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# Fatigue Life Reduction Due to Weld Defects in Submarine Pressure Hull Materials: A Review

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ABSTRACT

*Weld defects represent a critical challenge in the structural reliability of submarine pressure hulls, where components operate under severe cyclic hydrostatic loading and corrosive deep sea environments. In high strength steels and titanium alloys commonly used for submarine fabrication, welding introduces microstructural heterogeneity, residual tensile stresses, and geometric discontinuities that significantly reduce fatigue life. Even small imperfections such as porosity, inclusions, lack of fusion, and weld toe cracks act as potent stress concentrators, accelerating crack initiation and early propagation. These effects are intensified in spherical and cylindrical pressure hulls, where complex three dimensional stress fields and nonstandard crack shapes limit the applicability of conventional fatigue models. Hydrostatic compression, combined with residual stress redistribution, further promotes unexpected crack growth behavior, reducing fatigue thresholds and shortening service life. Evidence from experimental studies and numerical simulations consistently reveals that defect morphology, HAZ softening, local stiffness reduction, and environmental factors jointly govern fatigue degradation in submarine welds. Moreover, early short crack growth contributes disproportionately to total fatigue damage, emphasizing the need for defect sensitive assessment methods. Furthermore, localized plastic deformation at defect tips under extreme hydrostatic pressure necessitates fracture mechanics models explicitly accounting for non idealized crack geometries. This review synthesizes current understanding of how welding induced imperfections influence submarine pressure hull fatigue performance and highlights major research gaps related to multi axial loading, crack shape evolution, and deep sea failure mechanisms. The findings support the development of improved welding practices, advanced inspection techniques, and refined fatigue life prediction frameworks tailored for submarine structural safety.*

*Keywords: Submarine pressure hull; weld defects; fatigue life; crack growth; residual stresses*

## INTRODUCTION

Welding is a cornerstone manufacturing process in marine and structural engineering, yet the mechanical integrity and long term performance of load bearing joints are fundamentally compromised by inherent imperfections (Vaidya et al. 2009; Wahab et al. 2004). These weld defects stemming from unstable process parameters, metallurgical incompatibilities, or adverse assembly environments induce complex microstructural and mechanical alterations that significantly degrade fatigue resistance (Gajdoš et al. 2018; Shao et al. 2019). By disrupting uniform stress transfer and intensifying localized fields, such discontinuities serve as dominant initiators of fatigue failure, particularly in high-stakes structures like submarine hulls (Oliveira et al. 2016; Ullah et al. 2016). The acceleration of crack nucleation is further driven by localized microplasticity and the amplification of notch effects (Wang et al. 2015). Moreover, the heterogeneous microstructures generated during thermal cycling spanning the fusion zone (FZ), heat affected zone (HAZ), and base metal (BM) create mechanical mismatches that exacerbate cyclic strain localization (Liljedahl et al. 2008).

Consequently, ensuring pressure hull reliability necessitates a profound understanding of how high strength alloys respond to welding-induced changes and residual stresses. While these materials offer superior static strength, their sensitivity to environmental and microstructural anomalies dictates the need for a synthesized approach to structural assessment. By integrating experimental data, numerical modeling, and mitigation strategies, this review clarifies the governance of weld defects over fatigue performance in submarine applications. This holistic perspective, grounded in extensive research on weldability (Abdel et al. 2023), aims to refine production practices and enhance the reliability of fatigue life prediction models for underwater systems.

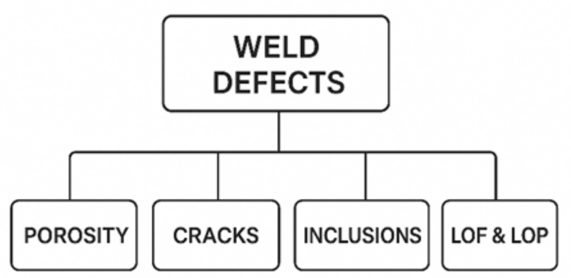


FIGURE 1. Classification of weld defects into volumetric (porosity/inclusions), planar (cracks/lack of fusion), and geometric (undercut/misalignment) categories.

## METHODOLOGY

The methodological framework of this review systematically evaluates the multifaceted impact of welding imperfections on the operational longevity and structural integrity of undersea vessels. Central to this analytical procedure is a multidisciplinary approach that correlates defect morphology with the mechanical degradation of high strength naval alloys, particularly quenched and tempered steels and titanium alloys (Vaidya et al. 2009; Zhao et al. 2011). By integrating empirical data, numerical simulations, and fracture mechanics models, this synthesis investigates the critical transition from crack initiation to propagation under severe cyclic hydrostatic loading (Shao et al. 2019; Ullah et al. 2016). To achieve a comprehensive assessment, the following integrated procedures were implemented:

### CLASSIFICATION AND CHARACTERIZATION OF WELD DEFECT

Weld discontinuities, though often microscopic, fundamentally compromise joint integrity by interrupting material continuity and intensifying localized stress gradients during cyclic service (Liu et al. 2012; Wang et al. 2017). These flaws ranging from planar defects like lack of fusion to volumetric voids and geometric irregularities collectively disrupt uniform stress transfer and amplify localized notch effects (Prokić et al. 2010; Akçakale et al. 2021). Regardless of their specific morphology, the presence of such irregularities reduces the effective load-bearing capacity and serves as a catalyst for fatigue resistance degradation. Consequently, a comprehensive mechanical characterization of these defect mechanisms is vital for ensuring the structural reliability and fatigue life accuracy of pressure-retaining systems.

