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Research Article

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Low-Cycle Fatigue Performance of Hydrogen Pre-charged X65 Girth Welds under Seismic Strain Conditions

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Abstract

To ensure the seismic integrity of hydrogen pipelines operating in hydrogen service, particularly in earthquake-prone regions, it is essential to clarify the low-cycle fatigue (LCF) behavior of girth welded joints under hydrogen-affected conditions. In this study, API 5L X65 girth welded joints were tested, using electrochemical hydrogen charging conditions designed to reproduce the hydrogen uptake equivalent to exposure in a 10 MPa hydrogen gas environment. Ex-situ strain-controlled LCF tests were conducted after hydrogen charging to evaluate the influence of pre-charged hydrogen on cyclic deformation and fatigue resistance.

The tests were performed on girth welded joint specimens both with and without artificial notches simulating internal weld defects. Two applied strain amplitudes of $\pm 0.2\%$ and $\pm 0.5\%$, corresponding to the expected strain levels under Level 1 and Level 2 seismic motions, respectively, as defined in the Japanese gas pipeline seismic design guidelines, were applied.

The results showed that, under all test conditions, the specimens satisfied the required number of loading cycles assumed for seismic events, and no through-thickness fracture was observed. Although hydrogen is generally known to reduce ductility and accelerate crack initiation under cyclic loading, no significant degradation in the seismic LCF performance of the tested girth welded joints was identified under the investigated hydrogen charging conditions. These findings indicate that X65 girth welded joints maintain adequate LCF resistance against large seismic strains even under hydrogen-affected conditions, providing further evidence of the structural integrity of welded hydrogen pipelines subjected to earthquake loading.

Keywords

Hydrogen embrittlement, API 5L X65, Pipeline steel, Low-cycle fatigue, Girth welded joints, Electrochemical hydrogen charging, Seismic loading

1. Introduction

1.1. Background

The global transition toward a carbon-neutral society has accelerated the deployment of hydrogen energy systems worldwide. In this context, high-pressure hydrogen gas pipelines are considered one of the most promising options for large-scale hydrogen transportation [1].

Despite their advantages, the long-term structural integrity of hydrogen pipelines remains a critical challenge due to the phenomenon of hydrogen embrittlement, one of the primary degradation mechanisms affecting steels used in hydrogen service. Hydrogen absorbed into the steel may reduce ductility, facilitate crack initiation, and accelerate crack propagation through hydrogen-assisted damage mechanisms, thereby compromising the structural integrity and fatigue performance of pipeline components. The susceptibility of any material to hydrogen embrittlement depends on several factors, including the material microstructure, the hydrogen concentration, the stress state, and loading conditions [2]. Consequently, understanding the combined effects of hydrogen exposure and mechanical loading is essential for the safe implementation of hydrogen pipeline infrastructure [2,3].

Under cyclic loading, the interaction between hydrogen and localized plastic deformation is particularly important because repeated plastic straining can promote damage accumulation and influence fatigue crack initiation and propagation[4]. This effect is expected to be more complex in girth welded joints because spatial variations in microstructure, mechanical properties, residual stresses, and local geometry produce heterogeneous stress-strain fields across the base metal (BM), heat-affected zone (HAZ), and weld metal (WM) [4,5]. In addition, weld imperfections and geometric discontinuities can introduce local stress concentrations that further increase the susceptibility of these critical regions to fatigue and hydrogen-assisted damage [5,6]. Consequently, the response of hydrogen-exposed girth welded joints under large cyclic strains cannot necessarily be inferred from the behavior of homogeneous BM specimens.

Hydrogen pipelines are expected to be deployed not only in North America and Europe but also in seismically active regions such as Japan. In these regions, ensuring structural integrity during earthquakes is an important design requirement, as is the case for natural gas pipelines. During seismic events, pipelines may experience significant cyclic plastic deformation, making the LCF performance of girth welded joints a critical consideration for design. In Japan, these requirements are reflected in the Japanese seismic design guidelines for high-pressure gas pipelines, which specify allowable strain limits, required loading cycles, and performance requirements according to the severity of seismic motion, as summarized in Table 1 [7]. Since hydrogen may alter the mechanisms of cyclic deformation and damage accumulation, assessing the LCF performance of hydrogen-exposed girth welded joints is essential for the reliable seismic design of hydrogen pipeline systems [3,4,8].

Table 1: Summary of the Japanese seismic design guidelines for high-pressure gas pipelines and representative applied strain levels adopted in this study.

	Seismic design guidelines for high-pressure gas pipelines [7]			Applied strain* ¹
	Allowable strain	Number of cycles	Required performance	
Level 1	±1% or 35t/D (Smaller value applies)	40~50	No damage, no repair required	±0.2%
Level 2	±3%	3~5	Deformation allowed, no leakage	±0.5%

*1 The applied strain corresponds to the maximum earthquake-induced ground strain calculated for all ground conditions in accordance with the Seismic design guidelines for high-pressure gas pipelines.

During earthquakes, pipelines are subjected to cyclic deformation caused by ground movement. Therefore, understanding the LCF behavior of girth welded joints is essential for the seismic design and integrity assessment of hydrogen pipelines. Furthermore, the issue becomes increasingly important in high-pressure hydrogen environments, where hydrogen embrittlement may degrade the mechanical performance and fatigue resistance of pipeline steels and welded joints. Girth welded joints specifically are considered critical locations due to the potential presence of weld

imperfections, geometric discontinuities, and local stress concentrations, making them key regions for structural reliability assessment of hydrogen pipeline systems.

1.2. Literature review and knowledge gap

Extensive studies have been conducted to evaluate the compatibility of pipeline steels with hydrogen environments, including investigations of mechanical properties such as strength and ductility [9-12], fracture toughness [9,11-14], and fatigue crack growth behavior [9,13-16]. The knowledge obtained from these studies has been incorporated into standards [17,18] and technical guidelines [19,20], supporting the practical implementation of hydrogen pipeline systems.

Beyond conventional fracture toughness and fatigue crack growth assessments, the response of pipeline steels to hydrogen under cyclic plastic deformation is of relevance to strain-based design. Unlike high-cycle fatigue and long-crack fatigue crack growth, LCF involves repeated plastic straining, cyclic hardening or softening, and progressive accumulation of plastic damage. In the presence of hydrogen, these processes may interact with hydrogen diffusion and trapping, particularly within regions of localized plastic deformation, thereby modifying crack initiation and subsequent fatigue damage evolution [4]. Previous investigations have demonstrated that hydrogen can interact with cyclic plastic deformation in pipeline steels and welded joints, resulting in degradation of ductility and changes in the cyclic damage response [21,22].

However, most previous studies of hydrogen effects in pipeline steels have focused on monotonic loading, fracture mechanics, or long-crack fatigue behavior, whereas relatively little attention has been given to the LCF under large plastic strains representative of seismic loading [22]. Also, the available LCF studies have primarily considered BMs, with comparatively limited study of hydrogen-affected welded joints.

Since girth welded joints represent the most critical regions of pipeline systems owing to their metallurgical heterogeneity, geometric discontinuities, and potential weld imperfections, their response under combined hydrogen exposure and seismic cyclic loading cannot be directly inferred from the behavior of the BM. Consequently, the hydrogen-assisted LCF behavior of girth welded joints, and its relationship to the performance requirements specified in seismic design guidelines, is far from completely understood.

