



Hydrogen Embrittlement and Fracture Mechanisms in Laser Beam and TIG Welded Joints of S960MC Ultra-High-Strength Steel

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Abstract

The application of ultra-high-strength steel (UHSS) S960MC in safety-critical sectors is significantly limited by its susceptibility to hydrogen embrittlement (HE). Since welding operations fundamentally alter the optimized microstructure of the base material, understanding the response of welded joints to hydrogen is crucial. This study presents a comparative analysis of S960MC joints fabricated by Tungsten Inert Gas (TIG) and Laser Beam Welding (LBW) to examine how distinct welding thermal cycles influence susceptibility to degradation. Utilizing Slow Strain Rate Testing (SSRT) on electrochemically charged specimens, the research aims to identify the dominant failure pathways. The results demonstrate that TIG welding, characterized by high heat input, produces a softened Heat-Affected Zone (HAZ) that is highly susceptible to Hydrogen-Enhanced Localized Plasticity (HELP). In contrast, the rapid cooling in LBW promotes the formation of a hard martensitic Fusion Zone (FZ), leading to premature and catastrophic brittle failure driven by Hydrogen-Enhanced Decohesion (HEDE) at stresses well below the macroscopic yield strength. Detailed fractographic analysis confirms the synergistic interplay between HELP and HEDE mechanisms, providing critical insights into the structural integrity of UHSS weldments in hydrogen-rich environments.

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1. Introduction

Ultra-High-Strength Steels (UHSS), such as the thermomechanically processed S960MC, are increasingly pivotal in the automotive and heavy-lifting industries due to their exceptional strength-to-weight ratio, which allows for significant gauge reduction and improved energy efficiency. This relevance is also reflected in recent research on materials-property improvement for electric-vehicle applications (Mikolajčík et al., 2025) and root-cause assessment of welded heavy-machinery components (Arsić et al., 2026).

However, the application of UHSS may be strictly limited by their high susceptibility to hydrogen embrittlement (HE), a phenomenon where the ingress of atomic hydrogen into the

metal lattice degrades mechanical properties, leading to premature failures (Schaupp et al., 2020). To ensure safety, the integrity of UHSS exposed to hydrogen-containing environments is checked using modern methods recently used to monitor the integrity of gas pipelines (Świt et al., 2024).

While the BM (Base Material) derives its properties from a controlled precipitation hardening and grain refinement process, subsequent welding operations significantly alter this optimized microstructure, creating zones with distinct sensitivities to hydrogen-induced degradation (Guo et al., 2015).

The aim of this paper is to perform a comparative experimental analysis of the HE susceptibility of S960MC steel joints fabricated by Laser Beam Welding (LBW) and Tungsten Inert Gas (TIG) welding. By utilizing slow strain rate test-



ing (SSRT) on electrochemically charged specimens combined with detailed fractography, this work seeks to correlate specific welding thermal cycles with the resulting fracture morphology and determine the dominant failure pathways in each welding regime.

2. Literature review

The susceptibility of welded joints to HE is determined by the welding thermal cycle, local phase transformations, residual stresses, and hydrogen transport in the individual zones of the joint. In thermomechanically processed UHSS, including S960 and S960MC grades, the required combination of strength and toughness is obtained through grain refinement, precipitation strengthening, and bainitic-martensitic constituents. Welding disturbs this optimized state and produces a heterogeneous system composed of the Fusion Zone (FZ), Heat-Affected Zone (HAZ), and Base Material (BM). The local response to hydrogen is therefore governed not only by the nominal strength level of the steel but also by hardness gradients, phase morphology, and the distribution of reversible and irreversible hydrogen traps (Guo et al., 2015; Mičian et al., 2020; Li et al., 2024).

The welding process has a decisive influence on the extent of these heterogeneities (Ivković et al., 2023; Ilić et al., 2020). Arc-based welding processes are usually associated with higher heat input, longer cooling time, and wider HAZ formation. Under such conditions, tempering of the initial bainitic-martensitic structure may occur in the Inter-Critical (IC) and Sub-Critical (SC) HAZ, resulting in local softening and preferential strain localization during loading. In contrast, laser beam welding introduces a highly concentrated heat source, steep thermal gradients, and rapid cooling (Ulewicz & Radek, 2026). This limits the width of the affected zone and reduces global deformation of the joint, but it may also promote hard, non-equilibrium microstructures in the FZ, especially martensite or martensite-bainite mixtures. Such regions can show favourable strength overmatching in air, while their resistance to hydrogen-assisted cracking may be reduced due to high hardness and a high density of trapping sites (Guo et al., 2015; Mičian et al., 2020).