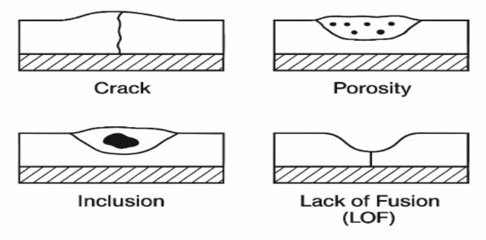


FIGURE 2. Classification of common weld defects in high-strength naval steels, illustrating the morphological differences between volumetric pores and planar cracks.

### CRACK

Cracks are critical maritime weld defects, acting as stress concentrators where geometric notches and tensile residual stresses converge to trigger fatigue (Du et al. 2023). Susceptibility varies by configuration: toe cracking dominates butt welds, while fillet welds are prone to root failure. Semi elliptical surface cracks drive degradation, their propagation dictated by local geometry, residual stresses, and mechanical mismatches across the weld, HAZ, and base material (Natori et al. 1986). XFEM studies confirm that high strain energy density regions serve as primary sites where tensile stresses accelerate growth (Ferro et al. 2016).

In submarine hulls, hydrostatic loading amplifies this hazard by introducing multiaxial stress states that increase predictive uncertainty (Ambriz et al. 2010). Accurate assessment requires coupled analysis of defect geometry and residual stresses (Kim et al. 2010; Ma et al. 2014). This complexity is underscored by crack behavior under cyclic compression, where unloading induced tensile stresses promote growth (Luo et al. 2018). Furthermore, non-penetrating 3D toe cracks in spherical or cylindrical hulls create unique stress states deviating from conventional tests, necessitating advanced predictive frameworks (Zhu et al. 2021).

### POROSITY

Porosity arises from gas entrapment, creating volumetric discontinuities that compromise joint integrity by reducing load-carrying areas and elevating local stresses (Liu et al. 2012; Wang et al. 2017). These voids are driven by inadequate shielding, contamination, and rapid cooling in

GMAW and GTAW processes (Prokić et al. 2010). To mitigate risks, pulsed heat inputs and helium-enriched shielding gases effectively suppress pore nucleation (Wang et al. 2017; Du et al. 2023). In submarine assembly, porosity criticaly interacts with residual stresses and cyclic hydrostatic loading, accelerating fatigue damage and lowering crack initiation thresholds (De et al. 2011; Ahn et al. 2017).

## INCLUSIONS

Non metallic inclusions, such as oxides and slag, emerge from contamination and serve as critical discontinuities that compromise fatigue resistance by intensifying local stresses (Cheng et al. 2021). Their mechanical severity is dictated by morphology; specifically, elongated or clustered formations induce greater anisotropic stress intensification than isolated spherical particles (Hu et al. 2018). In submarine pressure hulls, these effects are compounded by porosity, hydrogen uptake, and seawater corrosion, collectively accelerating stress corrosion cracking and diminishing fatigue margins (De et al. 2011; Ahn et al. 2017). Consequently, mitigating failures necessitates robust quality control integrating conventional ultrasonic testing with emerging AI-based vision systems (Hu et al. 2014).

## LACK OF FUSION (LOF) AND LACK OF PENETRATION (LOP)

Planar defects such as lack of fusion (LOF) and lack of penetration (LOP) behave as crack like discontinuities and can severely compromise joint integrity. They typically form when molten metal fails to bond properly due to insufficient heat input, improper technique, or misalignment during multi pass welding (Alam et al. 2009; Singh et al. 2002). These defects extensively increase stress intensity and promote crack growth under cyclic loading, which is particularly pivotal for enclosure structure where hydrostatic compression may contribute to through thickness failure (Farajian et al. 2006). Accordingly, real time monitoring systems, advanced sensors, and high resolution UT or radiography remain essential for detecting LOF/LOP and ensuring structural integrity (Feng et al. 2025).