Differences in microstructure and mechanical properties among the BM, HAZ, and WM, together with weld geometry, residual stresses, and possible fabrication imperfections, can produce localized stress and strain concentrations during cyclic loading [23,24]. Under hydrogen exposure, such localized deformation may further influence hydrogen redistribution and the development of fatigue damage through stress-assisted diffusion and the generation of dislocations which act as hydrogen traps. Therefore, the fatigue response of a hydrogen-exposed girth welded joint represents a coupled problem involving cyclic plasticity, weld heterogeneity, local stress concentration, hydrogen diffusion and hydrogen-assisted damage [25,26].

Despite the available knowledge on hydrogen-assisted degradation of pipeline steels, the LCF response of hydrogen-affected girth welded joints under large cyclic strains representative of seismic loading remains insufficiently understood, particularly in the presence of weld defects. The present study aims to address this knowledge gap by systematically evaluating hydrogen pre-charged X65 girth welded joints, with and without representative artificial defects, against the cyclic performance requirements for hydrogen pipelines deployed in earthquake-prone regions.

1.3. Research objectives

The objective of this study is to evaluate the LCF performance and fatigue damage behavior of a girth welded joint under hydrogen-affected seismic loading conditions. To mimic hydrogen service conditions, hydrogen was introduced into the specimens by electrochemical charging using charging conditions selected to reproduce hydrogen uptake corresponding to exposure to 10 MPa gaseous hydrogen, based on a study by Koren et al. [27] for the same steel grade. Subsequently, strain-controlled LCF tests were conducted using the hydrogen pre-charged specimens. During earthquakes, ground deformation induces axial strain in pipelines. Throughout this study, the resulting axial strain imposed on the specimen is referred to as the applied strain.

Based on ground strain evaluations conducted in accordance with the Japanese seismic design guidelines for high-pressure gas pipelines [7], representative applied strain levels corresponding to Level 1 and Level 2 seismic motions were determined as $\pm 0.2\%$ and $\pm 0.5\%$, respectively (cf. Table 1). These strain levels were adopted as representative deformation demands expected during earthquakes, and LCF tests were performed on both sound and defect-containing girth welded joints under these conditions. The experimental results were subsequently compared with the seismic performance

requirements specified in the Japanese design guidelines to assess the influence of hydrogen on the LCF resistance of girth welded joints and to evaluate their suitability for hydrogen pipelines in earthquake-prone regions.

2. Experimental Procedure

An overview of the experimental procedure is as follows. First, the hydrogen diffusion behavior in the BM was characterized by electrochemical permeation testing, and the resulting diffusion coefficient was used as input for numerical hydrogen diffusion simulations to determine the time to saturation of the specimens. Based on these results, hydrogen charging conditions were determined. Then, the specimens were electrochemically pre-charged with hydrogen and subjected to LCF testing.

2.1. Materials and welding conditions

The BM used in this study was an API 5L X65M (L450M) high frequency welded (HFW) pipe. The pipe had an outer diameter of 24 inches and a wall thickness of 15.1 mm. Circumferential (girth) welding was performed using an automatic metal active gas (MAG) welding process with a solid filler wire specified in JIS Z 3312 (G59JA1UC3M1) for 590 MPa-class steels. A shielding gas mixture of Ar–CO₂ (Ar: 70%, CO₂: 30%) was employed, and welding was carried out in the 1G position with continuous pipe rotation.

The welding operation and the macrograph of the girth welded joint are shown in Figure 1. The chemical compositions of the BM and WM are listed in Table 2, while their corresponding microstructures are presented in Figure 2. The WM was characterized in the as-welded condition, i.e. without any post-weld treatment. As shown in Figure 2(b), the WM consists predominantly of acicular ferrite and primary ferrite, which are characteristic microstructural elements of low-alloy pipeline steel weld metals produced by MAG welding process.

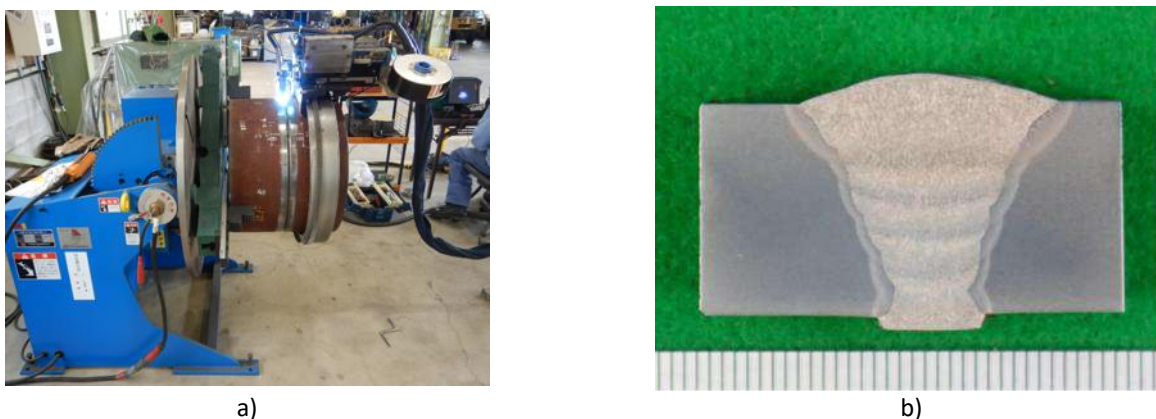


Figure 1: a) Welding operation and b) macro cross-section of the girth weld.

Table 2: Chemical compositions of base metal and weld metal (wt.%)

	C	Si	Mn	P	S	Nb	Ni	Cr	V	Ti	Cu	Mo	B
BM	0.08	0.20	1.27	0.012	0.003	—	0.02	0.02	0.002	0.012	0.01	0.16	0.0001
WM	0.09	0.61	1.32	0.008	0.005	0.005	0.31	0.03	0.003	0.002	0.03	0.21	0.0002

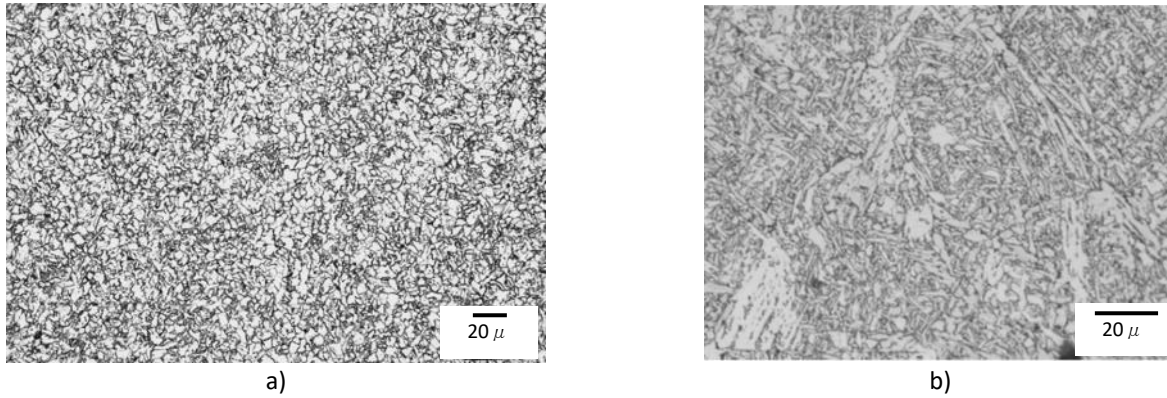


Figure 2: Microstructures of the BM and WM, a) BM exhibiting a ferrite–pearlite microstructure (x400); and b) WM in the as-welded condition, consisting mainly of acicular ferrite and primary ferrite (x500).

2.2. Hydrogen permeation test and evaluation of diffusion coefficient

To evaluate the hydrogen diffusion properties of the base material, electrochemical hydrogen permeation tests were conducted. Disk-shaped specimens with a diameter of 5 mm and a thickness of 0.5 mm were machined from the base metal. The specimens were prepared such that the specimen thickness direction, i.e., the hydrogen permeation direction, corresponded to the axial direction of the pipe.