For S960MC steel, the HAZ is of particular importance because its properties are strongly affected by the $t_{8/5}$ cooling time. Longer cooling times favour tempering and softening, whereas shorter cooling times may preserve or increase local hardness through martensitic and bainitic transformations. These changes create a metallurgical notch effect and determine the location of plastic deformation during slow strain rate testing. In hydrogen-containing environments, the same microstructural gradients may also control hydrogen accumulation, crack initiation, and the transition from stable plastic deformation to premature fracture. Consequently, the evaluation of welded S960MC joints requires the simultaneous consideration of heat input, cooling rate, local hardness, and fracture path (Mičian et al., 2020; Schaupp et al., 2020). Comparable studies on HSLA welded joints also indicate that welding procedure affects impact toughness, microstructure,

and microhardness distribution in the individual zones of the joint (Miletić et al., 2020).

Hydrogen-assisted cracking in welded high-strength steels is usually described by the simultaneous presence of diffusible hydrogen, tensile or residual stress, and a susceptible microstructure. Hard zones formed during welding, significant hardness gradients, non-metallic inclusions, prior-austenite grain boundaries, and interfaces between different phases may act as preferential sites for hydrogen trapping and crack initiation. In 960 MPa grade weldments, this problem is especially relevant because local mechanical properties may differ markedly from the nominal properties of the BM. Therefore, welds that meet conventional strength requirements in air may exhibit a significantly different response after electrochemical hydrogen charging or in hydrogen-containing service conditions (Schaupp et al., 2020; Zhang et al., 2024).

The mechanism of hydrogen embrittlement in steels should be interpreted as a combined action of several processes rather than as a single isolated phenomenon. It involves the synergistic interplay between Hydrogen-Enhanced Localized Plasticity (HELP) and Hydrogen-Enhanced Decohesion (HEDE) (Djukic et al., 2019).

The HELP mechanism proposes that hydrogen shields the elastic field of dislocations, thereby increasing their mobility and promoting localized plastic deformation even at stress levels below the macroscopic yield strength (Sofronis and Birnbaum, 1995). Conversely, the HEDE mechanism posits that high local concentrations of hydrogen reduces the cohesive strength of atomic bonds at crack tips, interfaces, or highly stressed microstructural traps, facilitating brittle cleavage or intergranular fracture (Djukic et al., 2015).

The dominant fracture mode depends on the local hydrogen concentration, trap character, stress state, and ability of the microstructure to accommodate plastic deformation. As a result, hydrogen-charged welds may exhibit mixed fracture morphologies, including shallow dimples, quasi-cleavage facets, intergranular features, and secondary cracking (Djukic et al., 2019; Li et al., 2024; Zhang et al., 2024).

Recent work on advanced high-strength steel weldments indicates that trap engineering and microstructural stabilization can improve resistance to hydrogen damage. Beneficial carbide precipitation may reduce the amount of harmful diffusible hydrogen and modify crack initiation behaviour, whereas incoherent oxide inclusions and hard martensitic regions may intensify local hydrogen accumulation and promote brittle fracture. This is directly relevant to the comparison of TIG and laser welded S960MC joints. The former is expected to produce a wider but softer HAZ with a more gradual loss of ductility, whereas the latter may form a narrow, hard FZ susceptible to sudden hydrogen-assisted failure. For this reason, the current research relates the welding thermal cycle, microhardness profile, hydrogen-charged mechanical response, and fracture morphology to identify the dominant degradation mechanism in each welded joint (Djukic et al., 2019; Zhang et al., 2024; Xue et al., 2025).

