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Application of line pipe and hot induction bends in hydrogen gas

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ABSTRACT

For the upcoming hydrogen economy, transport pipelines for hydrogen gas and gas mixtures of hydrogen and natural gas are one of the important components. For the application of steel in hydrogen gas it is necessary to handle the risk of hydrogen embrittlement by adapting the right knowledge. Compared to existing hydrogen pipelines, which are safely running since decades, higher gas pressures and steel strength levels are in discussion. For a safe operation and limited resource consumption it is necessary to clarify the product requirements. The semi-finished products medium and large line pipes and bends are regarded over the production chain: pre-material, hot rolled strip, welded pipes, and induction bent pipes. The interaction of hydrogen with steel is investigated since decades. For hydrogen gas, the surface reaction with steel is considerably reduced compared to other corrosion reactions i.e. with sour gas. This results in a much lower amount of introduced hydrogen atoms within the material. Results of lab trials of different materials after storage in pressured hydrogen gas will be shown to clarify this point. Furthermore, results of tests of applicability of commonly used flow coats in hydrogen atmosphere are shown. For a possible failure scenario of a hydrogen transport line the investigations must be focused on local effects of hydrogen enrichment in conjunction with mechanical loads. There are different laboratory tests possible to evaluate these material reactions. They are shown and discussed in the view of the following aspects: product qualification, further product and specification development and suitable approval tests.

1. Introduction

Hydrogen is often highlighted as an alternative energy carrier to fossil fuels, as it enables a CO_2 free economy. The European Union and Germany, among others, have recognized the potential of an H_2 economy and are promoting projects on a large scale, which pave the way for the implementation of an H_2 economy and support it in the best possible way.

The prerequisite for a functioning H_2 economy is the production of H_2, e.g. by electrolysis from surplus electricity or by steam reforming. However, H_2 is often not needed where it is produced making H_2 transport a necessity. The economically most reasonable way of transporting H_2 is then to use distribution networks of pipelines (Hydrogen Council, 2020).

Such distribution networks already exist for the transport of natural gas. This means that an important basis has already been laid for a quick attempt at solving H_2 transportation. Nevertheless, it must be clarified whether and to what extent existing pipelines are suitable for H_2 transport. A potential rededication of pipelines from pure natural gas to H_2/NG mixtures and 100% H_2 has to be well considered, because even small amounts of H_2 can lead to a strong reduction of material performances and hence the expected in service time of pipelines. How pipelines react to H_2 transport then depends largely on pressure fluctuations during operation, gas composition and pipeline material. The operator thus can extend the service life by reasonably managing the pipeline system in a way that is adapted to the new gas. However, the material used is not replaced in such a case. Therefore, only a fraction of the previously determined remaining service life is then available for operation with H_2/NG mixture or 100% H_2.

That H_2 has a degrading effect on ductility, fatigue behavior and toughness of materials has already been shown in detail in the past decades (Nanninga et al., 2012; Moro et al., 2010; Torres-Islas et al., 2005; Balitskii et al.,1987; Balitskii et al., 2000; Ćwiek, 2007; Nagumo et al., 2003; Tsuchida et al., 2010). Consequently, this effect is also reflected in a shortened remaining service life of a pipeline even though it is not as pronounced as is the case for sour service pipelines.

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In this context, new pipeline materials and the semi-finished products made from them, welded pipes and induction bent pipes, become relevant. These semi-finished products are attractive for use because they are better able to meet the special requirements in an H_2 economy than conventional pipeline materials for transporting natural gas. These so-called H_2 ready materials and pipes must then meet the specifications of design standards in terms of strength, toughness and fatigue properties.

In most cases, pipelines are designed using a variety of approaches. Simple approaches generally require less effort for material qualification, but the less is known about the material performance the more this is compensated by safety factors. The design is then usually conservative. Conversely, however, this means giving away the actual potential of the piping material. The more specific material parameters are known, the lower the safety factors can be. A pipeline can thus be designed more economically and also more ecologically. This benefits the pipeline operator, the pipe manufacturer and ultimately the environment.

For the economic design of pipelines, it is therefore necessary to determine the H_2-specific characteristic values and to qualify the materials/pipes. Salzgitter Mannesmann Forschung GmbH (SZMF) has therefore set itself the goal of examining the materials and pipes of Salzgitter AG (SZAG) with regard to their "H_2 readiness". The focus is on the correct adjustment of the H_2 content either in situ or with prior charging and the test with the corresponding characteristic value determination.

