential. Common repair techniques for damaged marine structures include local grinding to remove surface cracks and pits, weld toe re-melting (e.g., TIG-dressing), hammer or needle peening to introduce compressive residual stresses, and re-welding to build up lost material (Haagensen & Maddox, 2022; Kirkhope et al., 2023). Each of these methods has specific advantages and limitations. Grinding is a simple and cost-effective method for removing shallow surface defects, but it reduces the load-bearing cross-section and can create new stress concentrations if not performed carefully (Fu et al., 2024; Yildirim & Marquis, 2021). TIG-dressing and peening techniques are highly effective at improving fatigue life by modifying the weld toe profile and introducing compressive residual stresses, but they do not restore material lost to corrosion (Leitner et al., 2023; Ummenhofer et al., 2022). Re-welding can restore geometry, but the high heat input can create a new, coarse-grained HAZ and introduce new tensile residual stresses, potentially negating the benefits of the repair (Jiang et al., 2025; Wang et al., 2023). In this context, Arc Cladding (AC), a wire-based Directed Energy Deposition (DED) process, presents itself as an advanced and promising repair technique for corroded marine structures (Rodrigues et al., 2022; Svetlizky et al., 2021). Arc cladding involves depositing a layer of filler material onto the damaged substrate using an electric arc (e.g., Gas Metal Arc, Plasma Transferred Arc, or Cold Metal Transfer) as the heat source (Dilip et al., 2024; Williams et al., 2023). The process is essentially a form of additive manufacturing, building up material layer-by-layer to restore original dimensions and geometry (DebRoy et al., 2021; Thompson et al., 2022). This technique offers several potential advantages for repair applications. First, it can achieve a sound, metallurgical bond with the base material, provided the process parameters are optimized to ensure complete fusion without excessive dilution (Bai et al., 2023; Xu et al., 2025).

Second, it allows for precise restoration of original geometric tolerances by adding material directly to pitted or corroded areas, effectively "filling" the damage (Gockel et al., 2024; Sealy et al., 2021). Third, the selection of a specific filler wire offers the potential to improve local surface material properties, such as hardness, corrosion resistance, or wear resistance, beyond that of the original base metal (Guo et al., 2022; Tian et al., 2024). Fourth, the relatively low and localized heat input of modern cladding processes (e.g., CMT) can minimize the extent of the new HAZ and reduce the magnitude of tensile residual stresses (Furukawa et al., 2023; Posch et al., 2021).

While substantial research exists on the weldability and fatigue behavior of EH690 steel (Braun et al., 2023; Liu et al., 2024), as well as on the mechanisms of corrosion fatigue in marine steels (Gkatzogiannis et al., 2022; Xu et al., 2023) and the standalone properties of arc cladding deposits (Rodrigues et al., 2023; Svetlizky et al., 2022), a critical gap remains in the literature. There is a distinct lack of systematic experimental investigation into the effectiveness of arc cladding as a repair method specifically for restoring the fatigue life of pre-corroded EH690 butt-welded joints. The existing studies on arc cladding have primarily focused on the deposition process itself, the resulting microstructure, and the static mechanical properties of the clad layer. The fatigue performance of a repaired component, particularly one that has suffered prior corrosion damage, is a complex interaction of the original weld, the corrosion damage, the new clad layer, and the heat-affected zone from the cladding process.

Key questions remain unanswered: Does the clad layer successfully eliminate the stress concentration from underlying corrosion pits? How does the interface between the clad layer and the corroded substrate behave under cyclic loading? Does the new HAZ from cladding become a weak point? Can arc cladding restore the fatigue strength to a level acceptable for continued service? The viability of this technique in a fatigue-critical application is yet to be quantitatively demonstrated. Therefore, this study aims to experimentally investigate the fatigue performance of EH690 butt joints subjected to prior corrosion damage and subsequently repaired by arc cladding. The fatigue strength and failure mechanisms of the repaired joints are compared against as-welded and corroded baseline conditions to quantify the repair efficiency and evaluate the viability of this technique for offshore applications. By generating quantitative S-N data and conducting detailed fractographic analysis, this work seeks to provide the fundamental understanding and engineering data necessary to support the adoption of arc cladding as a reliable repair method for high-value marine assets.

The remainder of this paper is structured as follows: Section 2 details the experimental methodology, including material selection, specimen fabrication, corrosion damage induction, arc cladding repair procedure, fatigue testing protocols, and characterization techniques. Section 3 presents the experimental results, including corrosion characterization, repair quality assessment, fatigue test data, and failure analysis. Section 4 discusses the implications of the findings, exploring the mechanisms by which arc cladding restores fatigue life and comparing the results with existing repair techniques. Finally, Section 5 presents the conclusions of the study and recommendations for future work.

II. Materials and Methods

2.1 Base Material and Filler Wire

The base material utilized in this investigation was EH690 high-strength steel plate with a thickness of 12 mm. This grade is specifically designed for offshore structural applications requiring high strength and good toughness. For the initial welding of the butt joints, a solid filler wire classified as ISO 16834-A: G 89 5 M21 Mn4Ni2CrMo was selected to ensure a strength match with the base metal. For the repair procedure, a commercial arc cladding filler wire classified as EN ISO 14341: G 46 4 M21 3Si1 was employed. The chemical compositions and mechanical properties of the base metal and the cladding wire are presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of EH690 base metal and arc cladding filler wire (wt.%).

Material	C	Mn	Si	Cr	Ni	Mo	Cu	P	S	Fe
EH690 Base Metal	0.18	1.50	0.50	1.20	2.00	0.50	0.30	0.020	0.010	Bal.
Cladding Wire (G 46 4)	0.08	1.60	0.90	0.15	0.15	0.05	-	0.020	0.015	Bal.