## IDENTIFICATION OF CAUSAL FACTORS IN FABRICATION

This review evaluates how welding parameters, metallurgy, environment, and welder proficiency influence fatigue performance. By linking forgery anomalies to microstructural vulnerabilities and residual stresses, it establishes a technical framework for improved quality control in submarine pressure hull manufacturing, including:

## IMPROPER WELDING PARAMETERS

Welding parameters current, voltage, speed, and heat input determine bead geometry, microstructure, and defect formation. Deviations from optimal windows trigger discontinuities like porosity, undercutting, and incomplete fusion (Nakamura et al. 2001; Oikonomou et al. 2019). Thermal balance is critical: excessive heat enlarges the heat affected zone (HAZ) and coarsens grains, reducing toughness, while insufficient heat causes bonding and fusion defects (Kurt et al. 2007).

In pressure hull fabrication, precise control mitigates detrimental thermal cycles in steels like HY-80. High heat input induces unfavorable tensile residual stresses and HAZ softening, while inadequate penetration compromises pressure-bearing capacity. Consequently, structural integrity requires adaptive monitoring and predictive modeling to preemptively address welding induced discontinuities that undermine operational safety.

## MATERIAL QUALITY

The performance of submarine welds is fundamentally dictated by material quality, particularly in pressure hulls fabricated from high strength low alloy steels like HY-80 and HY-100. While these alloys are chosen for their superior toughness and strength to weight ratios, they remain inherently susceptible to welding induced phase transformations such as martensitic embrittlement and hydrogen assisted cracking driven by rapid cooling cycles. Research by Davis et al. (1983) underscores that these metallurgical sensitivities are further complicated by the welding process itself, which significantly influences corrosion fatigue crack growth in HY-100.

To address these challenges, the adoption of advanced techniques like hybrid laser-arc welding and optimized filler compositions has proven effective in reducing porosity and enhancing joint integrity, provided that stringent cleanliness and parameter stability are maintained (Cao et al. 2011). Ultimately, the preservation of microstructural uniformity and the mitigation of fatigue inducing anomalies rely on a holistic approach that integrates certified material selection, rigorous pre-weld preparation, and post weld heat treatment (PWHT) (Elmesalamy et al. 2014).

## ENVIRONMENTAL CONDITIONS

Environmental conditions ranging from atmospheric humidity and temperature to the presence of contaminants play a decisive role in governing weld quality and the subsequent susceptibility to cracking. High humidity levels are particularly detrimental, as they facilitate hydrogen absorption that leads to microporosity and hydrogen-induced cracking (Rouffet et al. 2010; Ahlatçı et al. 2010). These risks are further compounded by low ambient temperatures and drafts, which accelerate heat loss and increase the likelihood of cold cracking and incomplete fusion (Filho et al. 2010). Furthermore, the ingress of reactive gases like oxygen and nitrogen can induce the formation of brittle oxides and nitrides, ultimately degrading the ductility and fatigue performance of the joint (Li et al. 2022; Pal et al. 2011).

In the specialized context of submarine manufacturing, environmental control is critical during both fabrication and service life. The harsh marine environment exacerbates these vulnerabilities by promoting salt induced pitting corrosion and hydrogen diffusion, particularly within the heat affected zone (HAZ), where localized embrittlement accelerates fatigue crack growth from pre existing defects (Wu et al. 2005). Consequently, maintaining structural integrity requires strict regulation of humidity, shielding gas purity, and the implementation of rigorous pre and post weld storage protocols for electrodes and filler metals to mitigate moisture related defect initiation.

## WELDER SKILL

The proficiency of welding personnel is a decisive factor in the fabrication of submarine pressure hulls, particularly when joining high strength steels like HY-80 through processes such as GMAW and FCAW (Sun et al. 2022). Inadequate technique frequently introduces critical planar discontinuities specifically lack of fusion (LOF) and lack of penetration (LOP) which fundamentally compromise the structure's pressure resistance (Baykara et al. 2025). To mitigate these risks, certified welders utilize advanced training to precisely manage the interplay between heat input, travel speed, and shielding gas composition. This human expertise is increasingly augmented by integrated robotic systems, such as adaptive GMAW with real time feedback, which allow for superior consistency and the preemptive reduction of defect formation (Truong et al. 2025).

Ultimately, the synergy between skilled craftsmanship and automated technology must be validated through a robust quality assurance framework. By linking welder performance and robotic output to measurable integrity outcomes through ultrasonic and radiographic inspection, the industry can ensure the heightened safety and reliability required for submarine operational environments (Ramadayanti et al. 2024; Baykara et al. 2025).

## QUANTITATIVE EVALUATION ON FATIGUE LIFE

The methodology evaluates the governing role of weld flaws in fatigue life, specifically how geometric and metallurgical inconsistencies disrupt local stress-strain fields to drive crack initiation (Fuentes et al. 2014; Vaidya et al. 2009). A significant safety challenge lies in the nature of fatigue, which often originates from microscale discontinuities without manifesting macroscopic deformation, making early detection of microcracks vital for structural preservation (James et al. 2004).