3. Experimental

3.1. Material and sample preparation

The experimental material consisted of S960MC structural steel sheets (hot rolled under Thermomechanical Controlled Processing – TMCP) with a nominal thickness of 4 mm. The initial microstructure is typically composed of a complex mixture of bainite and tempered martensite, enhanced by microalloying elements (Ti, Nb, V) that form fine carbonitrides intended for grain refinement. The chemical composition was verified using Glow Discharge Optical Emission Spectroscopy (GDOES). The measurements revealed slightly elevated levels of carbon (0.17 wt.%), manganese (1.38 wt.%), and silicon (0.30 wt.%) compared to the EN 10149-2 standard limits, implying slightly higher hardenability of the investigated batch (detailed chemical composition is provided in Table 1 in Appendix A). Flat dog-bone tensile specimens were extracted from the sheets using wire electrical discharge machining (WEDM) to minimize thermal and mechanical alteration of the gauge section (Fig. 1).

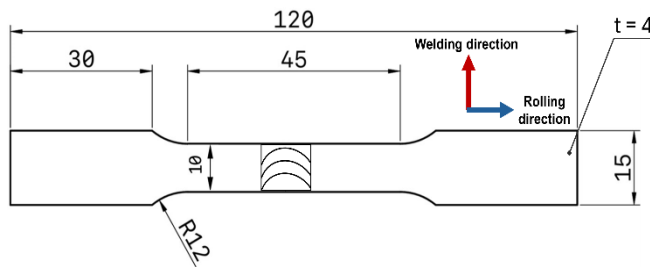


Fig. 1 Schematic representation of the tensile test specimen with a central weld.

3.2. Welding parameters

Autogenous bead-on-plate welded joints (without filler material) were fabricated using LBW and TIG processes. This approach was deliberately chosen to eliminate the effects of dilution with filler wire, ensuring that the microstructural evolution is primarily governed by the thermal history of the BM. LBW was performed using a high-power solid-state fiber laser (IPG YLR 4500) in keyhole mode with a focal position of -4 mm. TIG welding was executed automatically using a robotic arm in DCEN polarity. Pure argon (99.99%) was used as a shielding gas for both processes at a flow rate of 12 L/min. The heat input Q was calculated using the formula $Q = \eta \cdot (P/v)$. Assuming a thermal efficiency η of 0.5 for LBW and 0.6 for TIG, the calculated heat inputs were approximately 117 J/mm for LBW and 350 J/mm for TIG. The primary welding parameters are compared in Table 2.

Table 2. Summary of welding parameters and calculated heat input

Process	Power / Current & Voltage	Travel speed (mm/s)	Heat input (J/mm)
LBW	3500 W	15.0	117
TIG	170 A, 12 V	3.5	350

3.3. Hydrogen charging and mechanical testing

To evaluate HE susceptibility, specimens were electrochemically charged with hydrogen prior to testing. Cathodic polarization was carried out in an aqueous solution of 0.05 M H_2SO_4 with the addition of 1 g/L potassium thiocyanate (KSCN). The KSCN acts as a specific hydrogen recombination poison, effectively suppressing the recombination reaction ($H_{ads} + H_{ads} \rightarrow H_2$) at the steel surface and promoting atomic hydrogen absorption into the metal lattice (Drimalová et al., 2024). Charging was conducted at ambient temperature for 8 hours at constant current densities of 0.5 mA/cm² and 1.0 mA/cm². Schematic representations of the specimen geometry and the electrochemical cell are depicted in Fig. 2.

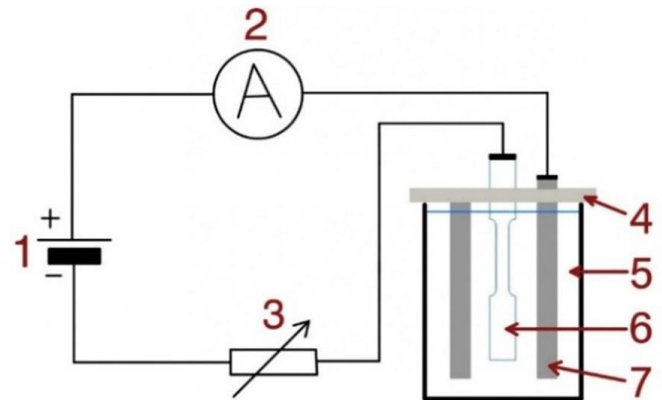


Fig. 2 Schematic representation of electrochemical hydrogen charging.

The electrical circuit (Fig. 2) comprised a stabilized DC power supply (1) (Mastech HY3003-3) connected in series with an ammeter (2) and a variable decade resistor (3) (XL6) to maintain constant current. The specimen (6) served as the working electrode (cathode), while a platinized tungsten mesh (7) was employed as the inert counter electrode (anode) to ensure stable conductivity without contaminating the electrolyte.