A two-cell electrochemical system was used, and all tests were performed at approximately 22°C. Hydrogen was generated on the cathodic side in 0.1 M NaOH solution under a constant current density of 1 mA/cm², while the anodic side was maintained at –0.5 V (vs. Hg/Hg₂SO₄) to oxidize the permeating hydrogen.

The apparent diffusion coefficient was determined from the hydrogen permeation curves based on the analysis of permeation transients, assuming a constant hydrogen flux on the entry side [28]. An example of the permeation curves is shown in Figure 3. The average diffusion coefficient obtained from two specimens was 4.65×10^{-11} m²/s, which was used as an input parameter for subsequent hydrogen diffusion simulations.

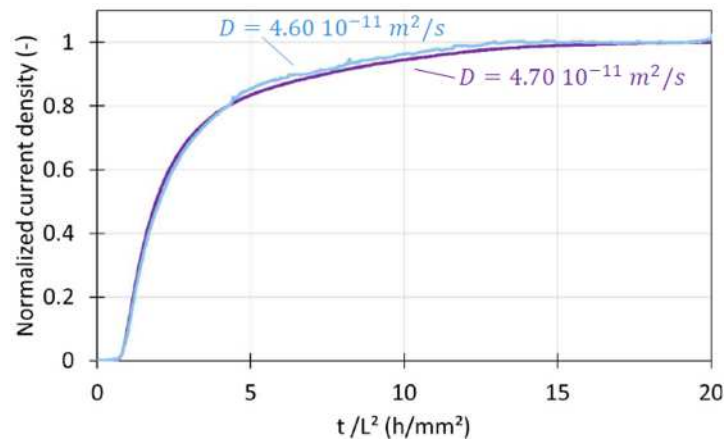


Figure 3: Normalized hydrogen permeation transients for two tests used to evaluate the apparent diffusion coefficient. The time axis is normalized by the specimen thickness L.

2.3. Hydrogen diffusion simulation and determination of charging conditions

One-dimensional hydrogen diffusion simulations were conducted to evaluate the hydrogen concentration distribution through the thickness of the fatigue specimens. The simulation model was defined as a flat semi-infinite plate with a thickness of 15.1 mm, assuming constant hydrogen concentration at both surfaces. The simulations were performed at 22°C, consistent with the experimental conditions as was previously demonstrated in [29].

The calculated hydrogen concentration profiles for different charging times are shown in Figure 4. Hydrogen gradually diffused from the surfaces toward the center, and after approximately 28 days, more than 98% of the saturation concentration was achieved throughout the thickness. Based on these results, the hydrogen charging duration for the fatigue specimens was set to 28 days.

In addition, the hydrogen desorption behavior during exposure to air was evaluated, assuming immediate desorption of hydrogen at the plate edges. The results indicated that more than 90% of the total initial hydrogen concentration in the specimen remained even after approximately one hour of air exposure. Figure 4(b) shows the calculated hydrogen profiles for different effusion times.

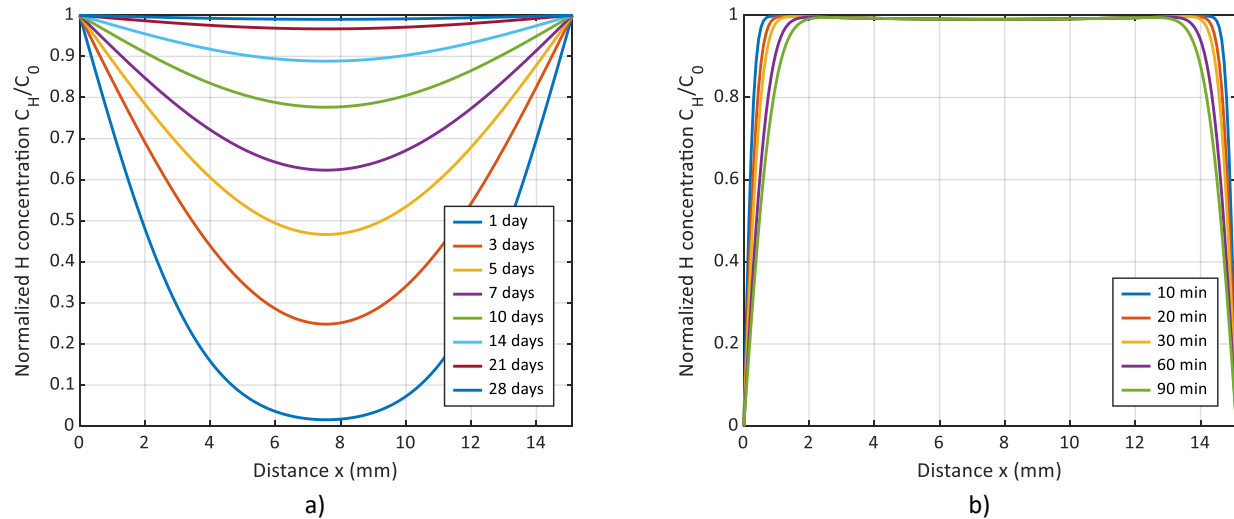


Figure 4: Calculated hydrogen concentration profiles through the specimen thickness; a) effect of charging duration, and b) effect of exposure to air after 28 days of hydrogen charging.

2.4. Hydrogen charging and hydrogen content measurement

Hydrogen charging of the low-cycle fatigue specimens was carried out electrochemically in a 3.5 wt% NaCl aqueous solution at a current density of 15 mA/cm² for 28 days. This charging duration was determined based on the hydrogen diffusion simulation described in Section 2.3. This charging condition was selected based on a previously reported correlation between gaseous and electrochemical hydrogen charging established using the hydrogen permeation technique, where a cathodic current density of approximately 15 mA/cm² corresponds to a hydrogen fugacity equivalent to about 100 bar (10 MPa) hydrogen gas pressure [27]. Charging was performed at room temperature (approximately 22°C). The hydrogen content was measured using separate small specimens extracted from both the base metal and weld metal, as shown in Figure 5. Considering the specimen dimensions, the charging duration for hydrogen content measurement was set to 18 hours.

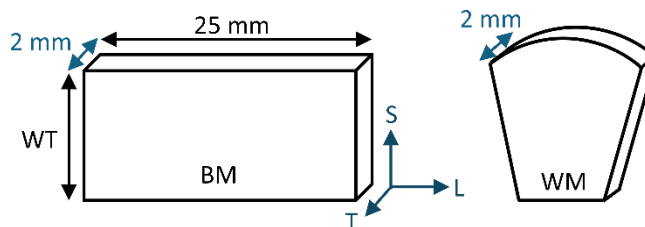


Figure 5: Schematic of specimen geometry for hydrogen charging tests: base metal (BM) and weld metal (WM). WT indicates the full wall thickness of the pipe.

Thermal desorption spectroscopy (TDS) was used to measure the hydrogen content. The specimens were heated from room temperature to 500°C at a rate of 100°C/h, and hydrogen desorption was continuously measured using a quadrupole

mass spectrometer. The amount of hydrogen released up to 350°C was evaluated as diffusible hydrogen. The results are summarized in Table 3. The hydrogen content measured was approximately 0.468 wppm for the base metal and 0.156 wppm for the weld metal. These values are slightly higher than those reported for specimens exposed to 10 MPa hydrogen gas(28), indicating that the electrochemical charging condition used in this study represents a possibly more severe hydrogen environment compared to the reference [28].

Table 3: Comparison of diffusible hydrogen contents measured in the present study and reported in previous studies.