In the specific context of submarine hulls, fatigue resistance is a complex function of material microstructure, residual stress, and cyclic hydrostatic pressure. In high-strength alloys such as HY-80, HY-100, and titanium, sub-millimeter imperfections act as primary catalysts for stress amplification, which can drastically reduce fatigue life regardless of the material's nominal static strength (Gandomkar et al. 2022; Wang et al. 2022; Hu et al. 2021). Consequently, the integrity of these pressure-retaining structures is dictated by the collective degradation caused by porosity, lack of fusion, and microstructural heterogeneity (Zhao et al. 2011; Kihara et al. 1981). These governing factors include:

## STRESS CONCENTRATION AND FATIGUE CRACK INITIATION

Welding imperfections function as localized discontinuities that elevate the Stress Concentration Factor (SCF) significantly above nominal levels, triggering localized microplasticity and subsequent fatigue crack nucleation (Wang et al. 2015; Méndez et al. 2017; Fonseca et al. 2001). Numerical and finite element analyses consistently identify weld toes and roots as the most critical regions, where geometric irregularities converge with HAZ heterogeneity and solidification flaws to intensify localized stress fields (Wisessint et al. 2018; Xu et al. 2017). These stress driven mechanisms are severely exacerbated in submarine carcasses due to the alternating tensile compressive stresses induced by repeated diving operations (Xu et al. 2017).

In the demanding marine environment, cyclic hydrostatic loading promotes a synergy between mechanical damage and corrosion assisted degradation, which accelerates the transition from microcrack nucleation to early coalescence (Wang et al. 2022). For high strength alloys such as HY-80, this failure process is predominantly governed by the interaction between surface geometry and internal inclusions, particularly at weld toes (Lawrence et al. 1970; Parmentier et al. 2013; Bogdan et al. 2021). Furthermore, the structural integrity of the pressure hull is compromised by depth induced bending stresses that interact with construction related residual stresses (Kim et al. 2010). This localized stress amplification is most pronounced at coaming weld regions and unfused zones, where porosity and severe intensification fields accelerate failure under extreme external pressure (Wang et al. 2022; Zhao et al. 2011; Takeda et al. 1981).

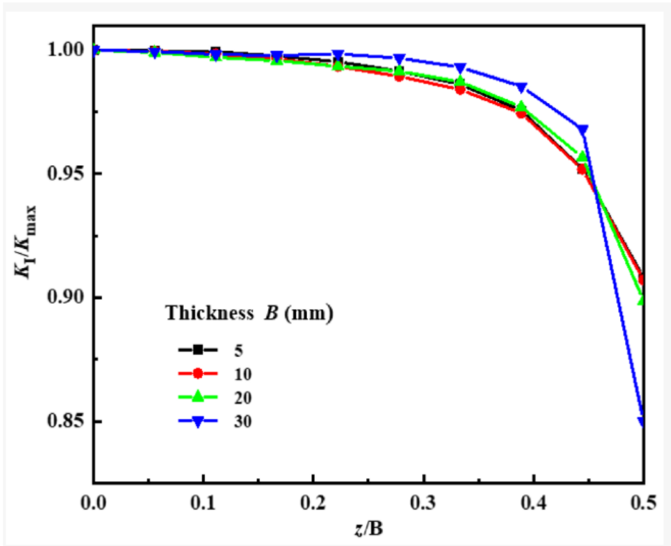


FIGURE 3. Distribution of the Stress Intensity Factor (SIF) through material thickness, showing stress peaks at the crack front under deep-sea pressure (Adapted from Zhu et al. 2021)

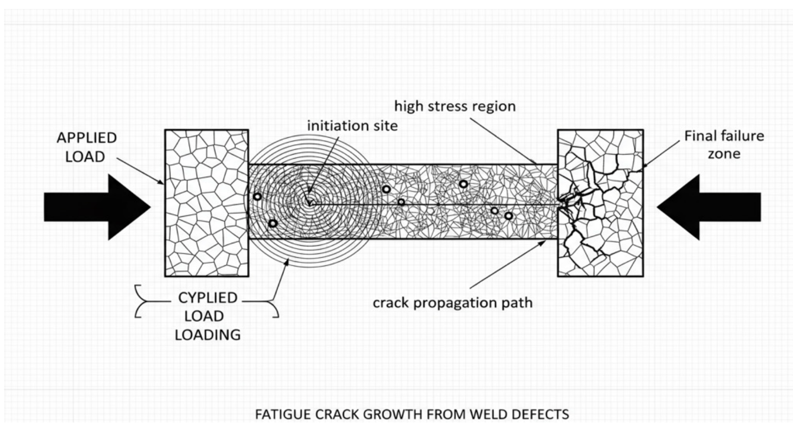


FIGURE 4. Schematic representation of the transition from microscale crack initiation at a weld defect to macroscale propagation and structural failure

## REDUCED LOAD CARRYING CAPACITY AND STRUCTURAL INTEGRITY

Weld imperfections fundamentally compromise structural integrity by reducing the effective load-bearing cross section and disrupting material continuity, which forces a redistribution of local stresses. These discontinuities specifically porosity, slag inclusions, and lack of fusion alter internal load paths, leading to localized plastic strain accumulation and premature yielding at stress levels significantly lower than those predicted for defect free joints (Riofrío et al. 2021; Song et al. 2018; Wahab et al. 2004). This degradation is particularly critical in submarine hulls, where investigations on HY-100 weldments demonstrate that geometric and material variations disproportionately influence both ultimate strength and fatigue crack initiation under variable compressive-tensile cycles (Kim et al. 2010; Cerik et al. 2013).

