WHITEPAPER

STEEL COMPONENTS IN THE HYDROGEN ECONOMY

SALZGITTER
MANNESMANN
FORSCHUNG
A Member of the Salzgitter Group

SECTION 1

APPLICATION OF STEEL COMPONENTS IN THE HYDROGEN INFRASTRUCTURE

Operational integrity and material qualification

For a successful energy transition targeting climate neutrality hydrogen as energy carrier is of crucial relevance. Hydrogen can be used on the one hand directly (e. g. combustion or steel production with hydrogen as reducer), on the other hand it can be converted to electricity via fuel cells, to be fed into the existing power grid or to drive electric motors.

If gained by electrolysis from renewable energies, e.g. wind or solar power, hydrogen is called Green Hydrogen. Production and use are climate neutral, because the only „exhaust" is steam. Next to production and utilization also transport and storage of Green Hydrogen are relevant, given that electrolysis will be installed decentralized due to efficiency reasons. For wind power as example offshore parks are envisaged, to achieve high performance in full load. The gained hydrogen needs to be transported to consumers and to be stored in between. Here, pressurized hydrogen gas is the favoured solution.

Europe-wide efforts are undertaken to install a hydrogen pipeline grid [1]. Existing natural gas pipelines shall be repurposed for hydrogen transport. A high portion of new hydrogen lines shall complement these. Furthermore, hydrogen vehicles and loading stations are in focus with rising demand for stationary and mobile high-pressure tanks and industrial lines. In all fields, steel components are suitable, as they are robust, recyclable and provide best mechanical properties. Future steel production will happen in CO_2-reduced processes, as Salzgitter AG project SALCOS [2] shows.

Basis for the acceptance of a hydrogen economy is the components' operational integrity. The application of steels for the hydrogen infrastructure, e. g. in pipelines, requires a safe design of all components for pressurized hydrogen gas. Steel tubes need sufficient resistance against hydrogen induced alterations of mechanical properties. To ensure operational safety the steels' relevant parameters are defined and determined. Appropriate material tests guarantee that the material and component properties fulfil the requirements.

[1] Gas to climate: European Hydrogen Backbone. The European Hydrogen Backbone (EHB) initiative, July 2022

[2] Salzgitter Low CO_2 steel making – SALCOS, Salzgitter AG, WE ale steel green, SALCOS®, Juli 2022, www.salzgitter-ag.com

Content:

Our Hydrogen-Team (from left) Dr. Georg Golisch, Dr. Nikolai Jacob,
Dr. Elke Wanzenberg, Dr. Paul Neddermann, Dr. Juliane Mentz, Dr. Susanne Höhler

> ***For qualification and component development for hydrogen economies we make use of our broad research competence and experimental resources of Salzgitter Mannesmann Forschung.***

ABOUT US

H2STEELAB

Hydrogen. Safe.

As a leading European steel research company, we have decades long experience both in steel tube production and in material testing and material qualification under pressurized hydrogen gas. Yearslong involvement in national and international standardization committees around steel pipes motivates us to co-create standards and guidelines for hydrogen infrastructure. We are in discussions with experts in the field due to numerous publicly funded research projects.

For these small H_2 molecules the devil is in the detail! Therefore, the tests must be performed with the necessary technical expertise and sufficient safety measures. One module for new tests is the new laboratory H2SteeLab which we are setting up. A lot of the already existing equipment as well as the new machines will be consolidated. Laboratory room of 150 square meters will allow numerous test places for different facilities. Pure hydrogen gases and hydrogen-gas-mixtures with pressures up to 400 bar will be safely operated.

Safe operation of steel components

The following sections treat important basics of the interaction of steel and hydrogen, relevant test methods and examples for tube application in hydrogen infrastructure.

SECTION 2

INTERACTION OF HYDROGEN AND STEEL

Safely avoid hydrogen embrittlement

In the application of steel components for the hydrogen economy concerns may occur due to potential hydrogen embrittlement. The mechanisms of hydrogen embrittlement and possible influences on the steel properties must be understood and can be handled for a safe use of steel components.