Material	Test environment	TDS Temperature	H ₂ content (wppm)	Remarks
Base Metal	3.5 wt% NaCl, 15 mA/cm ²	up to 350°C	0.468	This study
	10 MPa H ₂ gas	up to 350°C	0.1	Ref. [30]
	10 MPa H ₂ gas	up to 200°C	0.095	Ref. [22]
	0.1N NaOH -1.05V(vs Ag/AgCl)	up to 200°C	0.13	Ref. [22]
	0.1N NaOH -1.50V(vs Ag/AgCl)	up to 200°C	0.84	Ref. [22]
Weld Metal	3.5 wt% NaCl, 15mA/cm ²	up to 350°C	0.156	This study
	10 MPa H ₂ gas	up to 350°C	0.06	Ref. [22]

2.5. Specimen configuration and notch geometry

LCF tests were performed using segment-type specimens as proposed in DNV-RP-F108 [31] extracted from the girth welded joints. This specimen configuration preserves the original curvature and weld geometry of the pipe, providing a representative assessment of the structural response under seismic cyclic loading. The specimen geometry is shown in Figure 6. The gauge (parallel) section had a width of 50 mm and a length of 50 mm, with the girth weld located at the center.

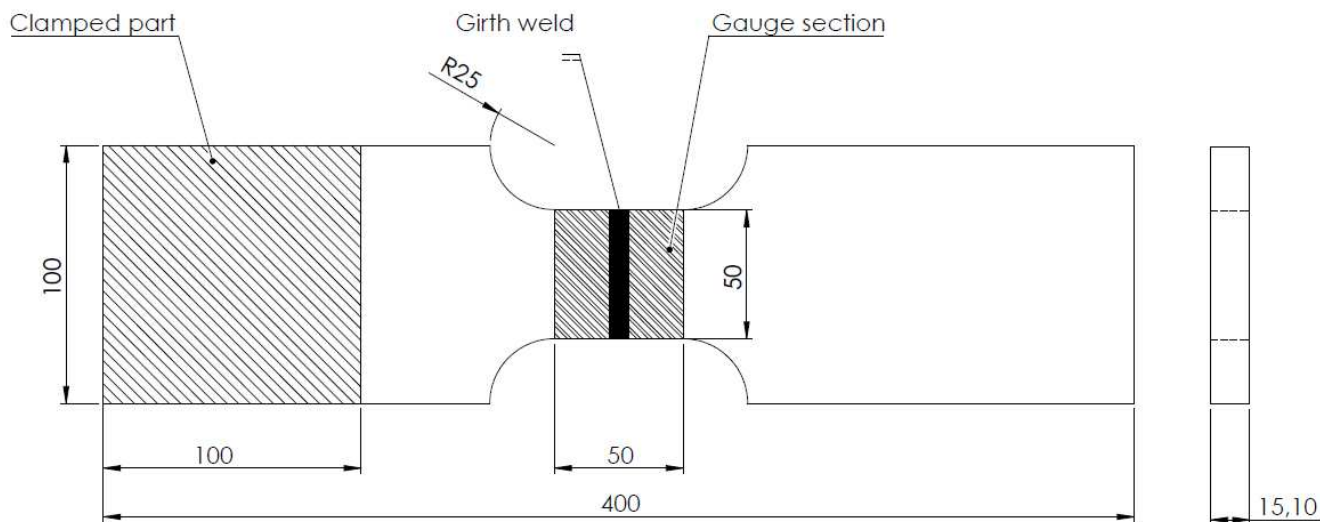


Figure 6: Geometry and dimensions of the segment specimen used for the low-cycle fatigue tests, dimension in mm.

Prior to electrochemical hydrogen charging, the specimen surfaces were ground to obtain a uniform surface finish and to minimize the influence of surface roughness and oxide layers on hydrogen absorption. The external weld reinforcement (cap) was retained in the as-welded condition, whereas the internal weld reinforcement (root bead) was completely removed by machining to produce a smooth internal surface and to eliminate its influence on stress concentration and hydrogen uptake.

To examine the influence of internal weld defects on low-cycle fatigue behavior, artificial defects were introduced into selected specimens by electrical discharge machining (EDM). The defects were generated as semi-elliptical surface notches

on the inner surface, centered within WM. The notch dimensions were $2c = 24$ mm in length and $a = 5$ mm in depth. These dimensions were determined in accordance with WES 2805 [32] to provide an equivalent stress intensity factor (SIF) representative of the maximum allowable internal weld defects in real pipeline conditions.

2.6. Low-cycle fatigue test method

The experiments were conducted using an MTS servo-hydraulic testing machine with a load capacity of 2500 kN, equipped with a hydraulic gripping system rated to 1000 kN . The experimental configuration is shown in Figure 7. The applied longitudinal strain was measured and controlled using a 50 mm gauge length clip-on extensometer attached to the specimen gauge section. For specimens containing artificial defects, the crack tip opening displacement (CTOD) was continuously monitored using a double clip gauge mounted across the defect mouth. This setup enabled the evolution of local crack opening deformation to be quantified throughout cyclic loading.

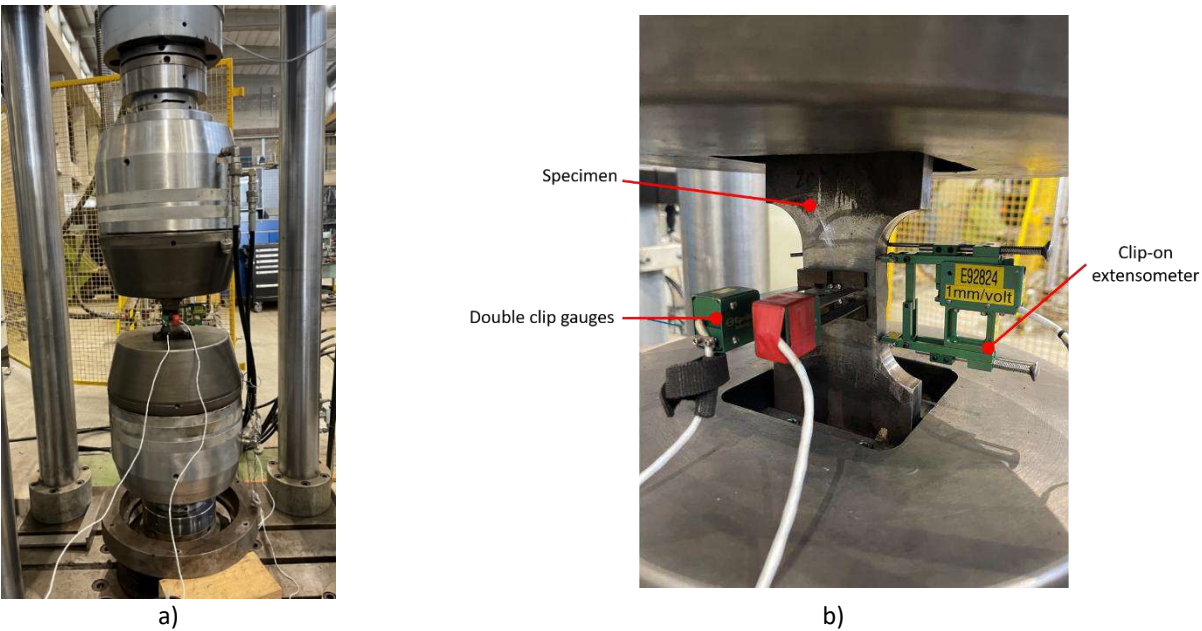


Figure 7: Experimental setup for the strain-controlled LCF tests: a) specimen installed in the hydraulic grips of the 2500 kN servo-hydraulic testing system and b) specimen instrumented with a clip-on extensometer and a double clip gauge.