The severity of these shortcomings is further magnified by the specific geometry of the pressure hull. In ring-stiffened cylinders, any reduction in effective shell thickness or stiffener performance can trigger a premature transition from global to local buckling, drastically decreasing the collapse pressure (Cho et al. 2018). Similar vulnerabilities are observed in spherical pressure hulls, where the synergy between welding induced microstructural discontinuities and residual stresses weakens global resistance under deep sea hydrostatic loading (Kihara et al. 1981; Wang et al. 2022). Collectively, these findings underscore that maintaining continuous load transfer paths and managing wide-band stress spectra representative of complex hydrostatic environments are essential for ensuring the operational longevity of welded naval systems (Zhou et al. 2023).

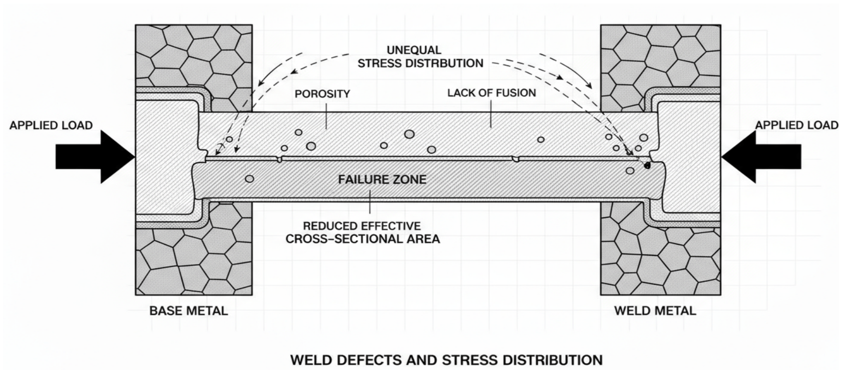


FIGURE 5. Conceptual illustration of stress concentration patterns around a weld discontinuity, showing the localized intensification that disrupts uniform load transfer in the joint

## PROPAGATION BEHAVIOR

The propagation of fatigue cracks is a complex process governed by the interplay between defect geometry, loading conditions, and local microstructural characteristics (Ye et al. 2011; Kong et al. 2011; Zhang et al. 2024). Cracks typically navigate along metallurgical boundaries or within the heat affected zone (HAZ), where reduced yield strength and the presence of micro deficiencies facilitate rapid coalescence and accelerated growth rates (Shipilov et al. 2002). This mechanical degradation is significantly exacerbated in marine environments, where hydrostatic pressure and corrosion promote anodic dissolution at the crack tip, deviating from classical Paris law behavior observed in air (Li et al. 2016; Larrosa et al. 2017).

In submarine-specific steels, the synergistic effect of seawater exposure and hydrostatic loading modifies crack morphology, often promoting preferential propagation through ferritic regions or impurity segregation lines. This interaction increases the risk of catastrophic failure through unstable crack coalescence, particularly in complex geometries such as spherical hulls. In these configurations, three dimensional surface cracks at weld toes experience intense out of plane constraints that render standard fatigue parameters less reliable for life prediction (Zhu et al. 2021). Furthermore, experimental evidence from deep sea weldments confirms that the combination of pre existing flaws and heterogeneous microstructures drives faster and less stable propagation under cyclic pressure, necessitating more robust predictive frameworks for underwater pressure hulls (Wang et al. 2022).

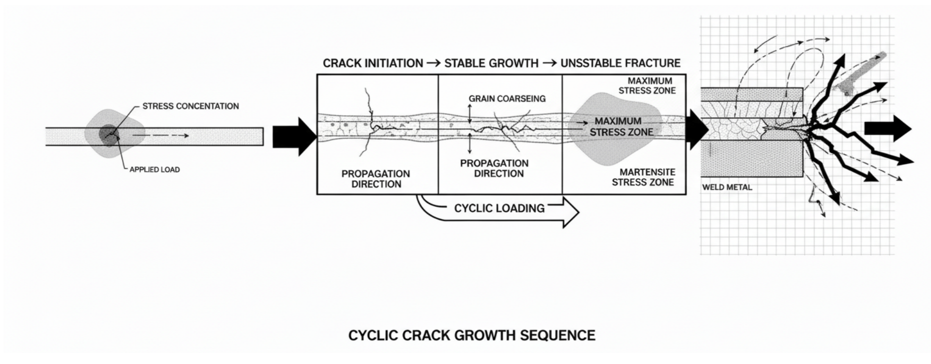


FIGURE 6. Schematic representation showing sequential stages of crack tip advancement and plastic zone evolution under cyclic loading conditions