In this paper some preliminary test results of investigations in high pressure H_2 gas will be shown which were obtained at the laboratories of SZMF in Duisburg, Germany. All tests were carried out on SZAG pipe or plate products. Additionally the applicability of common flow coat materials was tested.

2. Pipeline design and material qualification – Relevant investigation methods

An economical and resource-saving design of pipelines is only possible if the actual material characteristics are known. For this purpose, it is necessary to determine these characteristic values in advance in qualification tests and to define minimum requirements for the material characteristic values. These are determined using appropriate test methods whereby the testing conditions must reflect the loading conditions in the pipeline during operation as closely as possible. A conservative design based on minimum requirements then ensures safe operation, while at the same time allowing a more resource-efficient design with wall thickness and material properties adapted to operating conditions.

For pipeline operation, internal pressure and pressure fluctuations must be considered. Over time these can lead to damage of the pipeline material and must be quantified for a design. In order to compensate for the internal pressure, the pipeline material needs to provide the necessary strength and ductility under H_2 influence. Further, pressure fluctuations can be included as cyclic load in the determination of the service life of a pipeline. Various approaches are possible for a design:

The design can be based on fracture mechanics fatigue life assessment. A fracture mechanics approach is used, for example, in American Society of Mechanical Engineers standard ASME B31.12 (ASME, 2019). For a design, an additional safety factor is used, which greatly reduces the number of cycles for operational use, in order to design the pipeline with a correspondingly high level of safety. Furthermore, there are proposals to examine pipelines after a certain number of cycles with regard to occurring fracture mechanichal termed flaws (Steinbock, 2021). Alternatively, material fatigue can be determined in hydrogen in cyclic load tests using various specimen geometries (Wöhler / S-N curves).

However, pipelines are not only designed with regard to their service life, but also with regard to their toughness, among other things. The requirement of a minimum toughness shall prevent failure with long running brittle or ductile fracture. Characteristic values are determined, for example, in the notched bar impact test (Charpy V-notch) or the Battelle drop weight tear test. As with ductility, an H_2 influence is to be expected for the toughness parameters.

For the design of the pipeline and the corresponding requirements on the applied material suitable testing for the material's performance in H_2 is crucial. The amount of H_2 in the steel plays a decisive role. The following tests were subject of current investigations at SZMF and are presented in this paper.

2.1. Hydrogen uptake by immersion tests

Immersion tests with subsequent hydrogen measurements are a suitable method for investigating the hydrogen uptake of the steel material when exposed to high-pressure dry hydrogen gas. Immersion tests are performed to determine the hydrogen uptake with respect to different immersion times and surface conditions. The results enable the comparison with other kinds of hydrgogen charging, i.e. electrolytical charging.

2.2. Slow strain rate tensil (SSRT) test

The SSRT test is a tensile test with a low strain rate. The test is performed comparatively under H_2 in-situ loading and in air or nitrogen as inert reference gas. The aim is to determine the influence of H_2 on the mechanical properties of maximum tensile stress, elongation at break and constriction at break, as well as on the fracture behavior. There are standard practices for conducting SSRT tests in general. The testing conditions correspond in most cases the intended practical application.

2.3. Threshold stress intensity factor (K_{IH}) test

The threshold stress intensity factor K_{IH} is required by ASME B31.12 as a qualification criterion for the fracture mechanics service life analysis of a pipeline. The parameter is required to prevent the pipeline from failing prematurely due to pressure fluctuations. For realistic boundary conditions during testing, specimens are fatigue precracked, prestressed with a set constant displacement and charged in pressurized hydrogen for about 6 weeks. The K_{IH} value determines a threshold value below which no premature failure occurs under general in service conditions. This parameter is determined in accordance with the ASTM E1681 test standard in combination with ASME Boiler and Pressure Vessel Code (BPVC) Section VIII Division 3.

2.4. Charpy impact toughness test on H_2 pre-charged specimens

Generally, Charpy impact toughness tests are preformed to ascertain the pipe materials toughness against brittle and ductile fracture. In terms of hydrogen research, these Charpy impact toughness tests were performed after H_2 charging to consider which influence hydrogen may exhibit on dynamic toughness. By comparison with the results of standard Charpy impact toughness tests, the H_2 influence on the toughness parameters can be quantified. The testing is carried out according to the International Organization for Standardization (ISO) standard (ISO, 2016).