Following the establishment of the correlation between actuator displacement and the measured gauge strain, the fatigue tests were performed under actuator stroke control. A triangular loading waveform with a frequency of $f = 0.25$ Hz was employed, and all experiments were conducted in laboratory air at room temperature (approximately 22°C).

The applied strain amplitude was $\pm 0.2\%$ and $\pm 0.5\%$, corresponding to the representative deformation requirements associated with Level 1 and Level 2 seismic motions, respectively, as specified in the seismic design guidelines for high-pressure gas pipelines [7]. The experimental matrix is summarized in Table 4. For each condition, two specimens were tested for both the sound and artificially notched configurations.

To assess the extent of hydrogen desorption during mechanical testing, the elapsed time between the completion of electrochemical hydrogen charging and the end of each fatigue test was recorded and subsequently used to estimate retained hydrogen concentration.

Table 4 Test matrix for low-cycle fatigue tests.

Applied strain	Seismic design criteria for high-pressure gas pipelines	Test matrix
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		Allowable strain	Number of cycles	Required performance	Strain	Notch	Loading frequency	Number of repetitions
Level 1	$\pm 0.2\%$	$\pm 1\%$ or $35t/D$ (Smaller value applies)	40 ~ 50	No damage; Operation not affected No repair required	$\pm 0.2\%$	Unnotched Notched	0.25 Hz	2
Level 2	$\pm 0.5\%$	$\pm 3\%$	3 ~ 5	Deformation allowed; No leakage permitted	$\pm 0.5\%$	Unnotched Notched		

3. Results

3.1. Low-cycle fatigue response

The results of the LCF tests are presented in Figure 8 and summarized in Table 5. Under all test conditions, no through-thickness fracture was observed in either the sound or artificially notched specimens. As reported in Table 5, more than 90% of the initially charged hydrogen was retained in the specimens upon completion of the fatigue tests. This high hydrogen retention indicates that hydrogen desorption prior to and during testing was limited, confirming that the measured fatigue response is representative of hydrogen pre-charged specimens throughout the entire duration of the experiments.

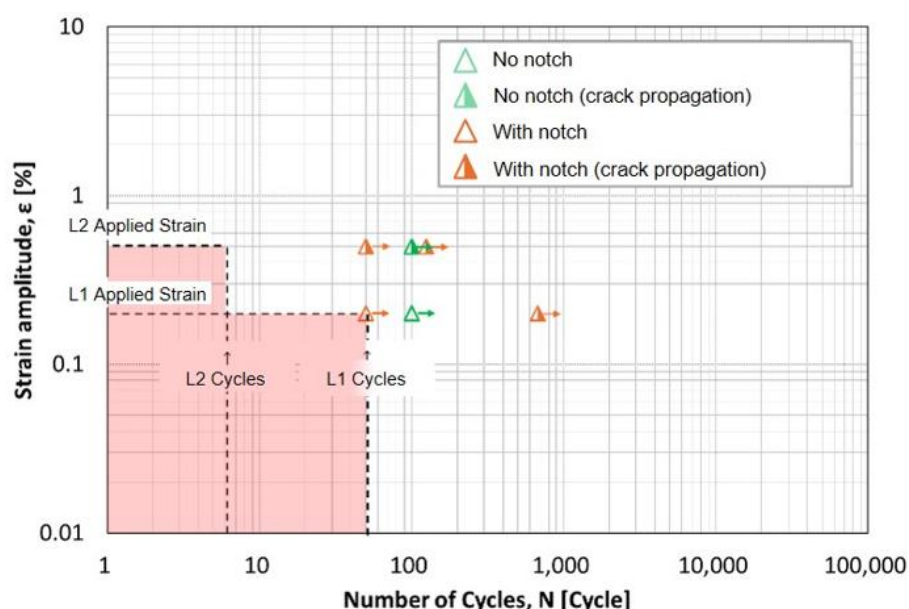


Figure 8: Relationship between the applied strain amplitude and the number of loading cycles for hydrogen pre-charged girth welded joint specimens.

Table 5: Results of low-cycle fatigue tests, including number of cycles at test termination, atmospheric exposure time, retained hydrogen ratio, and post-test observations.

Strain	Notch	Cycles at test termination	Atmospheric exposure time*1	Retained hydrogen ratio*2	Post-test observations
$\pm 0.2\%$	Unnotched	100	33.6min	94.6%	No visible change.

$\pm 0.5\%$	Notched	100	36.6min	94.4%	No visible change.
		50	32.7min	94.7%	No visible change.
		676	81.9min	92.0%	Crack propagation from the notch to the specimen side surface (no fracture).
	Unnotched	100	42.8min	94.0%	Crack initiation at the weld toe (not penetrating through the thickness).
		100	58.3min	93.2%	Crack initiation at the weld toe (not penetrating through the thickness).
	Notched	50	21.4min	95.5%	Crack propagation from the notch (no fracture).
		125	31.8min	94.7%	Crack propagation from the notch to the specimen side surface (no fracture).

*1 Time from removal after electrolytic charging to the end of fatigue test.

*2 Simulated value based on the atmospheric exposure time (total H content at removal = 100%).

3.2. Crack initiation and propagation paths

The post-test appearance of the specimens and the corresponding fatigue crack propagation paths are shown in Figure 9. In the sound specimens, fatigue cracks initiated at the outer-surface weld toe and subsequently propagated into the adjacent BM. In contrast, for the artificially notched specimens, crack initiation consistently occurred at the notch tip, with crack propagation occurring predominantly through the WM. In both cases, with increasing cycle number, the crack eventually reached the specimen side surface rather than penetrating through the thickness. These observations demonstrate that the presence of an artificial notch significantly influenced both the fatigue crack initiation site and the subsequent crack propagation path. The shift in the crack initiation site from the weld toe to the notch tip reflects the redistribution of the local stress field caused by the artificial notch.

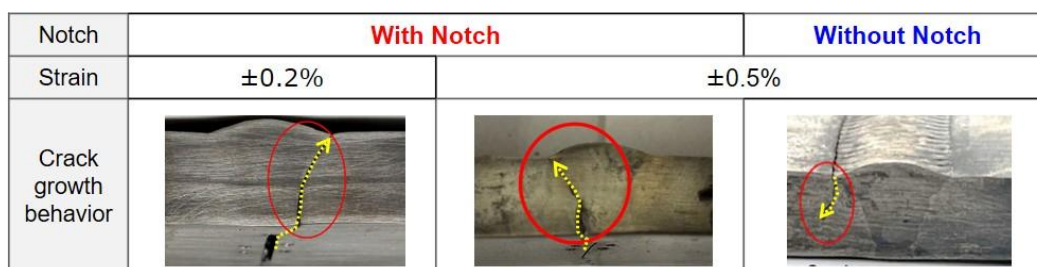


Figure 9: Post-test specimen appearance and crack propagation paths depending on notch condition.

4. Discussion

4.1. Seismic performance of hydrogen pre-charged girth welded joints

The primary objective of this study was to evaluate whether hydrogen pre-charged X65 girth welded joints can satisfy the seismic performance requirements specified in the Japanese seismic design guidelines for high-pressure gas pipelines. As shown in Figure 8 and Table 5, no through-thickness fracture was observed under any test condition, and all specimens exceeded the required number of loading cycles for the corresponding seismic level.

At an applied strain amplitude of $\pm 0.2\%$ (corresponding to Level 1 seismic motion), all specimens exceeded the number of loading cycles specified in the seismic design guidelines (40–50 cycles). In addition, no visible surface damage or crack initiation was observed in the unnotched specimens after 100 loading cycles.