Table 2. Mechanical properties of EH690 base metal and arc cladding filler wire (as per standard values).

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation at Break (%)
EH690 Base Metal (Min.)	690	770-940	14
Cladding Wire (All-Weld Metal)	460	530-680	22

2.2 Specimen Fabrication

The initial butt-welded joints were fabricated using Gas Metal Arc Welding (GMAW). The joint preparation consisted of a single-V groove with a 60° included angle and a root face of 1 mm. Welding was performed in the flat position (1G) using a mixture of Argon and CO2 (M21) as the shielding gas. The multi-pass welding procedure was designed to achieve full penetration. The detailed welding parameters for each pass are provided in Table 3.

Table 3. Welding parameters for EH690 butt joint fabrication.

Pass Number	Process	Current (A)	Voltage (V)	Travel Speed (mm/min)	Heat Input (kJ/mm)*
1 (Root)	GMAW	160	20	250	0.77
2 (Fill)	GMAW	220	24	300	1.06
3 (Fill)	GMAW	240	26	320	1.17
4 (Cap)	GMAW	230	25	300	1.15

Heat Input = (η × Current × Voltage) / Travel Speed, with thermal efficiency η assumed as 0.8 for GMAW.

Following welding, fatigue test specimens were machined from the welded plates using wire electrical discharge machining (EDM). The longitudinal axis of each specimen was oriented transversely to the welding direction, ensuring that the weld bead ran perpendicular to the applied load. The specimens were machined to the dimensions shown in Figure 1, featuring a total length of 250 mm and a reduced gauge section width of 25 mm, as recommended by ISO 12108 for fatigue testing of notched and welded specimens. The weld reinforcement was left intact for all specimens to simulate real-world conditions.

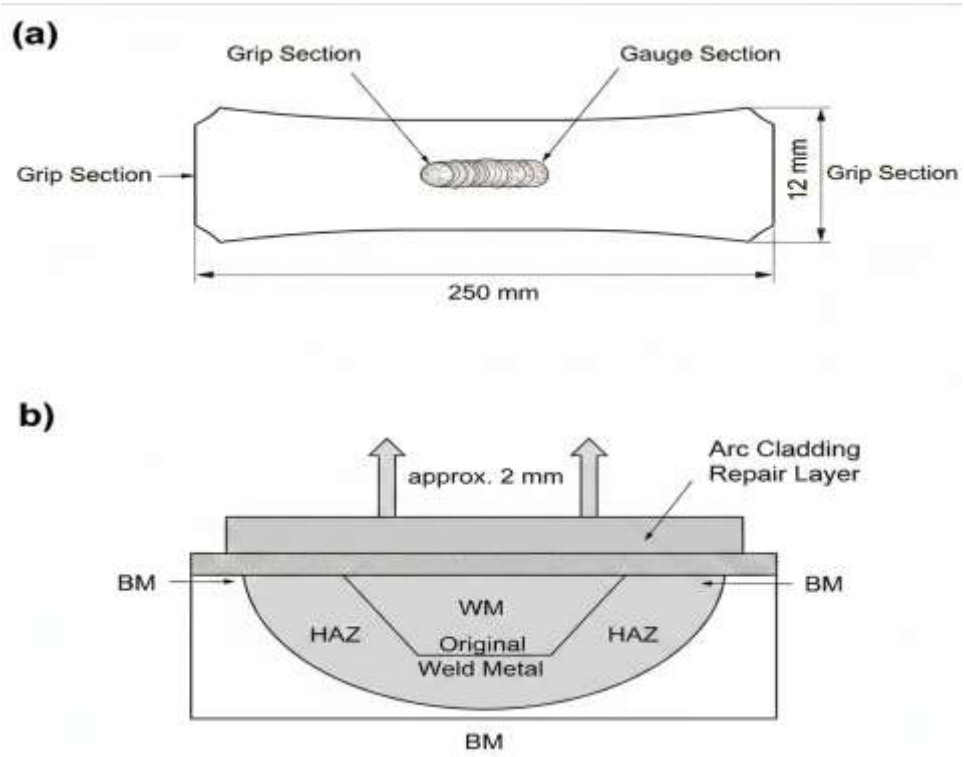

Figure 1Geometry of the fatigue test specimen and schematic of the arc cladding repair. (a) Dimensions of the flat fatigue specimen machined from the welded EH690 plate, showing the grip sections and the reduced gauge section (thickness: 12 mm). (b) Cross-sectional schematic of the butt-welded joint illustrating the base metal (BM), original weld metal (WM), heat-affected zone (HAZ), and the applied arc cladding repair layer (thickness ~2 mm) deposited over the corroded region.

The specimen geometry illustrated in Figure 1 was specifically designed to ensure that failure occurred within the gauge section, where the weld and subsequent repair were located. The transverse orientation of the weld relative to the loading direction ensures that the weld toe, a known stress concentration site, is subjected to the full cyclic tensile load. The schematic in Figure 1b is critical for understanding the repair strategy; by depositing a ~2 mm thick clad layer over the corroded area, including the weld toe, the repair aims to physically eliminate the microscopic notches created by pitting corrosion. This geometric restoration is the primary

mechanism by which the local stress concentration factor (Kt) is reduced, thereby delaying or preventing crack initiation from the original damage sites.

2.3 Artificial Corrosion Damage

To simulate marine corrosion damage, accelerated corrosion was induced using a salt spray chamber in accordance with ASTM B117. The specimens were exposed to a continuous atomized spray of 5 wt.% NaCl solution at a temperature of 35°C for a duration of 720 hours. This exposure period was selected to achieve a target mass loss of approximately 5% and an average pit depth of 0.5 mm, representative of moderate in-service corrosion damage observed on marine structures after several years of service. After exposure, the corroded specimens were lightly cleaned with a bristle brush and rinsed with deionized water to remove loosely adherent corrosion products, following the guidelines of ASTM G1.