When hydrogen penetrates the steel microstructure, there may be a risk of hydrogen embrittlement. Hydrogen absorbed by the steel structure diffuses through the metal lattice, accumulates at localised stress peaks, occupies hydrogen traps, changes the mobility of dislocations or destabilises grain boundaries. All of this can lead to changes in the mechanical properties of the steel and, under unfavourable circumstances, may cause premature failure of the steel component.

Whether and to what extent hydrogen embrittlement can occur is determined by the interaction between the present medium, the material and the mechanical load on the component. The occurrence of hydrogen embrittlement depends on the prior absorption of hydrogen into the metal lattice. Depending on the medium the mechanisms of hydrogen absorption vary and consequently lead to different extent of hydrogen uptake.

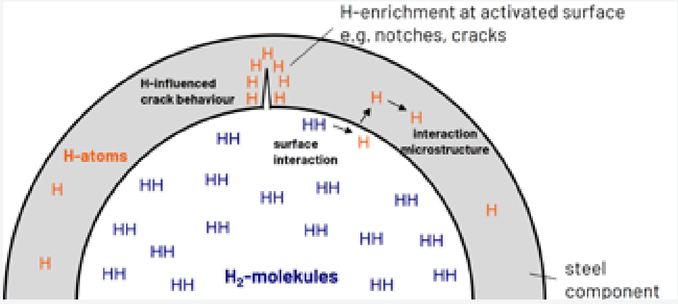
Absorption of hydrogen from gaseous pressurized hydrogen is different from sour service corrosion or electrochemical charging, where large quantities of hydrogen penetrate the steel.

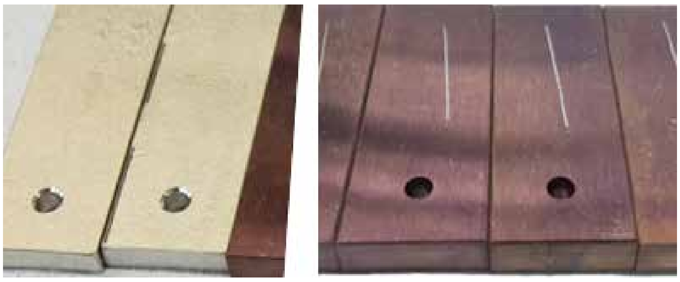
Hydrogen can only be absorbed in the metal lattice as a hydrogen atom (from the gaseous medium) or as an H+ ion (from the liquid phase). Hydrogen molecules cannot penetrate the metal lattice. In the presence of gaseous (pressurized) hydrogen, the hydrogen molecules must be adsorbed on the metal surface and dissociate to form hydrogen atoms. Afterwards some of the hydrogen atoms can pass through the metal surface and the absorption in the metal lattice is enabled. However, a large proportion of the hydrogen atoms on the metal surface recombines to form hydrogen molecules again. Only a small proportion of the hydrogen penetrates the metal lattice. This process of formation of hydrogen atoms and hydrogen uptake can only occur on an active bare metal surface. Even the presence of a common steel pipe surface with an natural oxide or passive layer or a covering of the surface with oxygen effectively prevents this process of hydrogen absorption. As the steel components used are generally stored in air before operation in pressurized hydrogen, there is normally - even with a visually bright appearance - a thin oxide layer on the steel surface. So hydrogen absorption is initially prevented. Breaking up this oxide layer e. g. due to plastic deformation or fatigue loading, can lead to areas with a bare metal surface and localised hydrogen ingress is possible.

In our investigations, specimens of various line pipe materials had been immersed in pressurized hydrogen for different immersion times. Afterwards the resulting hydrogen contents of the specimens were determined. For these investigations specimens with different surface conditions were prepared:

- Specimens without special surface treatment after machining
- Specimens with a freshly ground surface, so that the natural oxide layer was removed
- Specimens after thermal ageing (60' 250 °C) with partial injury of the oxide layer.

Hydrogen uptake from the pressurized gas phase was strongly dependent on the surface condition of the specimens. With an immersion time of up to thirty days, hydrogen uptake was only observed on specimens with freshly ground surfaces. Only after a longer immersion time of 6 months a very low hydrogen uptake





Specimens for immersion tests, left: without special surface treatment or freshly ground (no visible difference), right: after thermal ageing with partial injury of the oxide layer

was observed also in specimens without freshly grinding before immersion.