At an applied strain amplitude of $\pm 0.5\%$ (corresponding to Level 2 seismic motion), all specimens also exceeded the required number of loading cycles (3–5 cycles) by a substantial margin. Even the notched specimens sustained at least 50

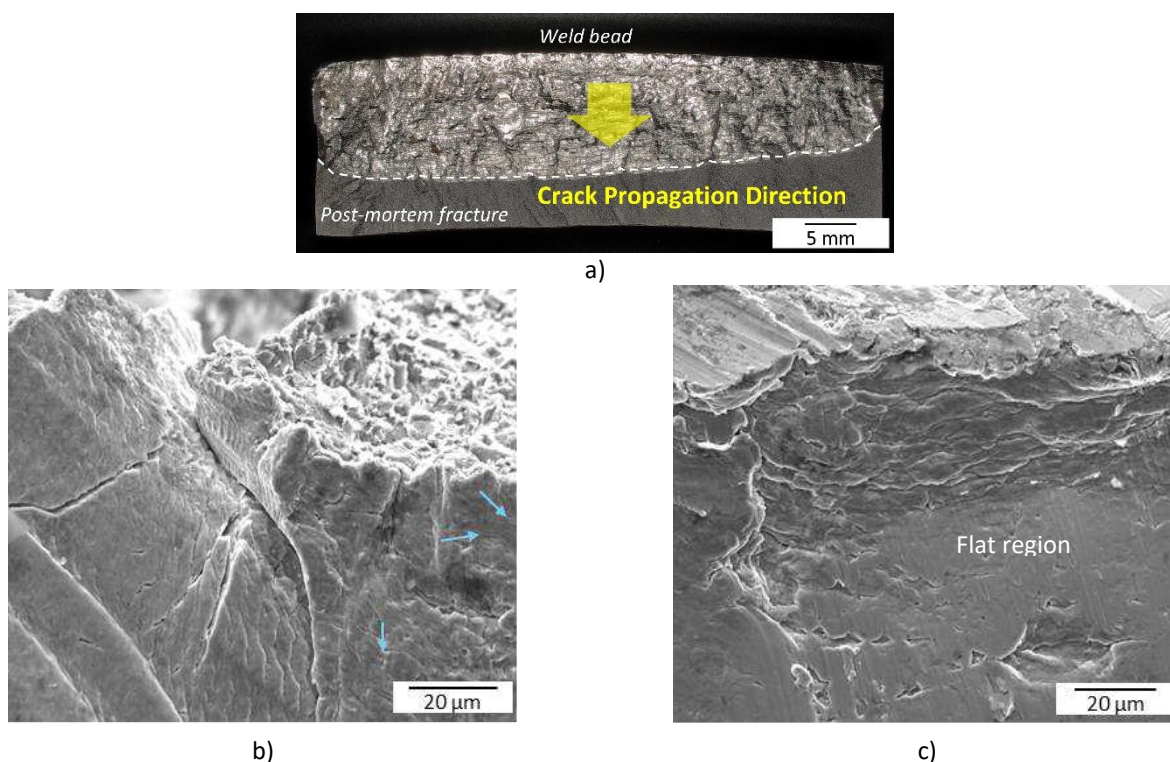
loading cycles, which is well above the required 3–5 cycles, demonstrating that the hydrogen pre-charged girth welded joints satisfied the seismic performance requirements under the investigated loading conditions.

4.2. Confirmation of hydrogen-affected test conditions based on fracture surface observations

As described in Section 3.2, the crack initiation site and propagation path differed depending on the presence or absence of a notch. Therefore, the fracture surfaces were examined separately for cracks propagating in the BM and WM to assess whether the fatigue tests were conducted under hydrogen-affected conditions.

Representative optical microscopy and SEM images of fracture surfaces associated with cracks propagating into the BM in specimens without an artificial notch are presented in Figure 10. The macroscopic crack propagation direction is illustrated in Figure 10(a). Higher-magnification observations near the crack initiation region at the weld toe (Figure 10(b) and 10(c)) revealed fatigue striations together with locally flat fracture regions. In the crack propagation region, localized dimple-like features were also observed (Figure 10(d)), while a lateral secondary crack was identified in Figure 10(e). Overall, these fracture surface features are characteristic of fatigue-dominated crack propagation under cyclic loading, although the locally flat regions and secondary crack may suggest a partial influence of hydrogen on the fracture process.

Fracture surfaces for cracks propagating in the WM are shown in Figure 11. The specimen tested for 50 cycles showed very limited crack growth (Figure 11(a)). In the vicinity of the notch tip, quasi-cleavage-like features were observed, as shown in Figure 11(c) and Figure 11(d). These features, together with the estimated hydrogen retention during testing, support the conclusion that the low-cycle fatigue tests were conducted under hydrogen-affected conditions.



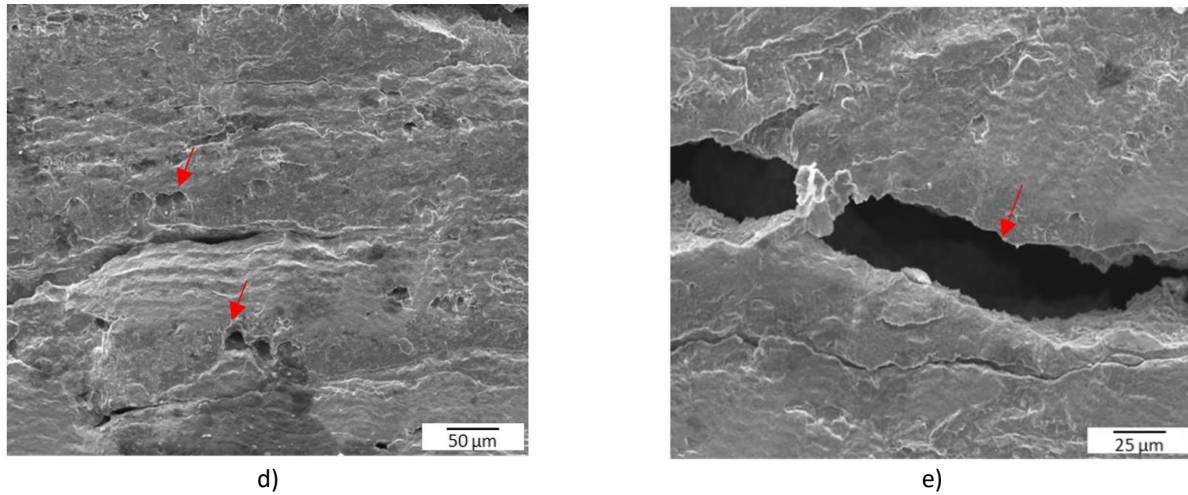
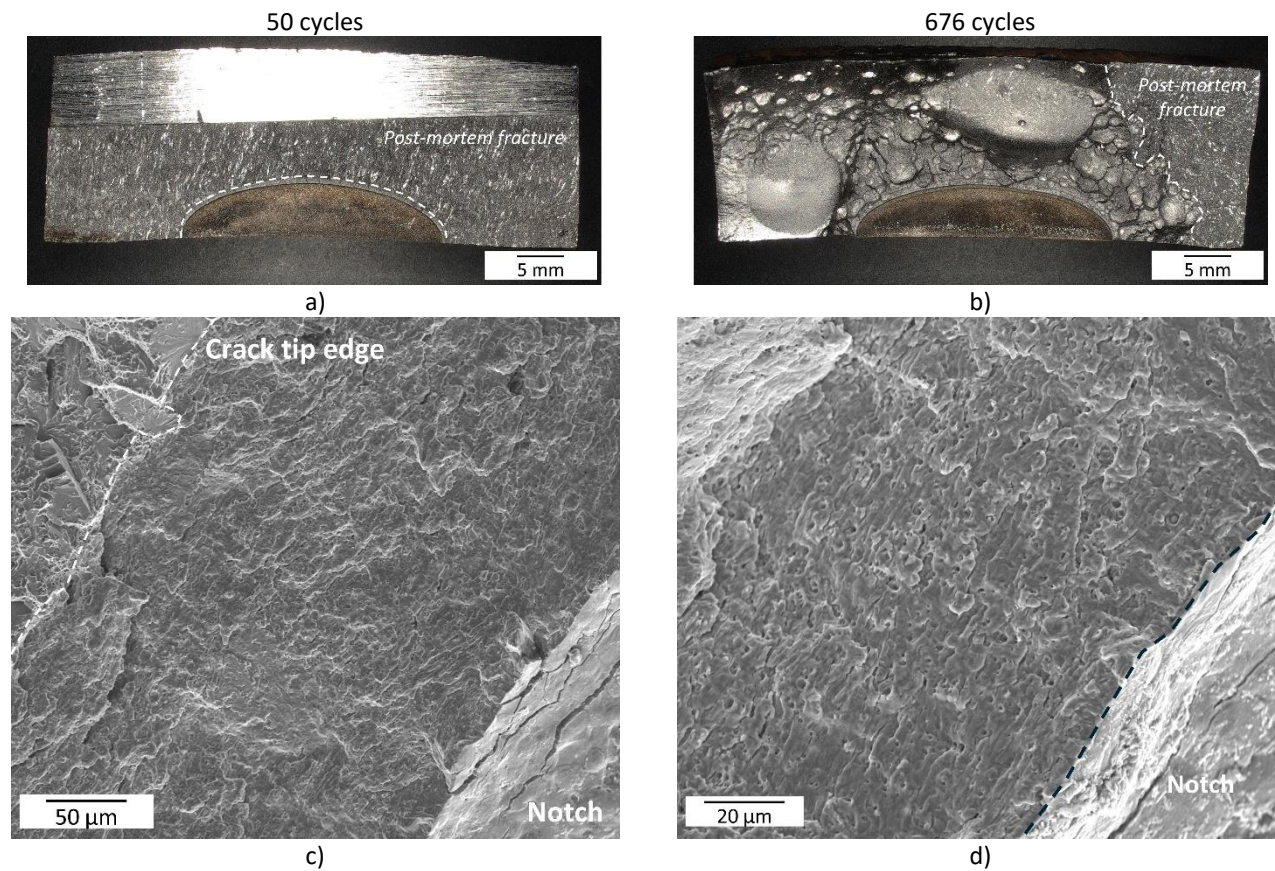