2.5. Flow coat testing

Beside the investigation on the steel materials also the applicability of commonly used flow coats in hydrogen atmosphere is proofed. Since hydrogen can easily diffuse into the coating, blistering or peeling from the steel substrate due to an impulsive pressure relief must be avoided. The requirements on internal coatings for line pipes are given in standards of the German Standardization Institute (DIN) and European Standard (EN) DIN EN 10301/ISO 15741 (ISO, 2016) and a recommended practice (RP) of the American Petroleum Institute (API, 2015). These specifications apply for the transport of non corrosive gasses and for the most parts the given requirements do not depend on the transport medium itself with the exception of the resistance to pressure variations and resistance to blistering in liquid transport media.

2.6. Tested materials

All investigations were performed on SZAG pipe or plate products as listed in Table 1. Investigations on flow coat materials were carried out on three common flow coats with different solids content as listed in Table 2. The tested flow coats were applied to plate substrates for line pipe materials. Also for induction bent pipes, flow coat 2 was manually applied and tested.

3. Results and discussion

3.1. Hydrogen uptake

Machined steel samples were placed in high pressure autoclaves (Fig. 1) and charged with hydrogen gas at 100 bar and room temperature. Tests were carried out varying test duration and specimen surface condition. The vessels were evacuated and purged with high purity nitrogen several times before each test to achieve low oxygen partial pressure.

After the immersion test, specimens were dismounted and stored in liquid nitrogen until hydrogen measurement to avoid unwanted hydrogen effusion. Carrier gas hot extraction technique was applied (400 °C, 20 min) to determine the hydrogen content.

Results of the hydrogen measurements are depicted in Fig. 2. Under the chosen environmental conditions hydrogen uptake was observed for the tested materials compared to samples without immersion. The hydrogen levels varied, but never significantly exceeded 0.2 ppm-w. The results show also the effect of exposure time and surface preparation. The surface preparation before loading in the autoclave was found to have significant impact on hydrogen uptake. The latter is attributed to the removal of the surface oxide layer, resulting in a more active surface condition and, thus, higher hydrogen uptake.

For line pipe material, similar hydrogen levels were found for different microstructures (X52M vs. X52N). Comparing L485ME and L485ME mother pipe, the different hydrogen uptake may be attribiuted to the higher alloy content in the mother pipe. The lowest hydrogen uptake in this study was found for the induction bend tangent with PBHT and extrados. Against expectations, the hydrogen uptake decreases with increasing exposure time the induction bend as well as L485ME helical welded line pipe.

3.2. Slow strain rate test

SSRT tests were performed on a testing machine equipped with a pressure vessel. Base metal round tensile specimens from material grades L485ME and L450ME were manufactured along pipe roll axis and from mid-wall position. Prior to test, specimens were degreased, cleaned, and dry purged using nitrogen.

After specimen installation the system was purged using inert gas (nitrogen), followed by cyclic application of vacuum and inert gas. Pure

Table 2
Flow coat materials.

Flow coat materials*	Solids content
Flow coat 1	ca. 47 Vol.-%
Flow coat 2	ca. 61 Vol.-%
Anti corrosion epoxy primer	ca. 97 Vol.-%

* all flow coat materials are two component epoxy resins.

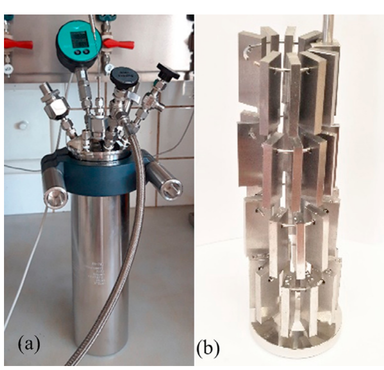


Fig. 1. Test equipment for measuring hydrogen content. (a) High pressure autoclaves for immersion tests in hydrogen gas. (b) Fixture used for mounting multiple specimens in the autoclaves.

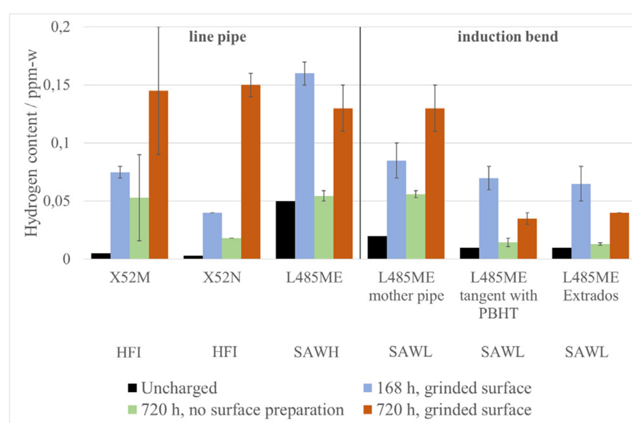


Fig. 2. Results of immersion tests for different steel grades/products.