Uniaxial SSRT was performed immediately after charging on a servo-hydraulic frame to minimize hydrogen effusion. The tests used a constant crosshead speed of 0.5 mm/min (initial strain rate of $\approx 1 \times 10^{-4} s^{-1}$). Susceptibility was quantified using the Hydrogen Embrittlement Index (HEI), defined as $HEI = (A_{air} - A_H) / A_{air} \times 100\%$, where A_{air} and A_H represent elongation at fracture in uncharged and hydrogen-charged conditions, respectively. Following the tests, fracture surfaces were examined using a ZEISS SUPRA 35 Scanning Electron Microscope (SEM). Additionally, microhardness profiles across the weld cross-sections were mapped using the Vickers method (HV0.5).

4. Results and discussion

4.1. Microhardness profiles

The hardness distribution strongly reflects the contrasting thermal cycles of the employed welding methods. The TIG

welded joint exhibited a wide HAZ with distinct softened regions (minimum ~ 310 HV0.5) located in the IC and SC zones (Fig. 3). As documented by Mičian et al. (2020) and Sun et al. (2025), this softening is primarily attributed to the tempering of the original TMCP martensitic/bainitic structure during the prolonged cooling cycle. In sharp contrast, the LBW joint displayed a steep hardness gradient without a softened zone, reaching a peak hardness of ~ 455 HV0.5 in the narrow FZ (Fig. 3). This high hardness corresponds to the formation of untempered lath martensite. According to Schaupp et al. (2020), local hardness exceeding 400 HV is generally associated with a significantly increased susceptibility to hydrogen-induced cracking due to the reduction of the critical stress intensity threshold.

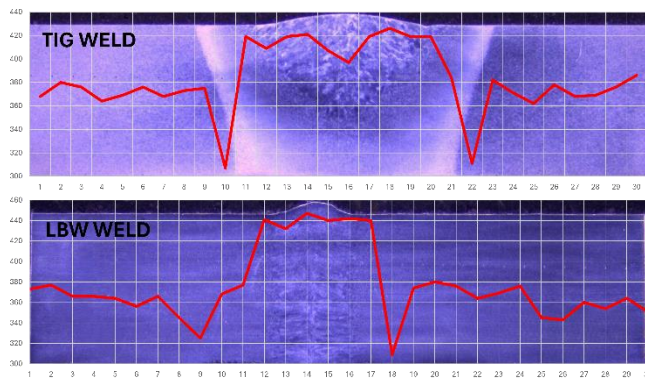


Fig. 3 Hardness measurement process in TIG and Laser welded samples.

4.2. Mechanical properties and HE susceptibility

The tensile test results for the uncharged (Air) and hydrogen-charged (1.0 mA/cm^2) specimens are summarized in Table 3. In the uncharged reference state, both welded joints exhibited high ductility. The TIG joints failed consistently in the softened HAZ, indicating that this region acts as a "metallurgical notch" where plastic strain localizes preferentially (Mičian et al., 2020). Conversely, the uncharged LBW joints failed in the BM rather than the Weld Metal (WM). This demonstrates a "strength overmatching" effect, where the constraint forces plastic strain localization into the softer BM, a phenomenon previously analysed in S960 weldments by Amraei et al. (2019).

Upon electrochemical hydrogen charging, both processes showed severe susceptibility to HE, but with fundamentally different mechanical responses. The TIG joints experienced a significant loss of ductility (dropping to 1.79%), yielding an HEI of 79.5%. The yield strength slightly decreased, consistent with hydrogen-enhanced dislocation mobility prior to fracture. This loss of ductility serves as the most sensitive indicator of hydrogen susceptibility in high-strength steels (Aiello et al., 2023).

The LBW joints exhibited catastrophic degradation. At 1.0 mA/cm^2 , the specimens failed at an average stress of 418 MPa, which is well below the macroscopic yield strength, recording

a residual elongation of only 0.26% (HEI = 97.2%). This transition to premature elastic fracture indicates a HEDE-dominated behavior (Djukic et al., 2019). This indicates that hydrogen embrittlement degraded the cohesive strength of the martensitic WM to such an extent that the structural benefit of strength overmatching was completely nullified (Rejeesh et al., 2025).