Figure 10: SEM observations of fracture surfaces in the base metal propagation region:

- a) macro view of unnotched, H-charged specimen. The yellow arrow indicates crack propagation direction. The white dashed line delineates the crack formed during the fatigue test,
- b), c) crack initiation region near the weld toe, some striations are indicated by blue arrows,
- d) dimple-like features observed in the crack propagation region, indicated by red arrows,
- e) lateral secondary crack observed in the crack propagation region, indicated by a red arrow.



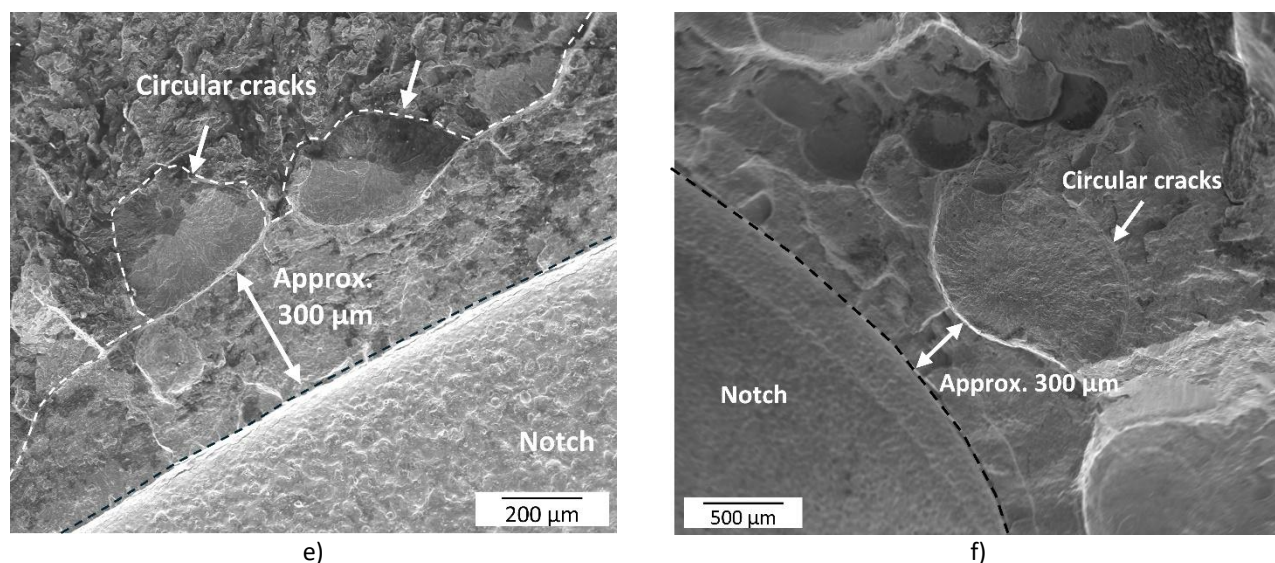
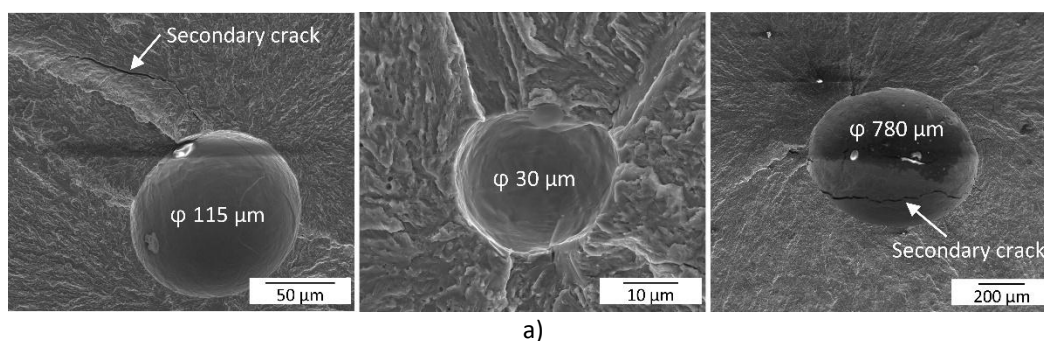


Figure 11: Fracture surfaces in the weld metal (DEPO region) for notched specimens under an applied strain of $\pm 0.2\%$:
 (a,b) macro views after 50 cycles and 676 cycles, respectively, where the white dashed line delineates the crack formed during the fatigue test;
 (c, d) crack appearance near the initial notch after 50 cycles and 676 cycles, respectively;
 (e, f) crack appearance in the crack propagation regions after 50 cycles and 676 cycles, respectively.

4.3. Characteristic fracture features in the weld metal: possible roles of gas pores and crack coalescence

As shown in Figure 11, characteristic circular or elliptical crack features, hereafter referred to as “circular cracks,” were observed in the WM propagation region of the notched specimens. These features were typically observed more than 300 μm away from the notch tip and appeared to extend radially from spherical depressions near their centers. The circular crack features were more developed in the specimen tested for a higher number of cycles, suggesting that they may have developed during cyclic loading.