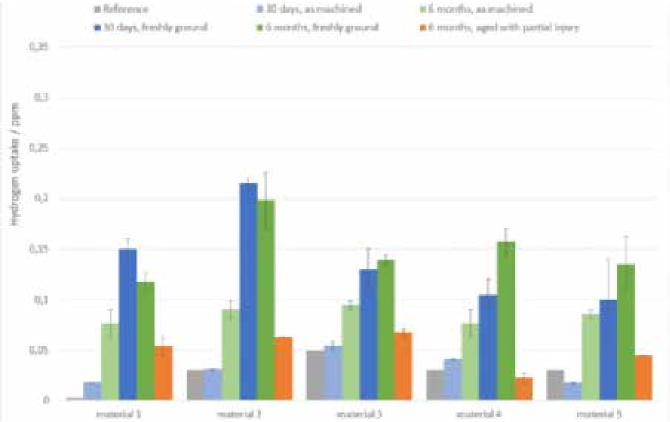
Samples which had been thermally aged showed no significant hydrogen uptake even after six months of immersion with a partially injured oxide layer.

For all tested samples, the measured hydrogen contents were very low with values < 0.25 ppmw. The hydrogen uptake from pressurized hydrogen gas has shown to be significantly lower than hydrogen contents that can occur after electrolytic loading or under sour service conditions (2-4 ppmw under NACE standard sour service conditions).

For steel components in gaseous hydrogen applications the results show that the materials generally absorb a very low amount of hydrogen from the gas phase. However, if there is mechanical damage like cracks or notches in the component metal surface or if there is plastic deformation, increased hydrogen absorption can occur locally.

Already very small amounts of oxygen in the medium (from approx. 100 ppmv) can inhibit the hydrogen uptake of the steel [1]. Oxygen has a high tendency to be adsorbed at the metal surface. Coating the metal surface with oxygen prevents the adsorption of hydrogen at the metal surface and thus the absorption of hydrogen in the steel structure.

Typical effects of hydrogen embrittlement under pressurized gas applications are reduced ductility parameters such as elongation at fracture and reduction of area, reduced fracture toughness, accelerated crack propagation and a degradation of the fatigue properties. Effects known from sour service corrosion such as HIC (hydrogen induced cracking) do not occur under pressurized hydrogen gas applications, as this requires larger quantities of hydrogen in the steel microstructure. In case of HIC, hydrogen atoms in the steel recombine to form H_2 molecules. Thereby a high gas pressure in the microstructure of the steel is build up and causes cracks in the component even without application of



Hydrogen uptake of different line pipe materials in pressurized hydrogen gas

---

[1] *NATURALHY Project: "Preparing for the hydrogen economy by using the existing natural gas system as a cata-lyst". Cordis proj. ref. 502661, Program FP6-SUSTDEV, 2004-2009, Final Public Presentation NaturalHy, 19.11.2009, Groningen, Niederlande*

SECTION 3

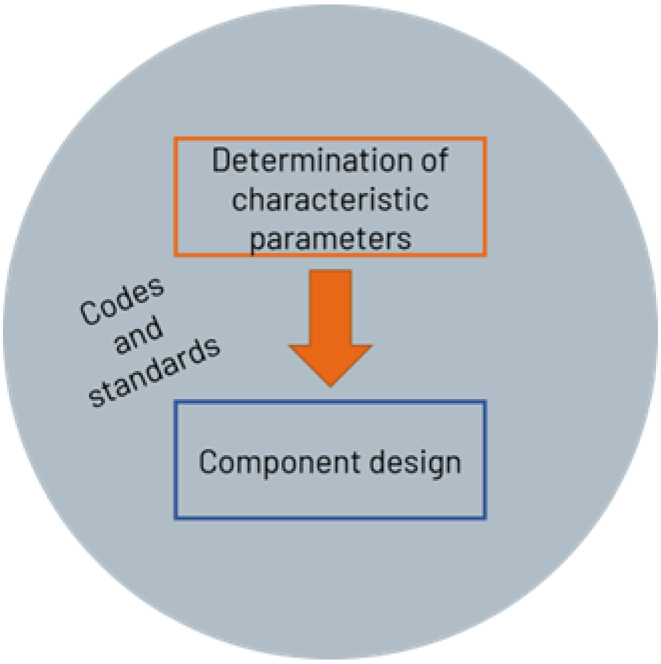
PROPERTIES OF METALS IN COMPRESSED HYDROGEN GAS: TEST METHODS

Are our steels H_2ready?