## MATERIAL BEHAVIOR

The welding process inherently generates a heterogeneous microstructural gradient across the fusion zone (FZ), heat affected zone (HAZ), and base metal (BM), leading to significant mechanical incompatibility (Liljedahl et al. 2008). This thermal cycling triggers grain coarsening and phase transformations that simultaneously degrade hardness and toughness, creating a scenario where softened HAZ regions accumulate localized cyclic strain while brittle weld metal becomes increasingly susceptible to intergranular cracking (Venkateswaran et al. 2005; Remes et al. 2017; Huang et al. 2022; Saju et al. 2022).In submarine grade steels, these microstructural anomalies are further compromised by the synergy of hydrostatic pressure and residual stresses, which modify the effective stress intensity range (ΔK_eff) and lower crack growth thresholds (Muñoz et al. 2023). This relationship is particularly evident in crack growth under CCT (Center Cracked Tension) conditions, where the correlation with (ΔK_eff) is often accelerated by cleavage fracture within the weld metal (Kitsunai et al. 1998). This behavior remains critical under cyclic compressive hydrostatic loading, where unloading induced tensile residual stresses can drive propagation even in the absence of external tensile loads (Luo et al. 2018). Ultimately, the welding induced alterations to the microstructure and chemistry of high strength alloys serve as the primary governors of deformation and fatigue degradation in pressure hulls (Kihara et al. 1981; Takeda et al. 1981).

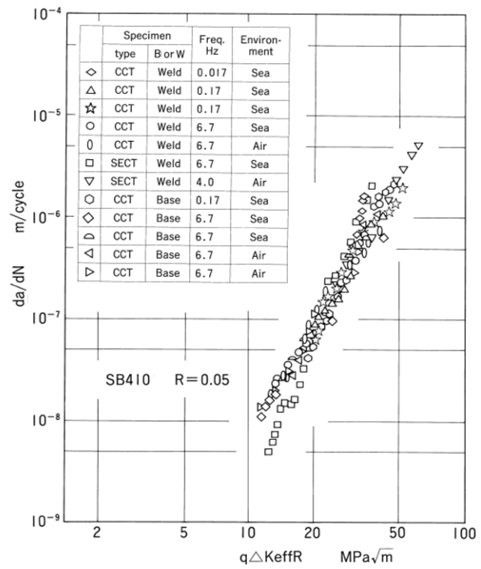


FIGURE 7. The base and weld metals show material behavior in which fatigue crack growth rates consistently follow the $q\Delta K_{eff}R$ trend in both air and synthetic seawater. (Kitsunai et al. 1998)

## FATIGUE LIFE REDUCTION

Fatigue life reduction in welded structures stems from the synergistic effects of discontinuities, residual stresses, and microstructural heterogeneity, which intensify localized stress fields (Venkateswaran et al. 2005; Remes et al. 2016; Kim et al. 2010). Degradation accelerates meaningfully when ferrite pearlite pathways or hydrogen embrittlement are present, particularly as tensile residual stresses and low loading frequencies enhance hydrogen assisted crack growth (Venkateswaran et al. 2005; Kitsunai et al. 1998). Crucially, long crack models often underestimate damage by neglecting short crack behavior, which is highly sensitive to local microstructure and can propagate below conventional thresholds (Remes et al. 2016). Ultimately, geometric notches and microstructural inhomogeneity disrupt load transfer and accelerate both initiation and propagation (Tang et al. 2018; Shi et al. 2010). Fatigue assessment must distinguish between short cracks, which are highly sensitive to localized notch effects and microstructural barriers, and long cracks whose growth is governed by linear elastic fracture mechanics. While long crack propagation follows stable power law trends, short cracks exhibit anomalous growth rates due to the intensification of localized stress gradients near the weld toe.