Table 1
Line pipe materials.

Steel grade	Remarks	Pipe dimensions	Producer	Manufacturing procedure	Testing method
X52M		219 mm × 8.2 mm	MLP	HFI	Hydrogen uptake
X52N		610 mm × 12.7 mm	MLP	HFI	Hydrogen uptake
L485ME		1,016 mm × 16.8 mm	MGR	SAWH	SSRT, Hydrogen uptake
L485ME	mother pipes for induction bending	1,422 mm × 22.5 mm	MGB	SAWL	Hydrogen uptake
L485ME	induction bend incl. PBHT*	1,422 mm × 22.5 mm	MGB	SAWL	Hydrogen uptake
L485ME	induction bend, extrados	1,422 mm × 22.5 mm	MGB	SAWL	Hydrogen uptake
L450ME		660 mm × 17.5 mm	MGR	SAWH	SSRT
L415ME		660 mm × 11.1 mm	MGR	SAWH	K_{IH}, CVN

* PBHT – post bent heat treatment.

hydrogen (100%, quality 5.0) gas was applied at 80 bar. Reference mechanical properties were acquired using the same SSRT test while using inert gas (nitrogen). Two specimens were tested in hydrogen for each material; reference properties were acquired using one specimen per material. All tests were performed at ambient temperature. SSRT tests were conducted at a strain rate of 2×10^{-5} s^{-1}. Mechanical testing started after pressurizing with H_2 or inert gas.

Two basic types of results were obtained: visual examination of the specimen gage section for evidence of cracking, and measurements of specimen ductility with exposure to hydrogen and inert gas. Two ductility parameters were used for evaluation: plastic elongation and reduction in area. Additionally, time to failure was measured.

Results of SSRT tests (average values) are summarized in Table 3. No significant reduction of ductility properties (< 10%) was observed for base metal and weld metal specimens of both materials. An abrupt drop in engineering stress was observed in the stress-strain curves (Fig. 3) for some specimens. As this drop appeared at very high strain values, it is assumed that the materials may suffer from hydrogen embrittlement at very high plastic deformation which is normally not expected in service operation. Visual examination at up to 20x (digital 3D microscope) did not reveal any indications for secondary cracking on tested specimens. The classical cup and cone fracture has been observed for all specimens.

Moreover, several investigations on HFI (high frequency induction) welded line pipes produced by MLP were performed in the last years. The test results showed similar effects as described above with an effect of hydrogen embrittlement occurring in the range of high plastic deformation. The test results are published by Brauer et al. (2020, 2019).

3.3. Threshold stress intensity factor (K_{IH}) test

K_{IH} tests were performed on spiral welded pipe material (grade L415ME) on three different pipes with outer diameter of 660 mm and wall thickness of 11.1 mm including base metal (BM), weld metal (WM) and heat affected zone (HAZ). K_{IH} specimens were manufactured in (TL) direction with a thickness (B) of 10 mm, see Fig. 4. A set of three specimens per location (BM, WM, HAZ) and heat was used for K_{IH} measurement. The tests were carried out in pure hydrogen gas at 100 bar.

For specimen preparation a machined notch was introduced into the specimens with final fatigue pre-cracking to acquire a conservative stress state for testing. Fatigue pre-cracking was conducted in an ambient air environment. For specimen loading a K_{IAPP} was applied with the constant displacement method using bolt tightened against a flattened pin according to ASTM E1681 and ASME BPVC Section VIII Division 3. The loading process took place in a glove box with inert gas to prevent the formation of oxides on the pre-crack surface which could inhibit hydrogen uptake during testing. The test specimens were then placed into a high pressure test chamber. The test chamber was evacuated to eliminate traces of air or moisture. Test specimens were subjected to the previously set displacement for 1,000 h at room temperature.

After the test, fatigue crack length was measured and scanning electron microscopy (SEM) was applied to measure any potential crack growth due to hydrogen uptake at 25%, 50% and 75% specimen thickness. Fig. 5 shows a typical fracture surface of an K_{IH} specimen. K_{IH} was calculated based on crack mouth opening displacement V_m as applied during the stressing procedure. Test results were calculated using Eq. 4 in ASTM E1681 and are given in Table 4.