Table 3. Average tensile test results (Air vs. 1.0 mA/cm^2 hydrogen-charged conditions)

Material/weld	Condition	Rm (MPa)	Rp0.2 (MPa)	A (%)	HEI (%)
S960MC	Air	1068	972	8.51	-
	hydrogen-charged	982	956	1.91	77.7
TIG	Air	1050	945	8.42	-
	hydrogen-charged	929	895	1.79	79.5
LBW	Air	1056	1007	9.21	-
	hydrogen-charged	418	-	0.26	97.2

4.3. Fractographic analysis

Fractography validated the mechanical metrics and revealed the underlying HE mechanisms. The uncharged TIG (Fig. 4) and Laser welded joints (Fig. 5) failed via classic Microvoid Coalescence (MVC) with deep, equiaxed dimples. The yellow arrows indicate large microvoids which in TIG welds nucleated at second-phase particles (inclusions) (Fig. 4).

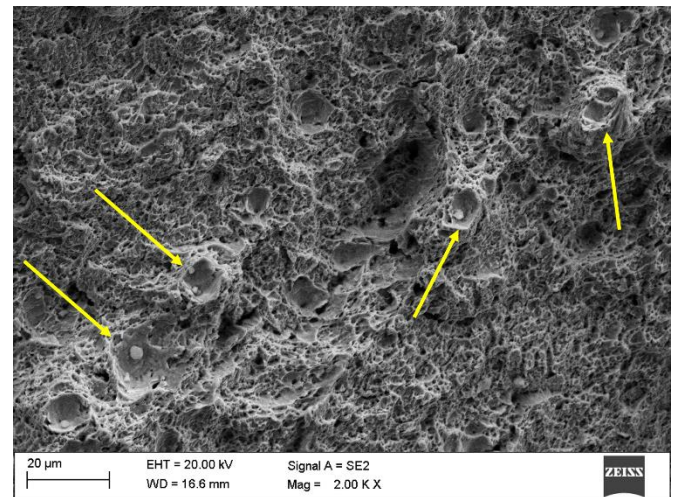


Fig. 4 Fracture surface of the uncharged TIG welded joints

The depth of these dimples serves as evidence of the significant plastic deformation capacity of the HAZ prior to failure (Mičian et al., 2020).

Fracture in uncharged TIG-welded samples occurred in the IC/SC part of the HAZ. In uncharged laser-welded samples, fracture occurred completely outside the weld and its HAZ, in the BM.

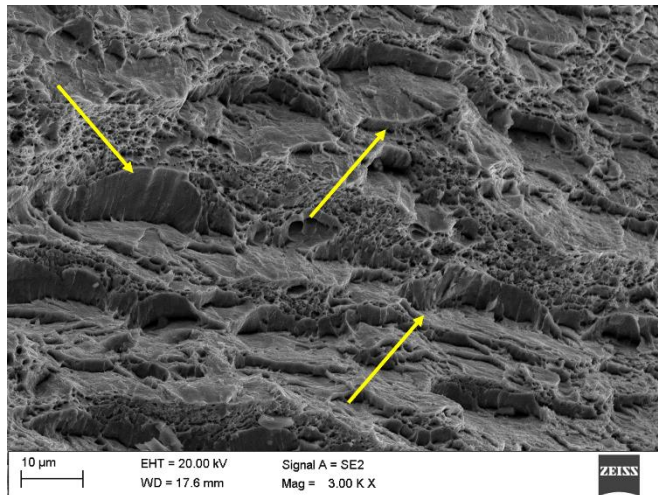


Fig. 5 Fracture surface of the uncharged LBW joints

After hydrogen charging, the fracture surface of TIG welded samples exhibited a mixed-mode morphology. The dominant feature was a network of shallow, fine dimples, providing evidence of the HELP mechanism (Fig. 6), where hydrogen accelerates void nucleation and coalescence (Martin et al., 2011). This localized softening effect primarily occurs within the ferritic-bainitic matrix of the HAZ. Consequently, the material undergoes microscopic ductile tearing at significantly lower macroscopic strain levels compared to the uncharged reference specimens.