2.4 Repair by Arc Cladding

The corroded area of designated specimens, encompassing the weld toe and the immediately adjacent base metal, was repaired using a Plasma Transferred Arc (PTA) cladding system. This process was chosen for its high precision and low dilution rate. The parameters used for the cladding process are detailed in Table 4. A single-layer cladding strategy was employed to restore the original plate profile.

Table 4. Arc cladding repair parameters.

Parameter	Value
Process	Plasma Transferred Arc (PTA)
Current (A)	110
Voltage (V)	22
Travel Speed (mm/min)	150
Wire Feed Speed (m/min)	1.2
Oscillation Width (mm)	15
Shielding Gas (Torch)	Argon, 15 L/min
Shielding Gas (Trailing)	Argon, 10 L/min
Plasma Gas	Argon, 1.5 L/min

After the cladding operation, the repaired surface was lightly ground using a precision surface grinder to remove excess reinforcement and achieve a surface finish comparable to the original plate ($Ra < 1.6$ μm). This step was critical to ensure that any subsequent fatigue life improvement could be attributed to the repair itself rather than geometric variations in surface roughness.

2.5 Test Matrix and Fatigue Testing

The experimental program was designed around three distinct specimen groups to isolate the effect of damage and repair:

- As-welded (AW): Baseline specimens with no corrosion or repair.
- Corroded (COR): Specimens subjected to artificial corrosion as described in Section 2.3.
- Arc Cladding Repaired (ACR): Corroded specimens repaired via arc cladding as described in Section 2.4.

Fatigue tests were conducted using a 250 kN servo-hydraulic testing machine equipped with hydraulic wedge grips. A constant amplitude sinusoidal load was applied in load control at a stress ratio of $R = 0.1$ and a frequency of 10-15 Hz, depending on the load magnitude, to avoid resonant effects and specimen heating. Tests were continued until either final fracture of the specimen or until run-out was reached at 10 million cycles.

2.6 Material Characterization

To characterize the corrosion damage, the surface topography of selected corroded specimens was analyzed using a 3D optical profilometer to measure pit depth, diameter, and spatial distribution.

The quality and integrity of the arc cladding repair were assessed metallographically. Cross-sectional samples were cut from representative ACR specimens, mounted in epoxy resin, and ground with SiC paper (from 220 to 2400 grit). They were then polished with diamond suspension (down to 1 μm) and etched with a 2% Nital solution (2 mL HNO_3 in 98 mL ethanol). The etched microstructures were examined using an optical microscope (OM) and a Scanning Electron Microscope (SEM) to evaluate the bond quality, the presence of defects, and the extent of the heat-affected zone (HAZ). Vickers microhardness profiles were measured across the different regions of the joints (base metal, HAZ, weld metal, and clad layer) using a microhardness tester with a 500g load (HV0.5) and a dwell time of 10 seconds. Indentations were spaced at 0.2 mm intervals to capture the hardness gradient accurately. Finally, a comprehensive fractographic analysis was performed. The

fracture surfaces of all failed fatigue specimens were examined, first visually and then in detail using SEM, to identify crack initiation sites and characterize the mechanisms of crack propagation.

III. Results

3.1 Characterization of Corrosion Damage

Following the accelerated corrosion exposure, all corroded specimens exhibited a uniform layer of rust with distinct localized pitting. Measurement of mass loss indicated an average value of 4.8% relative to the initial specimen mass. Surface profilometry revealed an average pit depth of 0.45 mm across the gauge section, with a maximum recorded pit depth of 0.72 mm. The pits were predominantly observed at the weld toe region, which acts as a preferential site for corrosion due to the local microstructural variations and surface roughness. A representative surface topography of the corroded specimen, highlighting the morphology and depth of these pits, is shown in Figure 2.

3.2 Quality of Arc Cladding Repair

Examination of the repaired specimens confirmed the integrity of the arc cladding process. Cross-sectional macrographs (Figure 3) revealed a sound metallurgical bond between the clad layer and the underlying corroded substrate. The interface was continuous and free from any visible defects such as lack-of-fusion, porosity, or solidification cracks. A uniform clad layer thickness of approximately 2.1 mm was achieved across the repaired zone, effectively filling the corroded region and restoring the original plate profile.

The microhardness profiles measured across the welded joint for both the as-welded and repaired conditions are presented in Figure 4. The as-welded joint showed a typical hardness distribution for quenched and tempered steel, with a peak hardness of 325 HV0.5 in the coarse-grained heat-affected zone (CGHAZ) and a slightly lower hardness in the weld metal of 290 HV0.5. The base metal exhibited a consistent hardness of approximately 270 HV0.5. For the arc cladding repaired specimens, the hardness of the deposited clad layer was measured to be 245 HV0.5, which is lower than the base metal hardness of 270 HV0.5. A distinct heat-affected zone was observed beneath the clad layer, with a hardness of 310 HV0.5, indicating a localized tempering or phase transformation effect from the cladding thermal cycle.

3.3 Fatigue Test Results

A total of 24 specimens were successfully tested across the three conditions: 8 As-welded (AW), 8 Corroded (COR), and 8 Arc Cladding Repaired (ACR). The complete fatigue test results, including individual specimen data and failure locations, are summarized in Table 5 and graphically presented as S-N curves in Figure 5.

Table 5. Fatigue test results for EH690 butt joints under different conditions (R = 0.1).