The calculated K_{IH} values lie in the range of 55 to 62 MPa$\sqrt{m}$. SEM examinations showed no crack propagation on any of the specimens due to hydrogen. For all cases (BM, WM, HAZ) a $K_{IH,min}$ value ≥ 55 MPa$\sqrt{m}$ was calculated. The requirements of ASME B31.12 PL-3.7.1 (2) Option B, are accordingly met. The material investigated is therefore qualified and can be used in the upcoming hydrogen economy.

The K_{IH} values for BM, WM and HAZ show a similar range, since they depend only on the applied constant displacement and the fatigue crack length. For all specimens, prestressing and fatigue pre-cracking were equally applied. The range of results is mainly due to the slight variations of the fatigue crack length.

It is reasonable that larger K_{IH} values would have been possible, since even at 62 MPa$\sqrt{m}$ no sign of crack propagation due to hydrogen was detected. Consequently, at which K_{IH} value crack propagation due to H_2 occurs is not evident in this study due to the approach required by ASME BPVC Section VIII Division 3. A limiting K_{IH} may be acquired on the basis of several pre tests with stepwise increased constant displacement.

Table 3
SSRT test results for grades L485ME and L450ME at 80 bar total pressure and room temperature. RAR: reduction in area ratio; EpR: plastic elongation to failure ratio; TTFR: time to failure ratio.

Test condition	RAR /%		E_pR /%		TTFR /%	
	L485ME	L450ME	L485ME	L450ME	L485ME	L450ME
100% H_2	94.9	98.6	97.6	97.9	94.5	98.5

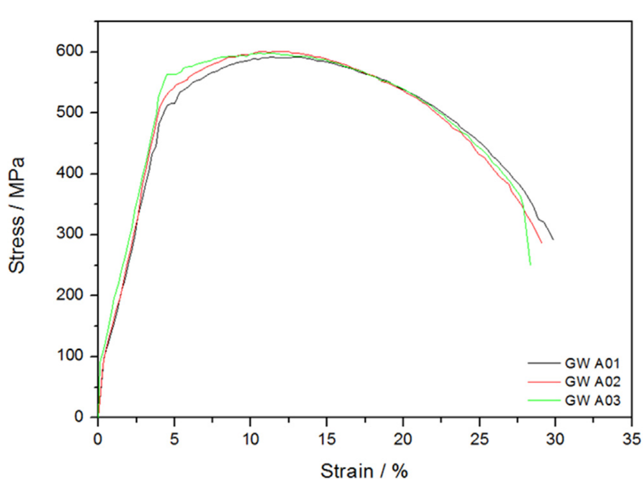


Fig. 3. Stress-strain curves for the base metal of grades L485ME (curves for material L450ME similar). A01: reference specimen in nitrogen; A02 and A03: specimens tested in hydrogen.

3.4. Charpy impact toughness test on H_2 pre-charged specimens

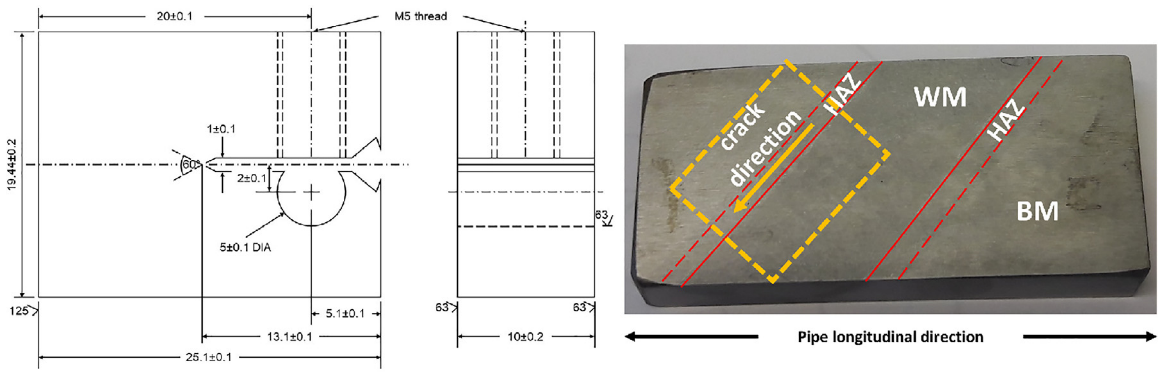
The effect of hydrogen on the notch impact strength of large diameter spiral-welded tube (grade L415ME) was evaluated. For this purpose, CVN tests after hydrogen charging were performed on base metal and spiral weld.