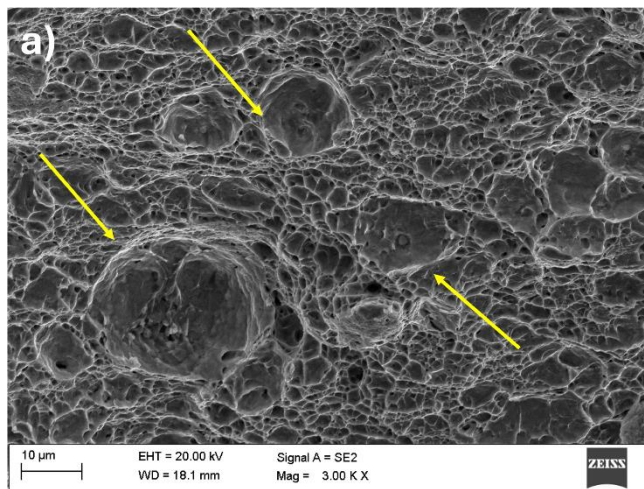


Fig. 6 Fracture surface of the TIG welded joint charged at 1.0 mA/cm²: a) High-magnification of Zone 1 (HELP)

However, localized regions of transgranular quasi-cleavage facets were also observed, indicating the simultaneous activation of the HEDE mechanism in areas of critical hydrogen accumulation (Fig. 7) (Zhang et al., 2024). These brittle features emerge when the local hydrogen concentration at specific microstructural traps, such as boundaries or phase interfaces, reaches a critical threshold. At this stage, the cohesive strength of the atomic lattice is drastically reduced, leading to sudden, unstable crack propagation amid the surrounding plastic deformation (Djukic et al., 2019).

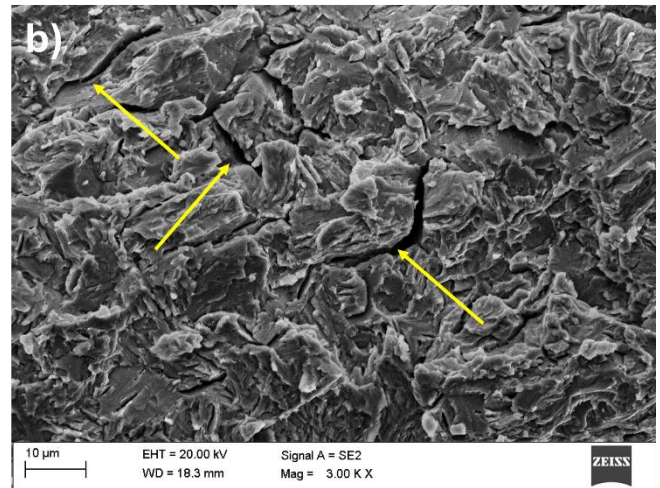


Fig. 7 Fracture surface of the TIG welded joint charged at 1.0 mA/cm²: b) High-magnification of Zone 2 (HEDE)

The LBW joints exhibited a complete shift in failure mode. The fracture occurred strictly within the FZ and was characterized by flat, featureless macroscopic surfaces without any necking. Microscopic analysis revealed fully brittle transgranular quasi-cleavage with distinct river patterns. As noted by Lynch (2012), these features mark the direction of local crack propagation through the crystal lattice and are typical for hydrogen-assisted cracking in martensitic microstructures driven by the HEDE mechanism (Fig. 8).

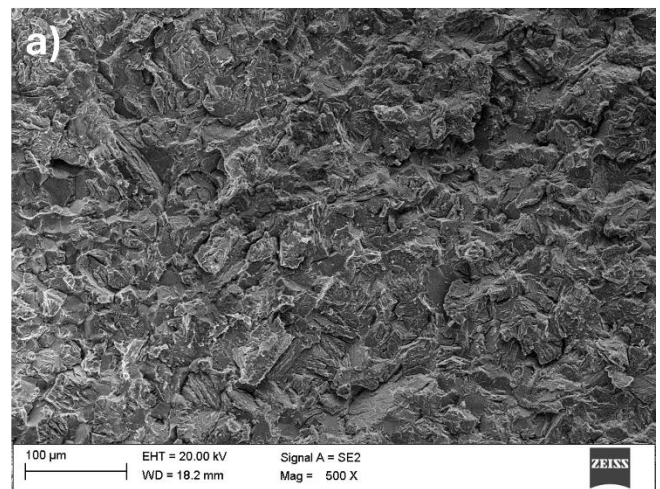


Fig. 8 Fracture surface of the LBW joint charged at 1.0 mA/cm²: a) Morphology of transgranular quasi-cleavage (HEDE)