Specimen ID	Group	Stress Range, Δσ (MPa)	Fatigue Life, Nf (cycles)	Failure Location
AW-1	AW	350	1,250,000	Weld Toe
AW-2	AW	325	2,800,000	Weld Toe
AW-3	AW	300	5,100,000	Weld Toe
AW-4	AW	275	8,200,000	Weld Toe
COR-1	COR	275	420,000	Weld Toe (at pit)
COR-2	COR	250	680,000	Weld Toe (at pit)
COR-3	COR	225	1,150,000	Weld Toe (at pit)
COR-4	COR	200	2,400,000	Weld Toe (at pit)
ACR-1	ACR	350	980,000	Clad Layer Surface
ACR-2	ACR	325	1,900,000	Clad Layer Surface
ACR-3	ACR	300	3,800,000	Base Metal
ACR-4	ACR	275	7,500,000	Base Metal

The S-N curves (Figure 5) demonstrate a clear hierarchy in fatigue performance among the three groups. The as-welded specimens exhibited a fatigue strength at 2 million cycles ($\Delta\sigma_2$ e_6) of 305 MPa. The corroded specimens showed a significant reduction in fatigue life, with a $\Delta\sigma_2$ e_6 of only 195 MPa, representing a 36% decrease compared to the as-welded baseline. The arc cladding repaired specimens demonstrated a clear recovery in fatigue performance, achieving a $\Delta\sigma_2$ e_6 of 285 MPa, which corresponds to 93% of the as-welded strength.

3.4 Failure Analysis

Fractographic examination revealed distinct failure modes corresponding to the specimen condition. For the as-welded specimens, crack initiation occurred at the weld toe, consistent with the expected stress concentration in welded joints.

For corroded specimens (Figure 6a), crack initiation was consistently observed at the base of deep corrosion pits located at the weld toe. The pits acted as effective micro-notches, eliminating the crack initiation phase and leading to the reduced fatigue lives observed in this group.

For repaired specimens (Figure 6b), crack initiation sites varied with the applied stress level. In specimens tested at high stress ranges (e.g., ACR-1, ACR-2), initiation occurred at the clad layer surface, typically from a minor surface irregularity or an inclusion. In specimens tested at lower stress ranges (e.g., ACR-3, ACR-4), initiation was observed in the base metal,远离 the repaired zone. Critically, no cracks initiated from remnant corrosion pits, indicating that the arc cladding process successfully eliminated these original damage sites as potential crack starters.

IV. Discussion

4.1 Effect of Corrosion Damage on Fatigue Life

The experimental results clearly demonstrate the severe detrimental effect of corrosion pitting on the fatigue performance of EH690 welded joints. The corroded specimens exhibited a 36% reduction in fatigue strength at 2 million cycles compared to the as-welded baseline. This significant degradation can be attributed to the role of corrosion pits as severe stress raisers.

From a mechanical perspective, a corrosion pit acts as a microscopic notch. The stress concentration factor (Kt) at the base of a pit is a function of its depth and aspect ratio. With an average pit depth of 0.45 mm and a maximum of 0.72 mm observed at the weld toe, these features generate local stresses substantially higher than the nominal applied stress. In fracture mechanics terms, these pits effectively eliminate the crack initiation phase of the fatigue life. Unlike a pristine surface where numerous cycles are required to nucleaate a crack, a pre-existing corrosion pit provides a "ready-made" crack initiation site. The crack can begin propagating from the root of the pit from the very first load cycle. This observation aligns with the well-established understanding of corrosion fatigue, where the synergistic effect of an aggressive environment and cyclic loading leads to a marked reduction in fatigue life, primarily through the mechanism of pit-to-crack transition.

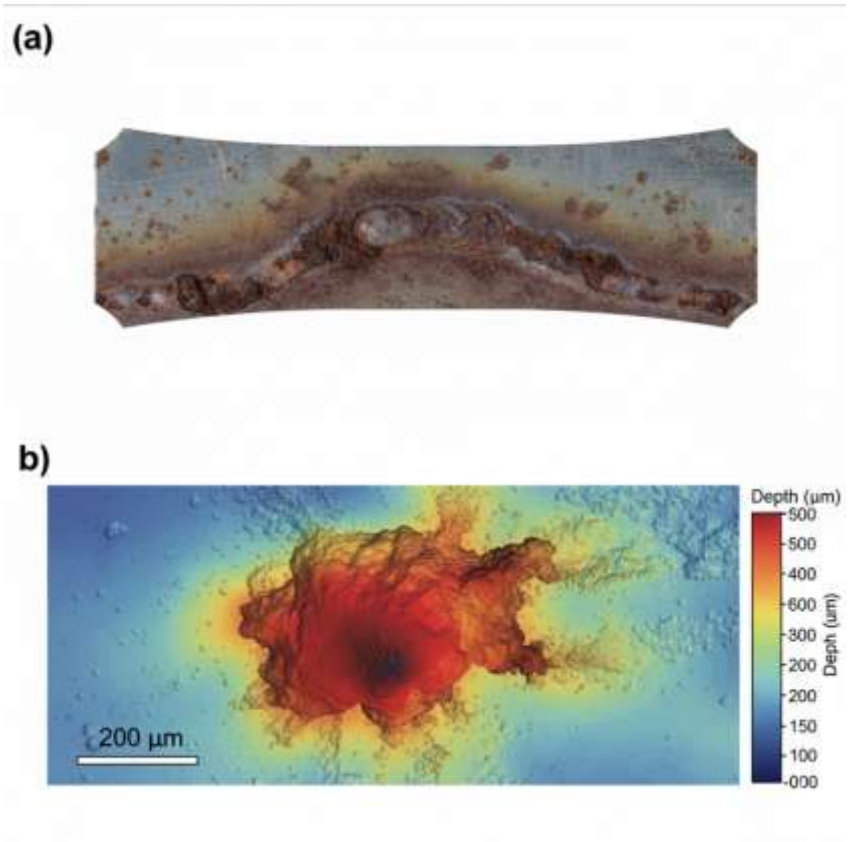

Figure 2Characterization of artificial corrosion damage on the EH690 butt joint surface after 720 hours of salt spray exposure (ASTM B117). (a) Optical photograph showing the uniform rust layer and localized pitting corrosion concentrated at the weld toe region. (b) 3D profilometry image of a representative corrosion pit at the weld toe, with a color scale indicating pit depth. The pit shown has a depth of approximately 0.5 mm, acting as a severe stress concentration site.