Hydrogen charging was performed in NACE TM0177 solution A saturated with 100% hydrogen sulfide (H_2S) at room temperature (24 ± 3 °C). The solution was de-aerated with nitrogen (N_2) for 1 h prior to H_2S saturation. The test duration was six hours. After hydrogen charging, all specimens were cleaned, dried and then immediately stored in liquid nitrogen (−196 °C) until just before hydrogen measurement or CVN test. Hydrogen content was determined using the same technique and parameters as described above (see “Immersion test”).

CVN impact toughness was measured according to DIN EN ISO 148–1 with a striker radius of 2 mm at 0 °C, −10 °C and −20 °C. All specimens

Table 4
K_{IAPP} and K_{IH} test results and the parameter range.

Specimen / notch location	K_{IAPP}/(MPa$\sqrt{m}$)		K_{IH}/(MPa$\sqrt{m}$)	
	min	max	min	max
Base metal	113	123	56	61
Weld metal	110	124	55	62
Heat affected zone	115	122	57	61



(a) (b)

Fig. 4. Specimen sketch and specimen location. (a) K_{IH} specimen geometry with a thickness (B) of 10 mm. (b) Position of specimens including HAZ.

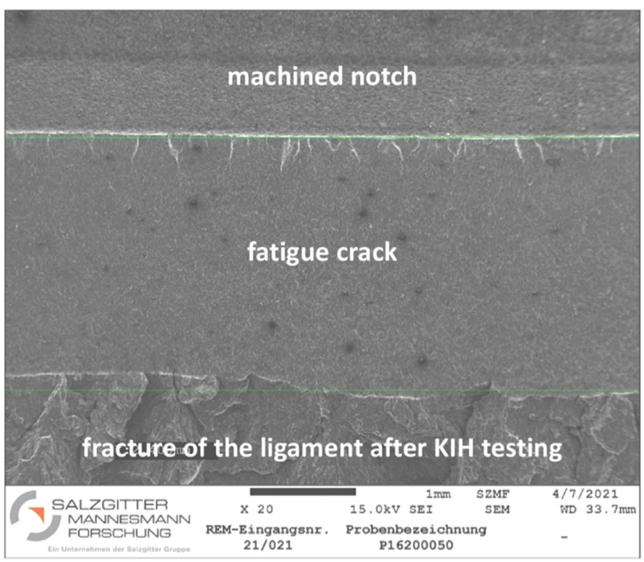


Fig. 5. Typical fracture surface of a K_{IH} specimen without hydrogen crack growth.

were stored in liquid nitrogen (−196 °C) until CVN testing. Then, specimens were taken out of the liquid nitrogen and put in tempering bath (ethanol/liquid nitrogen) for 5 min. The tempering bath was set to the desired test temperatures of 0 °C, −10 °C and −20 °C. The specimen thickness was 10 mm for base material (BM) and 7.5 mm for spiral weld (weld) specimens (weld centerline) respectively. The specimens' position was transverse. The notch position was through thickness. A set of three specimens was tested per temperature condition.

Hydrogen charging conditions were controlled in terms of pH and hydrogen sulfide concentration. The initial pH value was 2.9, increasing to 3.3 after 6 h charging. The H_2S concentration after saturation and after the duration of 6 h was 2,418 ppm and 2,589 ppm, respectively. No blister formation after charging end was observed for any of the specimens.

Results from hydrogen measurements are summarized in Table 5. As reference, uncharged specimens were used. No (diffusible) hydrogen was detected in reference specimens for both, base metal and weld. For the charged specimens 3.43 ± 0.10 ppm and 3.75 ± 0.03 ppm of (diffusible) hydrogen were measured.

CVN results are summarized and depicted in Fig. 6 for both base metal and spiral weld in both hydrogen charged and uncharged (reference) conditions. As expected, CVN impact toughness is higher for base metal specimens compared to spiral-welded specimens. Also, a distinct decrease in the CVN values was observed for the hydrogen charged specimens compared to the respective reference (uncharged) specimens. It is worth noting that the difference between charged/uncharged was in the same range for base metal and spiral-welded material (84 J to 99 J). In the selected temperature range (−20 °C to 0 °C), the obtained CVN values were in the same range for base material (303 J to 314 J for uncharged and 204 J to 229 J for charged condition) and spiral weld (135 J to 153 J for uncharged and 49 J to 68 J for charged condition), respectively.