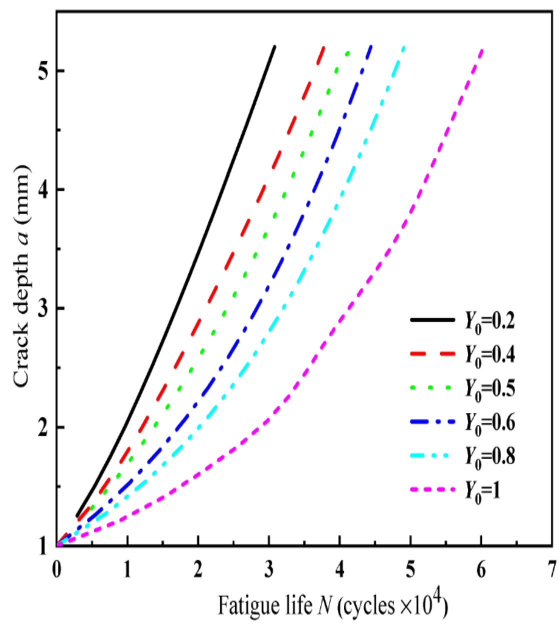


FIGURE 8. Fatigue crack growth a-N curves for different initial shape ratios, illustrating the sensitivity of service life to defect geometry (Adapted from Zhu et al. 2021).

In shell structure, this reduction is amplified by cyclic compressive hydrostatic pressure and deep-sea loading. Imperfections reduce local stiffness and promote yielding, while surface cracks at weld toes evolve toward major configurations under cyclic compression (Mackay, 2007; Zhu et al. 2021; Luo et al. 2018). Even modest residual stresses must be integrated into assessment frameworks for hulls with narrow safety margins (Liang et al. 2021). The convergence of weld errors, microstructural softening, and 3D stress states especially in pit repaired sections can reduce fatigue life beyond standard predictions (Zhao et al. 2011; Wang et al. 2022; Zhu et al. 2021). Thus, precise defect characterization is vital for submarine operational safety (Wang et al. 2022).

Fatigue life estimation is obtained by integrating the crack growth behavior. First, the local stress intensity factor is determined as $K(a) = \sigma max\ Y(a)\sqrt{\pi a}$ where the geometry function $Y(a)$ is extracted from numerical simulation. The crack opening component is then calculated using closure relation $K_{op} = f_{op}K_{max}$, allowing the effective range to be defined as $\Delta k_{eff} = K_{max} - K_{op}$. The crack growth rate may follow the modified Paris type relation, $da/dN = C_{eff}(\Delta k_{eff})^{neff}$, or the more detailed model $da/dN = A\ [K_{max}–K_{op} - \Delta K_{eff}\ th]^m \cdot [1- (K_{max}/KC_{eff})^n]$. The total fatigue life is obtained by numerical integration from the initial crack size $a_0$ to the necessary crack size $a_c$ using $N = \int_{a0}^{ac} \frac{da}{(\frac{da}{dNa})}$. During this iterative procedure, each increment updates the geometry factor, the 3-D stress intensity components, and the closure level, ensuring that the predicted life reflects the combined crack growth mechanisms. Some equation used compute residual stress, crack and fatigue life are:

1. Residual stress:

$$R_{res} = \frac{K_{min} + K_{res}}{K_{max} + K_{res}} \quad (1)$$

where $K_{min}$ and $K_{max}$ are the minimum and maximum stress intensity factors, respectively.

2. Crack growth:

a) $da/dN = A\ (K_{max} - K_{op} - \Delta K_{th})^m / (1 - (K_{max} / K^{Ic})^p)$ (2)

(A Paris-type, using an effective SIF amplitude $\Delta K_{eff}$.)

b) $da/dN = Ceff\ (\Delta keff)^{neff}$ (3)

2) Fatigue Life:

$$N = \int_{a0}^{ac} \frac{da}{(\frac{da}{dNa})} \quad (4)$$

## DISCUSSION

### OVERALL INTERPRETATION

Across the literature, welding induced imperfections including cracks, porosity, inclusions, lack of fusion, and microstructural heterogeneity are consistently identified as major contributors to fatigue degradation in welded structures (Liu et al. 2012). Under deep sea operating conditions, these weaknesses interact with cyclic hydrostatic loading, overloading, and sustained loads, thereby accelerating crack growth and reducing structural capacity (Wang et al. 2022). For spherical and cylindrical pressure hulls, complex three dimensional crack geometry and multiaxial stress fields highlight limitations of traditional plate based fatigue models (Zhu et al. 2021). Overall, the coupled effects of defect morphology, welding induced microstructural variation, and residual stress constitute the primary mechanisms governing fatigue performance in submarine welds.

### RESEARCH GAPS

Despite substantial progress in understanding weld defect driven fatigue degradation, several research gaps remain. First, many investigations emphasize isolated mechanisms such as microstructural gradients, short crack behavior, tensile residual stresses, and geometric notch effects (Venkateswaran et al. 2005; Remes et al. 2016) yet relatively few studies integrate these factors into unified predictive frameworks applicable across diverse welding procedures and service conditions. As a result, interpretations remain fragmented and model transferability is limited.

Second, conventional fatigue parameters exhibit reduced applicability to container structures, where surface cracks in spherical and cylindrical shells propagate under complex three dimensional constraints and stress states that differ greatly from standard specimen configurations (Zhu et al. 2021). Moreover, the widespread use of simplified long crack models often neglects early crack growth behavior, even though short crack propagation may dominate fatigue damage accumulation in welded joints (Remes et al. 2016). This limitation can lead to systematic underestimation of defect influence during the most momentous early stages of crack evolution.