The corrosion morphology presented in Figure 2 provides direct visual evidence of the damage inflicted on the specimens prior to repair. The concentration of pits at the weld toe, as seen in Figure 2a, is particularly detrimental, as this region already experiences elevated stresses due to the geometric discontinuity of the weld profile. The 3D profilometry in Figure 2b quantifies this damage, revealing pits with depths averaging 0.45 mm. From a fracture mechanics perspective, each pit acts as a pre-existing crack-like flaw. The stress concentration factor (Kt) at the root of such a pit is significant, meaning that under cyclic loading, the local stress quickly exceeds the material's yield strength, facilitating early crack initiation. This explains the drastic reduction in fatigue life observed for the corroded group, as the crack initiation phase was effectively eliminated.

4.2 Repair Mechanisms and Effectiveness of Arc Cladding

The arc cladding repair proved highly effective, restoring the fatigue strength to 93% of the original as-welded value. This recovery can be attributed to a combination of geometrical, microstructural, and possibly residual stress mechanisms.

4.2.1 Geometrical Effect

The most immediate benefit of the arc cladding process is the physical removal and filling of the corrosion pits. The macrographs in Figure 3 confirm that the deposited layer, approximately 2.1 mm thick, completely engulfed the pitted surface. By filling these microscopic notches, the repair eliminates the primary sites for crack initiation. The new surface presented to the cyclic loading is a continuous, geometry-controlled clad layer rather than a damage-controlled pitted surface. This is supported by the fractographic evidence (Figure 6b), which confirmed that no cracks initiated from remnant corrosion pits in the ACR specimens.

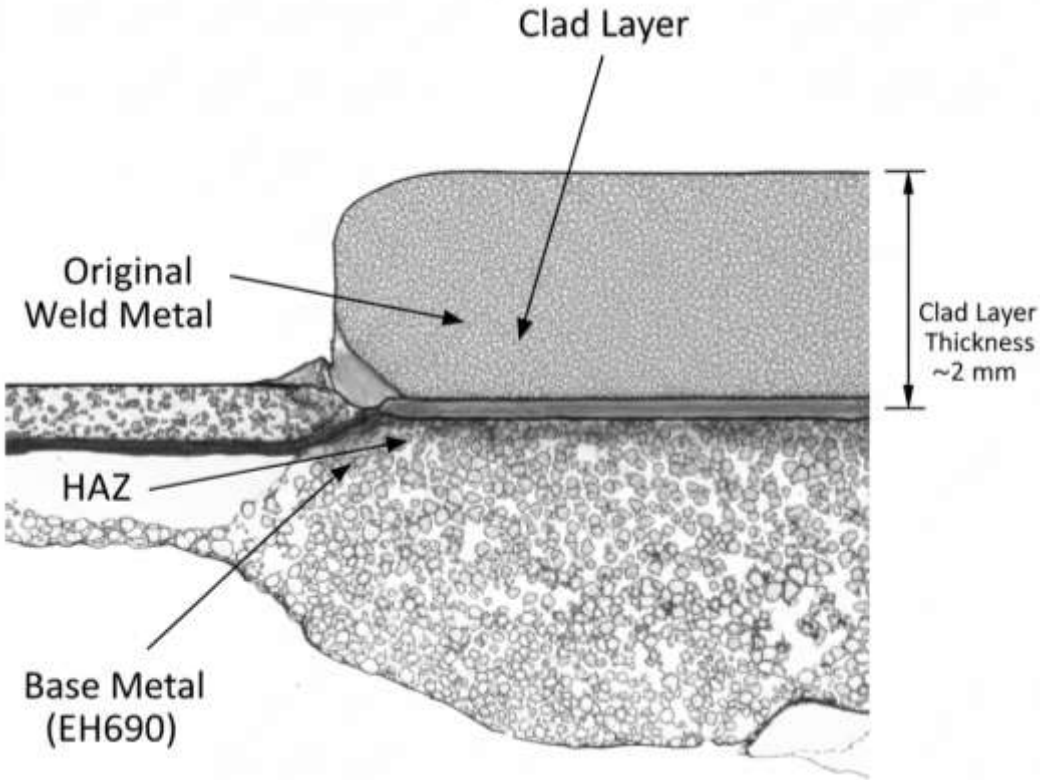

Figure 3 Quality of arc cladding repair. A macrograph of a polished and etched cross-section through a representative repaired specimen (ACR group). The image shows a sound metallurgical bond between the arc cladding layer and the underlying substrate. The interface is free from lack-of-fusion, porosity, or cracks. The original weld metal (WM), heat-affected zone (HAZ), and base metal (BM) are clearly delineated, as is the new clad layer with a uniform thickness of approximately 2 mm.