Detailed SEM and EDS observations of the centers of the circular cracks are shown in Figure 12. Spherical depressions with diameters of approximately 30–780 μm were identified at the centers of these cracks. In some cases, inclusions containing Si, Mn, Al, and O were detected inside the depressions by EDS, and secondary cracks were also observed around the depressions. Based on these morphological and compositional features, the spherical depressions were interpreted as micro gas pores.



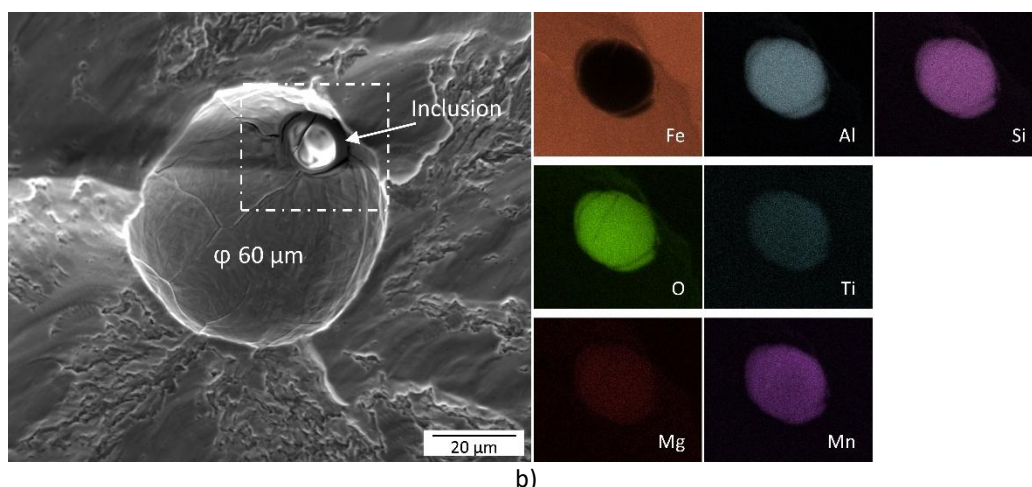
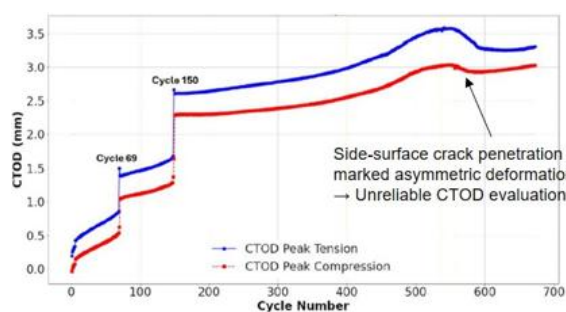


Figure 12: Detailed SEM and EDS observations of circular crack centers in the weld metal:

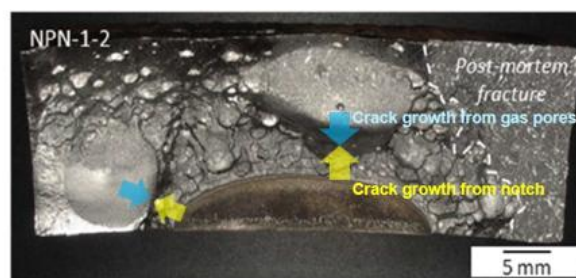
(a) SEM images showing circular cracks with diameters ranging from approximately 30 μm to 780 μm and associated secondary cracks,
(b) enlarged SEM image of a gas pore with an inclusion at the center, and corresponding elemental maps obtained by EDS analysis.

Based on these observations, gas pores and inclusions in the weld metal may have contributed to local crack formation under hydrogen-affected cyclic loading. A possible interpretation is as follows. First, local stress concentration may occur around gas pores or inclusions in the weld metal. Next, hydrogen may enhance localized crack initiation or crack opening around these stress concentration sites. The resulting small cracks may then develop into circular or ring-like crack features. Finally, these gas-pore-related cracks may coalesce with the main crack initiated from the notch, leading to an apparent increase in the effective crack length.

Figure 13 shows the evolution of crack tip opening displacement and the corresponding macroscopic fracture surface. The abrupt changes in crack opening behavior may be associated with crack coalescence between the notch-initiated crack and gas-pore-related cracks in the weld metal. These observations indicate that weld-metal heterogeneities, including gas pores and oxide inclusions, locally influenced the fatigue crack propagation morphology. The occurrence of quasi-cleavage-like features and secondary cracking may also be consistent with hydrogen-assisted crack growth. However, attributing these features specifically to hydrogen would require comparison with corresponding hydrogen-free fracture surfaces. Therefore, the detailed roles of hydrogen, gas pores, and oxide inclusions in circular crack formation and crack coalescence should be investigated further in future work.



a)



b)

Figure 13: Relationship between crack coalescence and crack opening behavior;

a) evolution of crack tip opening displacement (CTOD) with increasing cycle number, showing abrupt changes during cyclic loading,
b) macroscopic fracture surface showing the notch-initiated crack and gas-pore-related crack features, which may be associated with crack coalescence in the weld metal.

5. Conclusions

The low-cycle fatigue performance of hydrogen pre-charged API 5L X65 girth welded joints was evaluated under cyclic strain conditions representative of seismic loading. The main findings of this study are summarized as follows:

(1) Seismic performance under hydrogen-affected conditions

The hydrogen pre-charged girth welded joints satisfied the required number of loading cycles specified in the Japanese seismic design guidelines for high-pressure gas pipelines under both Level 1 ($\pm 0.2\%$) and Level 2 ($\pm 0.5\%$) seismic strain conditions. No through-thickness fracture was observed in any specimen, including notched specimens simulating internal weld defects. These results indicate that the X65 girth welded joints maintained sufficient low-cycle fatigue resistance against the seismic strain demands considered in this study, even under hydrogen-affected conditions.

(2) Confirmation of hydrogen-affected testing conditions

More than 90% of the hydrogen charged was estimated to remain in the specimens at the completion of the fatigue tests. In addition, fracture surface observations revealed locally flat regions, quasi-cleavage-like features, and secondary cracks, confirming that the fatigue tests were conducted under hydrogen-affected conditions.

(3) Characteristic fracture features in the weld metal

In the notched specimens, characteristic circular or ring-like crack features were observed in the weld-metal propagation region. Spherical depressions interpreted as micro gas pores were identified at the centers of these features. In some cases, inclusions containing Si, Mn, Al, and O were detected inside the depressions. These observations suggest that gas pores and inclusions may have contributed to local crack formation and possible crack coalescence in the weld metal under hydrogen-affected cyclic loading. However, the detailed mechanism of circular crack formation and crack coalescence remains to be clarified in future work.

Overall, the results demonstrate that hydrogen pre-charged X65 girth welded joints satisfied the seismic performance requirements considered in this study, although localized hydrogen-assisted fracture features were observed in the weld metal.

Author contributions

Tsubasa Katayama coordinated the experimental programme and prepared the original draft of the manuscript. Keigo Manabe] fabricated the all-around welded joint specimens. Yuki Kiyokawa, Fumiaki Kimura, Yasuhiro Kawai, Yuji kisaka, and Shusuke Fujita contributed to the experimental planning and reviewed and edited the manuscript. Behzad Vasheghani Farahani and Margo Cauwels developed the detailed experimental plan and performed the experiments and data analysis. Kim Verbeken, Tom Depover, and Wim De Waele contributed to the experimental planning and reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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