Table 5
Results of (diffusible) hydrogen measurements after charging for 6 h. Uncharged condition: single measurements; charged condition: average value of three measurements.

Location	Condition	$[H_2]$/ ppm	σ/ ppm
BM	Uncharged	0.00	–
	Charged	3.43	0.10
Weld	Uncharged	0.00	–
	Charged	3.75	0.03

The effect of (artificially charged) hydrogen on the notch impact strength of the selected material was unambiguously proven. However, the obtained impact toughness still exceeds by far the requirements of the established engineer standards. Also, in this work the artificially charged hydrogen may be much higher than expected for pipelines used for transport and/or storage of pressurized gaseous hydrogen.

3.5. Flow coat testing

The investigations on the flow coat materials were carried out according to DIN EN 10,301 annex C.

For the evaluation of the resistance to pressure variations samples of steel substrates coated with the three flow coat materials were subjected to 10 pressure cycles in a high pressure autoclave: Cycles 1 to 4 and cycles 6 to 9 comprised 20 hours immersion at 100 bar hydrogen, pressure relief and 3 hours atmosphere pressure; cycles 5 and 10 comprised 68 hours immersion at 100 bar hydrogen, pressure relief and 3 hours atmosphere pressure. All samples passed the tests without blistering.

For evaluation of the resistance to blistering in liquid transport media the coated samples representing internal coatings for line pipe and induction bends were completely submerged in saturated $CaCO_3$ solution and pressurized with 100 bar hydrogen with a pressure relief after 24 hours immersion. All samples passed the tests without blistering.

The investigations show that all three flow coat materials are applicable for the use in hydrogen transport pipelines.

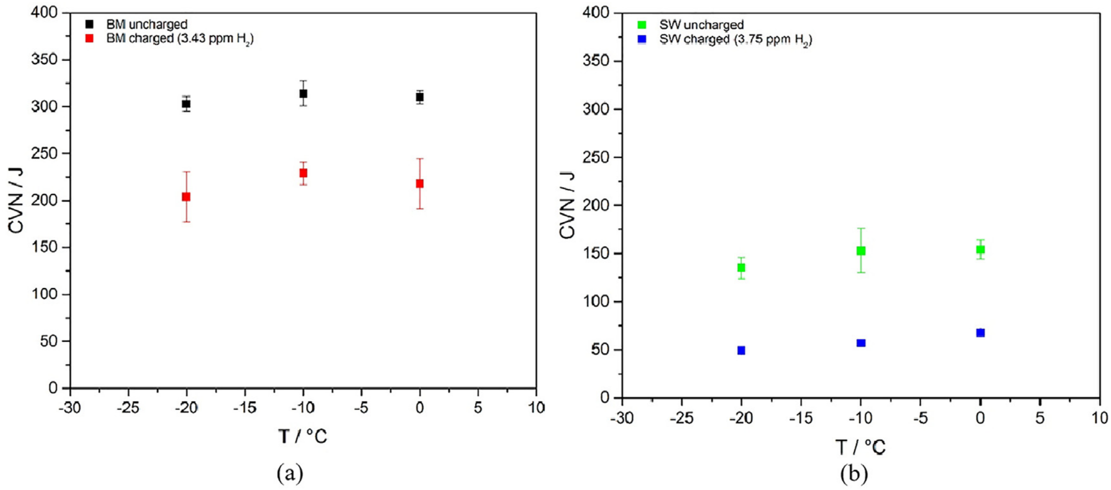


Fig. 6. Plots of CVN impact toughness (mean values) as a function of test temperature for (a) base metal and (b) spiral weld. Hydrogen (diffusible) content determined in separate measurements are given for the charged condition. No (diffusible) hydogen was detected in the uncharged condition.

4. Discussion and conclusions

In this paper, results were presented regarding the material performance of the products (pre-material, hot rolled strip, welded pipes, and induction bent pipes). The results show that H_2 diffused in to the tested materials depending on surface condition and charging time. Even though in some cases H_2 affects material properties the influence was still neglecteable.

The individual material characteristics show that they not only meet the current requirements set in the standards, but amongst other can also withstand far more disadvantageous conditions at higher H_2 contents. The materials are supplied by the companies, which have been mentioned in Section 1.

Further relevant material parameters are currently discussed in standardization bodies, which are to be used for material qualification. These parameters are mainly focused on the service life of pipelines. Fracture mechanics parameters are considered that go beyond the K_{IH} requirement of ASME B31.12 due to several reasons.