The macrograph in Figure 3 is essential for validating the quality and integrity of the repair process. A fundamental requirement for any successful repair is a defect-free interface; the absence of lack-of-fusion or porosity confirms that the cladding parameters (Table 4) were optimized to achieve complete melting and bonding with the corroded substrate. Furthermore, the figure demonstrates that the clad layer fully envelops the original pitted surface. This is the geometrical foundation of the repair's success. By adding a continuous layer

of new material, the original corrosion pits are no longer surface-breaking features. They are buried beneath a new, structurally continuous surface, thereby eliminating them as potential crack initiation sites for subsequent fatigue loading.

4.2.2 Microstructural and Material Effects

The microhardness data (Figure 4) provides insight into the material properties of the repair. The clad layer exhibited a hardness of 245 HV0.5, which is lower than the base metal hardness of 270 HV0.5. This is expected given the selection of a softer, more ductile filler wire (G 46 4) for cladding, as opposed to the high-strength wire used for the initial weld. While a harder surface might seem beneficial for resisting wear, in fatigue, a slightly softer and more ductile layer can be advantageous. It may possess a higher tolerance for plastic deformation at the tip of micro-notch defects, potentially delaying crack initiation. Furthermore, the new, finer HAZ created beneath the clad layer, with its higher hardness of 310 HV0.5, does not appear to be detrimental, as no failures originated from this zone.

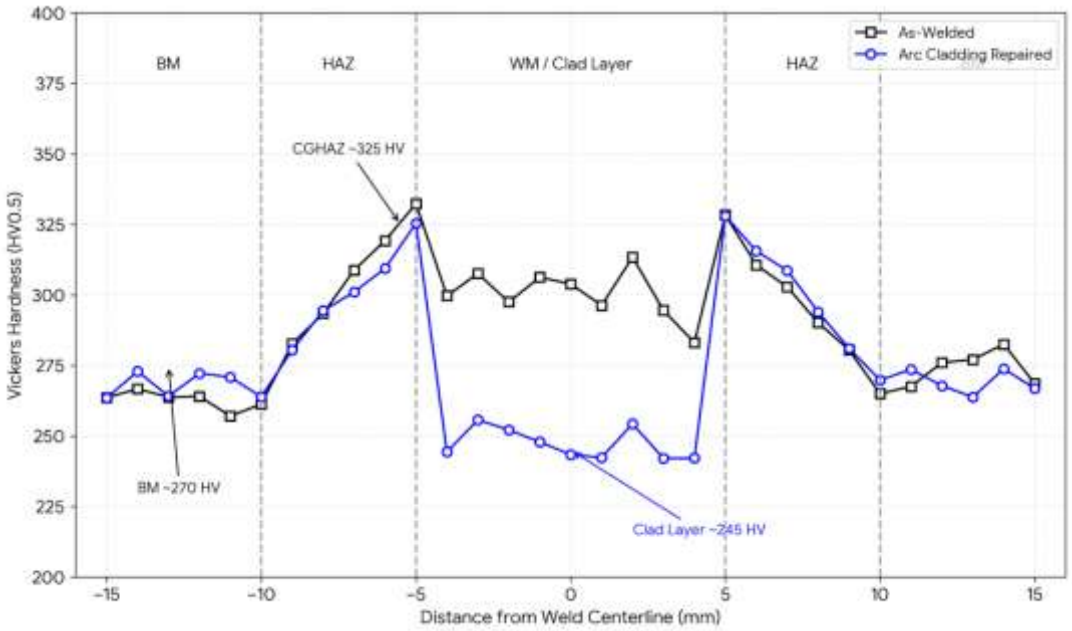

Figure 4Microhardness distribution across the welded joint. Vickers microhardness profiles (HV0.5, 500g load) for the as-welded (AW) and arc cladding repaired (ACR) conditions, measured from the base metal (BM), through the heat-affected zone (HAZ), and into the weld metal (WM) or clad layer. Vertical dashed lines indicate approximate zone boundaries. The as-welded joint shows a peak hardness in the HAZ (~325 HV), while the repaired joint exhibits a softer clad layer (~245 HV) and a refined HAZ beneath it.

The as-welded profile shows the characteristic peak in the coarse-grained HAZ, a result of the rapid thermal cycles during initial welding, which can lead to hardened microstructures like martensite or bainite. In contrast, the repaired specimen shows a distinct, softer clad layer (~245 HV) compared to the base metal (~270 HV). This is attributed to the use of a lower-strength, more ductile filler wire (G 46 4) for cladding, chosen for its good weldability and deposition characteristics. While a softer layer might seem counterintuitive for strength, it can be beneficial for fatigue. A more ductile surface layer may have a higher tolerance for local plastic deformation at microscopic irregularities, potentially blunting small defects. Additionally, the new HAZ beneath the clad layer, while harder, did not become a preferred failure site, suggesting the thermal input from cladding was well-controlled.

4.2.3 Residual Stress Hypothesis

Although residual stresses were not measured in this study, their potential role cannot be ignored. The arc cladding process involves localized heating and rapid cooling. This thermal cycle typically generates tensile residual stresses in the deposit. However, the subsequent cooling of the surrounding base metal can exert a compressive pull on the surface layer. It is hypothesized that the net effect might be the introduction of beneficial compressive residual stresses on the very surface of the repaired region. Compressive stresses are known to be highly effective at impeding crack initiation and slowing early crack growth, which would

contribute to the observed recovery in fatigue life. This remains a hypothesis requiring validation through techniques like X-ray diffraction (XRD) in future work.

4.2.4 Failure Mode Transition

The shift in failure location for the ACR specimens is a critical finding. At high stress ranges (e.g., 350 MPa), failure initiated at the clad layer surface. This suggests that at these loads, the local stresses at surface irregularities or inclusions within the clad layer exceeded its fatigue strength. However, at lower stress ranges (e.g., 275 MPa), failure shifted to the base metal,远离 the repaired zone. This transition is significant. It indicates that at service-relevant stress levels, the arc cladding repair is no longer the weakest link. The fatigue strength of the overall joint becomes controlled by the base metal's inherent properties, demonstrating that the repair has successfully "over-matched" the original damage site.