Third, although interactions among residual stresses, weld geometry, and deep sea loading have been documented (Wang et al. 2020), the combined influence of overloading events, load sustaining cycles, multiaxial hydrostatic pressure, and welding induced microstructural heterogeneity remains insufficiently represented in existing models. Most available approaches capture only partial aspects of these coupled mechanisms and often fail to explain how residual tensile stresses evolve under fully compressive hydrostatic loadingan effect shown to accelerate crack growth in submarine structures (Luo et al. 2018). Likewise, experimentally observed effects of local stiffness reduction, early yielding, and structural scale defect interactions (Mackay, J. R., 2007) remain weakly incorporated in predictive methodologies.

Finally, despite strong evidence that weld-induced inadequacies reduce load capacity, accelerate crack growth, and shorten fatigue life (Wang et al. 2022; Luo et al. 2018; Zhu et al. 2021), current standards provide limited design level guidance addressing deep sea specific failure mechanisms. In particular, practical frameworks are still lacking for the combined effects of defect morphology, crack shape evolution, residual stress fields, and cyclic hydrostatic loading on pressure hull fatigue performance.

TABLE 1. Summary Table comparative synthesis of literature on the fatigue behavior of welded naval alloys, categorized by material type, defect morphology, evaluation methodology, and key experimental or numerical findings

| Author (Year) | Material | Weld Defect Type | Method | Main Findings | Notes / Limitations |
|---|---|---|---|---|---|
| Gandomkar et al. (2022) | HY-80 steel | Sub millimeter defects | Experimental | Small mistakes cause abrupt fatigue life reduction | Limited crack propagation data |
| Hu et al. (2014) | Subsea welded steel | Inclusions | NDT + numerical | Inclusion shape and distribution govern stress concentration | Limited fatigue life prediction |
| Kim et al. (2010) | HY-100 steel | Weld toe geometry | Experimental + FEM | Maximum stress and fatigue cracks localize at weld toes | No corrosion effects included |
| Luo et al. (2018) | Submarine pressure hull | Residual stress | Numerical crack growth | Residual tensile stress accelerates crack growth under compressive loading | Assumes idealized crack shapes |
| Mackay (2007) | subsea structures | Geometric defects | Structural assessment | Local stiffness reduction accelerates fatigue damage | specific to submarine hulls |
| Remes et al. (2016) | Welded steel joints | Short cracks | Fatigue crack growth experiments | Short crack growth dominates early fatigue life | Limited to laboratory scale joints |
| Takeda et al. (1981) | Submarine hull steel | Weld defects, residual stress | Experimental | Weld defects dominate fatigue crack initiation under cyclic pressure | Limited defect morphology analysis |
| Kihara et al. (1981) | Steel & Ti alloys | Weld defects | Experimental | Weld induced heterogeneity reduces load capacity and fatigue resistance | Early-generation testing methods |
| Wang et al. (2022) | HY series steel | Porosity, LOF | Experimental + numerical | Combined defects and hydrostatic loading severely reduce fatigue life | High test complexity limits sample size |
| Zhao et al. (2011) | Submarine hull steel | Porosity, repair defects | Fatigue testing | Weld defects dominate fatigue crack initiation under cyclic loading | Focus on surface cracks only |
| Zhu et al. (2021) | Spherical pressure shell | Weld toe surface crack | 3D FEM + fracture mechanics | Crack shape evolution strongly affects fatigue life prediction | Model dependent geometry factors |

## CONCLUSION

Weld defects remarkably reduce fatigue life by acting as stress concentrators that promote crack initiation and accelerate crack propagation. Across validated experimental and numerical studies, foibles such as porosity, lack of fusion, inclusions, and cracks consistently produce significant fatigue life reductions compared with defect free joints. This degradation is further intensified by tensile residual stresses, welding induced microstructural heterogeneity, and environmental factors including corrosion and hydrogen assisted damage.

In submarine engineering, where welded joints experience cyclic hydrostatic pressure and corrosive seawater exposure, effective defect management is hence essential. Optimization of welding parameters, use of high quality consumables, and implementation of rigorous surface preparation and heat treatment practices can improve resistance to cyclic loading. These measures should be supported by advanced non destructive testing (NDT), finite element based fatigue assessment, and real time monitoring to ensure that small limitations are detected and mitigated before progressing to basic failure.

Ultimately, achieving fatigue resistant welded structures particularly in naval and offshore applications requires multidisciplinary integration of welding science, material selection, inspection technology, and computational modeling. Establishing a cohesive framework for defect control and fatigue life management will support extended service life and improved safety of substantial systems operating in extreme deep-sea environments, including submarine pressure hulls.

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## DECLARATION OF COMPETING INTEREST

None.

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