Firstly, the K_{IH} test standard (ASTM, 2013) requires the characteristic values to be determined on specimens of a certain minimum thickness. For typical strengths in pipelines, this means that speficically large specimen thicknesses must be given. By strictly following the test standard, the determined K_{IH} values with lower specimen thicknesses are therefore invalid. In combination with (ASME, 2013), an engineering characteristic value can be determined that allows 85% of the pipe wall as specimen thickness criterion. Such an approach is reasonable considering the difficulty / impossibility to determine K_{IH} values above a cccertain pipe wall thickness. Nevertheless, this means that K_{IH} values may only be transferred to other wall thicknesses within very narrow limits. Exceeding said limits means performing new pipe material qualification. This is associated with considerable costs for the pipe manufacturers.

Secondly, the determined K_{IH} values only allow a statement of a certain limit value. The actual material performance is not determined in the K_{IH} test, as it is required in ASME B31.12. Other characteristic values, which are determined in standard fracture mechanics tests, however, allow such statements. These values are also capable of taking material behavior (brittle, plastic deformation, ductile crack propagation) into account (K_{IC}, J-integral, K_{JIC}).

These values may be used for material qualifications and product approvals/acceptance tests. SZMF is already capable of performing tests under high pressure conditions. Testing machines allowing the determination of fracture mechanics parameters, which are relevant for fatigue life assessment (K_{IC}, J-integral, K_{JIC}) are also planned in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

API, 2015. Recommended Practice for Internal Coating of Line Pipe For Non-Corrosive Gas Transmission Service: API RP 5L2. American Petroleum Institute, New York, USA.
ASME, 2013. Section VIII Division 3 Alternative rules for construction of high pressure vessels. The American Society for Mechanical engineers, New York, USA.
ASME, 2019. Hydrogen piping and pipelines: ASME B31.12-2019. The American Society for Mechanical Engineers, New York, USA.
ASTM, 2013. Standard test method for determining threshold stress intensity factor for environment-assisted cracking of metallic materials: ASTM E1681. ASTM International, West Conshohoken, USA.
Balitskii, A.I., 1987. Cyclic crack resistance of rotor steel as a function of loading conditions. Metal Sci Heat Treat 29, 266.
Balitskii, A., Krohmalny, O., Ripey, I., 2000. Hydrogen cooling of turbogenerators and the problem of rotor retaining ring materials degradation. Int. J. Hydrogen Energ. 25, 167.
Brauer, H., 2020. Energiewende mit Wasserstoffrohren H2Ready und Umstellung existierender Erdgasleitungen, 3R, 03/2020 32.
Brauer, H., 2019. Stahlrohre für den Transport von gasförmigen Wasserstoff, gwf Gas + Energie, 2-3/2019 58.
Ćwiek, J., 2007. Hydrogen degradation of high strength weldable steels. J. Achiev. Mater. Manuf. Eng. 20, 223.
Hydrogen Council, 2020. Path to hydrogen competitivenss - A cost perspective. Hydrogen Council.
ISO, 2016. Paints and varnishes-friction reduction coatings for the interior of on- an offshore steel pipelines for non-corrosive gases: ISO 15741. Interrnational Organisation for Standardization, Geneva, Switzerland.
ISO, 2016. Metallic materials – Charpy pendulum impact test – Part 1: Test method: ISO148-1. Interrnational Organisation for Standardization, Geneva, Switzerland.
Moro, I., 2010. Hydrogen embrittlement susceptibility of a high strength steel X80. Mater. Sci. Eng. A 527, 7252.
Nanninga, N.E., 2012. Comparison of hydrogen embrittlement in three pipeline steels in high pressure gaseous hydrogen environments. Corros. Sci. 59, 1.
Nagumo, M., 2003. Fatigue damage and its interaction with hydrogen in martensitic steels. *Mater. Sci. Eng. A* 2003 348, 192.
Steinbock, J., 2021. Der bruchmechanische Lebensdauernachweis – ein wesentlicher Baustein des Sicherheitskonzeptes für den Betrieb mit Wasserstoff. IRO Seminar Wasserstoff 2021, April 15-16, Oldenburg, Germany.
Torres-Islas, A., 2005. Effect of hydrogen on the mechanical properties of X-70 pipeline steel in diluted NaHCO3 solutions at different heat treatments. Int. J. Hydrogen Energ 30, 1317–1322.
Tsuchida, Y., 2010. Effect of hydrogen absorption on strain-induced low-cycle fatigue of low carbon steel. Procedia Eng. 2, 555.