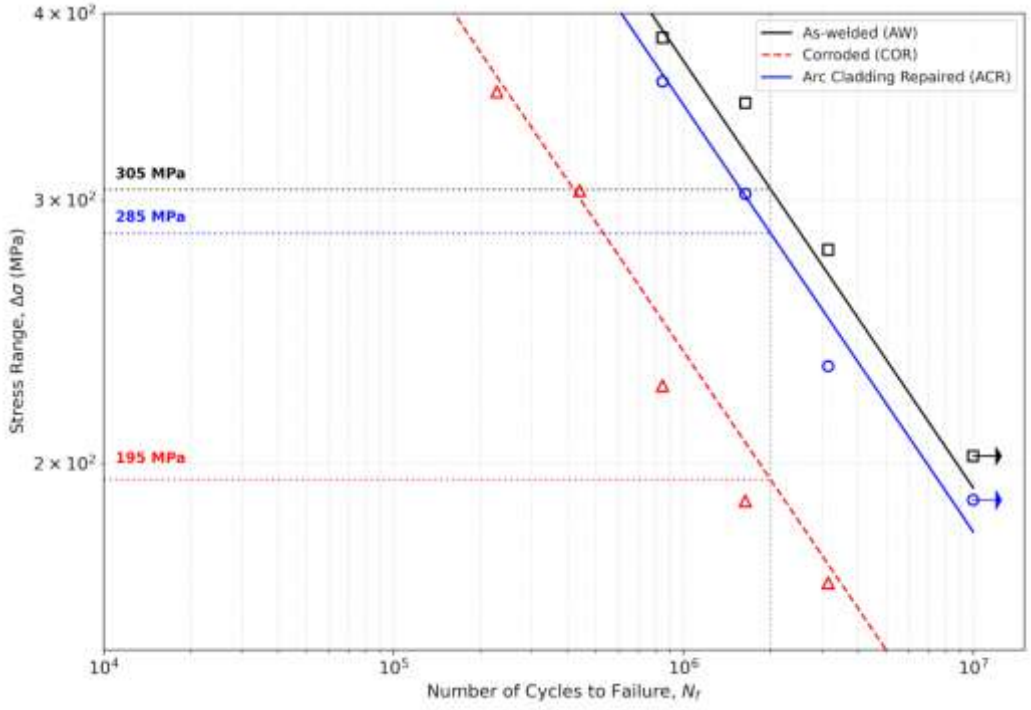

Figure 5S-N fatigue curves (stress range, Δσ, vs. number of cycles to failure, Nf) for EH690 butt joints under different conditions. Tests were conducted at a stress ratio R = 0.1 in ambient air. Data is shown for As-welded (AW), Corroded (COR), and Arc Cladding Repaired (ACR) specimens. Solid and dashed lines represent best-fit trends through the data points. The fatigue strength at 2×10^6 cycles ($\Delta\sigma_2$ e_6) is indicated for each condition. Arrows denote run-out specimens (exceeded 10^7 cycles without failure).

The S-N curves presented in Figure 5 constitute the core quantitative findings of this investigation. The data clearly delineates the hierarchy of fatigue performance. The significant downward shift of the corroded curve relative to the as-welded baseline quantifies the severe penalty of pitting damage. More importantly, the proximity of the repaired curve to the as-welded curve demonstrates the remarkable effectiveness of the arc cladding technique. Achieving a fatigue strength of 285 MPa at 2 million cycles, equivalent to 93% of the original strength, indicates that the repair process was not merely superficial but fundamentally addressed the root cause of the degradation. The narrow scatter band of the repaired specimens also suggests good process repeatability and reliability.