A critical feature identified in the LBW joints was the formation of "fish-eye" defects nucleating at non-metallic oxide inclusions (Fig. 9). The incoherent interface between the hard oxide particle and the martensitic matrix acted as a strong irreversible hydrogen trap (Murakami et al., 2013). Upon loading, trapped hydrogen diffused radially, critically lowering the cohesive strength of the interface and triggering unstable crack propagation. This fractographic evidence aligns with the findings of Xue et al. (2025), supporting the conclusion that the

untempered martensitic lattice in LBW, lacking beneficial coherent carbides, leaves incoherent inclusions as the primary initiation sites for catastrophic brittle failure.

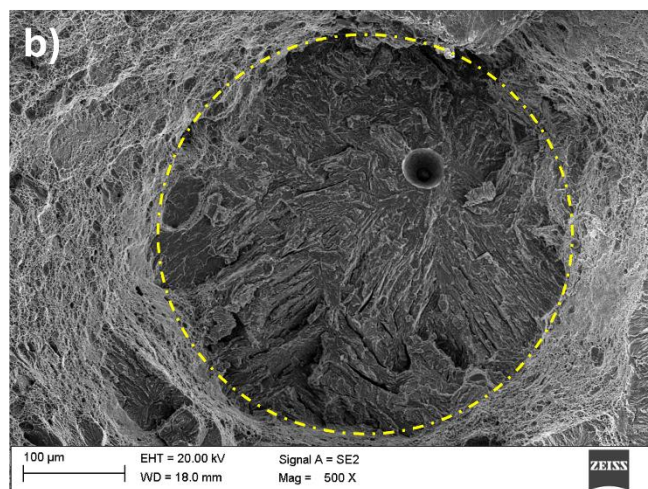


Fig. 9 Fracture surface of the LBW joint charged at 1.0 mA/cm²: b) "Fish-eye".

5. Summary and conclusion

This study investigated the susceptibility of S960MC high-strength steel welded joints to hydrogen embrittlement using slow strain rate testing on TIG and LBW joints. Based on the experimental results and microstructural analysis, the following conclusions can be drawn:

The welding thermal cycle plays a decisive role in hydrogen degradation. Rapid cooling in LBW produced a hard, martensitic fusion zone (>450 HV), which exhibited high susceptibility to HE due to a high density of reversible hydrogen traps. In contrast, the slower cooling in TIG welding resulted in a softer, ferritic-bainitic HAZ, which demonstrated superior resistance to hydrogen-assisted cracking despite its lower mechanical strength.

Hydrogen charging induced a distinct transition in failure mechanisms. TIG joints showed a ductility reduction driven by the HELP mechanism, evidenced by micro-void coalescence. LBW joints suffered a sudden transition to HEDE, characterized by brittle transgranular quasi-cleavage and inter-dendritic cracking.

A fundamental finding is the hydrogen-induced shift in the failure location of laser welds. While uncharged LBW joints benefited from strength overmatching (failing in the BM), hydrogen embrittlement degraded the cohesive strength of the FZ to such an extent that it became the "weakest link," failing in the elastic region. This invalidates the safety benefit of overmatching in hydrogen-rich environments (Fig. 10 in Appendix B).

Non-metallic oxide inclusions were identified as critical initiation sites for "fish-eye" defects in laser welds. These inclusions act as irreversible traps that facilitate local hydrogen accumulation, confirming that strict purity control is essential for the hydrogen service of S960MC steel.

For applications involving hydrogen exposure, the "softer" TIG welds provide a safer failure mode with predictable residual plasticity. Conversely, high-strength laser welds pose a significant risk of unpredictable brittle fracture. In line with recent predictive HE models, future research should focus on the application of targeted Post-Weld Heat Treatment (PWHT) to temper the susceptible martensitic microstructure and enhance the intrinsic HE resistance of laser welded joints.

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Appendix

Appendix A

Table 1. Chemical composition of S960MC [wt. %]

Element	C	Mn	Si	P	S	Nb	V	Ti
Standard	≤ 0.12	≤ 1.3	≤ 0.25	≤ 0.02	≤ 0.01	≤ 0.05	≤ 0.05	≤ 0.05
Measured (GDOES)	0.17	1.38	0.30	0.006	<0.001	<0.001	0.05	0.015