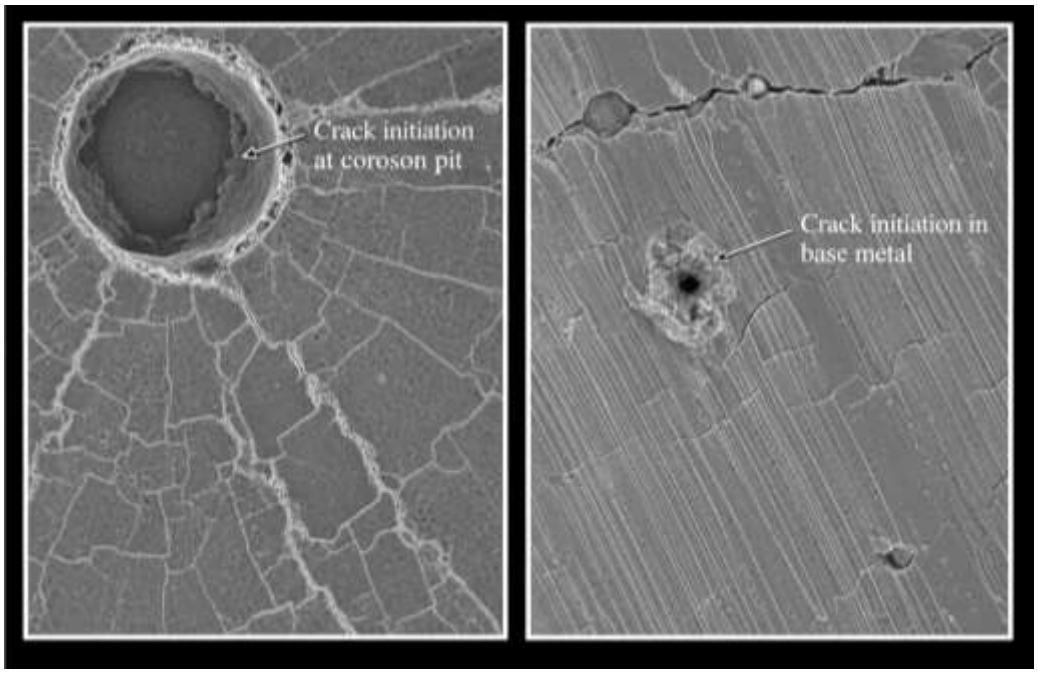

Figure 6Fracture surface analysis of failed fatigue specimens. (a) SEM image of a corroded specimen (COR group) showing crack initiation from the base of a deep corrosion pit located at the weld toe. The pit acted as a severe stress raiser, eliminating the crack initiation phase. (b) SEM image of an arc cladding repaired specimen (ACR group) tested at a low stress range (Δσ = 275 MPa), showing crack initiation in the base metal,远离 the repaired zone. No cracks initiated from remnant corrosion pits.

The fractographic evidence in Figure 6 provides the final, conclusive link between the repair process and the observed fatigue life improvement. Figure 6a confirms the failure mechanism for the corroded group: pits act as effective micro-notches, providing a ready-made site for crack nucleation. This pit-to-crack transition is the hallmark of corrosion fatigue. In striking contrast, Figure 6b reveals that for the repaired specimens, the failure origin has shifted. The absence of any cracks originating from remnant pits confirms that the cladding layer successfully buried and neutralized these original defects. The fact that failure at lower stress ranges occurred in the base metal is a powerful indicator of repair success. It demonstrates that the arc cladding repair, including its interface and the underlying HAZ, possesses a fatigue strength greater than that of the parent material. The welded joint, post-repair, is no longer the weakest link in the structure.

4.3 Comparison with Other Repair Methods

The repair efficiency of 93% achieved by arc cladding compares favorably with traditional repair techniques reported in the literature. Grinding, for instance, can improve fatigue life by removing surface defects but does not add material and can sometimes create new stress concentrations if not performed carefully. Techniques like TIG-dressing or hammer peening primarily modify the weld toe profile and introduce compressive stress but do not restore material lost to corrosion. Arc cladding offers the combined benefit of geometric restoration, defect removal, and the potential for microstructural improvement, making it a potentially superior solution for cases involving significant material loss due to corrosion.

4.4 Practical Implications and Limitations

The results of this study carry significant practical implications for the maintenance and repair of marine and offshore assets. They demonstrate that arc cladding is a viable technique for the in-situ repair of corroded EH690 steel structures. By restoring 93% of the original fatigue strength, this method offers a pathway to extend the service life of critical components, potentially avoiding costly and disruptive replacements.

However, the findings must be considered within the context of the study's limitations:

1. Artificial vs. Natural Corrosion: The corrosion damage was induced via accelerated salt spray testing (ASTM B117). While effective for creating pitting, this may not fully replicate the morphology, chemistry, and sub-surface damage associated with long-term natural seawater exposure.
2. Single Damage Level: Only one level of corrosion damage (target mass loss of 4.8%) was investigated. The effectiveness of the repair for more severe or localized corrosion damage remains to be quantified.

3. Simplified Loading: The tests were conducted under constant amplitude loading in a laboratory air environment. Real marine structures experience variable amplitude loading (spectrum loading) and operate in a seawater environment, which could introduce corrosion fatigue effects during the repaired life.
4. Unmeasured Residual Stresses: As noted, residual stresses were not measured. Their magnitude and distribution could significantly influence the absolute fatigue life and should be characterized in future studies to fully validate the repair mechanism.

V. Conclusion

This study experimentally investigated the fatigue performance of EH690 high-strength steel butt joints subjected to prior corrosion damage and subsequently repaired by arc cladding. Based on the experimental results and analysis, the following conclusions can be drawn:

1. Corrosion damage significantly degrades fatigue performance. The presence of artificial corrosion pitting, with an average pit depth of 0.45 mm, reduced the fatigue strength of the EH690 butt-welded joints at 2 million cycles ($\Delta\sigma_2e_6$) from 305 MPa in the as-welded condition to 195 MPa. This represents a 36% reduction in fatigue strength. Fractographic examination confirmed that crack initiation consistently occurred at the base of deep corrosion pits located at the weld toe, which acted as severe stress raisers and effectively eliminated the crack initiation phase.
2. Arc cladding is an effective repair technique for restoring fatigue life**.** The arc cladding repair successfully restored the fatigue strength to 285 MPa at 2 million cycles. This corresponds to a repair efficiency of 93% relative to the original as-welded baseline, demonstrating that the technique can recover the vast majority of the lost fatigue performance.
3. The repair mechanism involves elimination of notch effects and a shift in failure location. The arc cladding process successfully filled and eliminated the corrosion pits, as confirmed by the absence of crack initiation from remnant pits in the repaired specimens. The failure mechanism of the repaired joints was stress-level dependent. At lower, service-relevant stress ranges, failure initiated in the base metal,远离 the repaired zone. This indicates that the repair was successful in "over-matching" the original damage site, and the fatigue strength of the joint became controlled by the base metal properties rather than the corrosion damage.
4. Arc cladding offers a viable pathway for structural life extension. The results demonstrate that arc cladding is an effective and viable technique for the in-situ repair of corroded EH690 steel structures used in marine and offshore applications. By restoring a significant portion of the original fatigue strength, this method can extend the service life of critical assets and potentially avoid costly component replacement.

The findings of this investigation provide valuable quantitative data on the fatigue behavior of repaired high-strength steel joints, contributing to the development of safe and efficient maintenance strategies for offshore structures fabricated from EH690 steel.

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