PREFACE

The component behaviour in hydrogen applications and the occurrence of a possible hydrogen embrittlement depend on the material and component properties, such as strength, microstructure, alloy, potential initial cracklike defects or notches, and on the operating conditions governing hydrogen pressure, hydrogen content, pressure cycles, temperature, etc.

For a safe operation the material properties under the required operating conditions must be well known. Plus, a reliable determination of these properties in experiments is essential. A wide number of test methods exist to assess the steel materials and components for hydrogen applications. The tests either provide precisely defined material parameters or allow comparative mechanical investigations in hydrogen. Depending on the question to answer, all test methods are justified. Here, standardization committees have the task to define the relevant characteristic parameters for a safe design and to specify the appropriate requirements in the codes and standards.
Different applications involve distinct requirements on the materials. Our laboratories are equipped with a sound portfolio of testing techniques for experiments on materials and components in hydrogen.



PART 1:

HYDROGE UPTAKE VIA CHARGING

Hydrogen uptake in pressurized hydrogen gas

When pressurized hydrogen gas interacts with steel, potential damages must be cared for. Before hydrogen can lead to an embrittlement of the material, the hydrogen atoms need to enter the material. A hydrogen uptake from the gaseous hydrogen phase is not expected under normal conditions, as the steel surface has an oxide layer which prevents hydrogen adsorption. Nevertheless, under certain conditions, e. g. where the steel has been plastically deformed or if the surface has been locally activated, a significant hydrogen uptake can take place. In uptake tests samples of various steels can be charged with pressurized hydrogen gas for a certain test duration. Afterwards the overall portions of hydrogen in the sample can be measured. The test parameters as surface condition, hydrogen gas pressure, temperature and charging duration can be varied.

The quantitative analysis of the hydrogen content taken up is measured via carrier gas hot extraction at temperatures up to 900 °C.

Coupons for hydrogen charging

Autoclave for hydrogen charging

For carrier gas hot extraction we apply Bruker G4 Phoenix

PART 2:

CARRIER GAS HOT EXTRACTION

Quantitative measurement of hydrogen in metals

Carrier gas hot extraction is a method to determine the hydrogen diffusion and concentration in the metal structure in a quick and precise way, for very small hydrogen contents the analysis can be done in the ppb-range. Specific heating of the specimen causes hydrogen to be released which is transported with a carrier gas (nitrogen) to the thermal conductivity detector. The temperatures in an infrared oven can reach from 25 °C up to 900 °C maximum. In addition to tests with constant temperatures (isothermal) also temperature ramps can be applied, that can provide information of differently bonded hydrogen in the material.
Larger sample sizes (e. g. welded specimens according ISO 3690) can be measured in the charging vessel with diameter of approx. 28 mm. For the carrier gas hot extraction measurement a Bruker G4 Phoenix device is available.
Furthermore, we have the availability with a Bruker G8 Galileo to measure the overall hydrogen content in a sample. This is carried out with the melt extraction.

Sample before carrier gas hot extraction and red-hot sample during the measurement

PART 3:

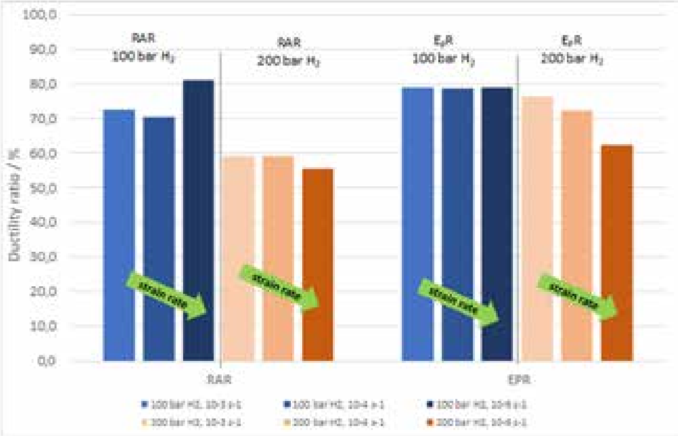
SLOW STRAIN RATE TEST

Ductility behaviour under pressurized hydrogen gas

The Slow Strain Rate Test (SSRT), according to e. g. NACE TM0198 or DIN EN ISO 7539-7 provides the possibility to investigate the effects of a hydrogen atmosphere on the mechanical properties of a material under quasistatic loading. The very low strain rate allows the medium hydrogen to interact with the steel and to diffuse to critical positions in the microstructure. The test can be carried out both with smooth or notched tensile test specimens under relevant test conditions (e. g. 80 bar pressure in pure gaseous hydrogen or in a mixture of hydrogen with methane or natural gas). Comparative tests are tests in inert gas atmosphere, e. g. nitrogen, in otherwise same test conditions.

Tensile test rig for SSRT with H_2-autoclave

For evaluation of the hydrogen impact on the material's ductility relative values are used. These are the ratios of test results in pure hydrogen atmosphere or a hydrogen mixture, respectively, and the reference test results gained in reference medium nitrogen. RAR (reduction of area ratio) describes the relative area of reduction and EPR (plastic elongation at fracture ratio) the relative plastic elongation of the specimen after failure. Higher values of RAR und EPR indicate a lower susceptibility to hydrogen embrittlement.



SSRT results: Hydrogen in comparison with nitrogen (reference) for a typical line pipe steel, varied pressures and strain rates

PART 4:

FATIGUE TEST

Cyclic tests for fatigue strength evaluation

For the operation of pipelines or storage tanks load cycles from fluctuating pressures must be considered. Such stress cycles can lead to fatigue damage which needs to be estimated and quantified for integrity and design. Pressure cycles are one design parameter for the lifetime assessment of components.
A fatigue assessment can be realized via several concepts. One is the determination of the material's fatigue behaviour with fatigue load cycle tests that are evaluated with Wöhler concept (S-N-curves). A database is necessary that includes the influence of hydrogen on the fatigue performance.
Fatigue test specimens have no initial fatigue crack inserted, but they are either with smooth surface or have a geometric notch. Thus, the test results include the crack initiation phase and the crack growth phase. The specimens are loaded with stress cyles

Round bar specimens for fatigue tests

to evaluate the fatigue strength and number of cycles in correlation with the inserted stress range.
For hydrogen applications the tests are performed in the environment of pressurized hydrogen gas in an autoclave under the selected hydrogen test pressure. The test specimens are commonly round bar specimens, but also strip specimens with or without notches.

PART 5:

FRACTURE MECHANICS

Fracture toughness, crack growth rate

For design for hydrogen applications several current standards require that fracture mechanics concepts are adapted. The availability or determination of the relevant material parameters is essential. In a fracture analysis the material's fracture toughness must be known. The standard fracture toughness test method as in ASTM E1820 / ISO 12135 can be applied. Furthermore, cyclic loads from e. g. pressure fluctuations in a pipeline, need to be considered, if they can effect fatigue damages. The corresponding test to obtain fatigue crack growth parameters is described in ASTM E647.

We are extending our laboratory capacity to determine fracture parameters acc. to these standards in pressurized hydrogen gas up to a pressure of 400 bar. The fracture toughness values (K, J-integral, CTOD) can be stated as J_{IC} or K_{JIC}. The fatigue crack growth rate da/dN will be quantified under pressurized hydrogen. Fracture properties will be relevant for future qualification and design concepts for the hydrogen infrastructure. They provide the basis for integrity concepts to be used for e. g. pipelines, storage pipes and other components. Several standards as ASME B31.12 or DVGW G463 already have implemented fracture toughness properties or require that certain limit values are met.

Tensile test rig with H_2-Autoclave

PART 6:

K_{IH}-TEST

Standardized material qualification

Hydrogen pipelines can be designed with lifetime assessments based on fracture mechanics. For the analysis the material's fracture toughness is the limit criterion. Reaching this limit state represents the end of the calculated operating lifetime. While the fracture toughness value K_{JIC} acc. ASTM E1820 is the characteristic material property, the K_{IH}-test acc. ASME B31.12 presents a threshold stress intensity factor as a qualification value in accordance to this limit state.
With the K_{IH}-test the effects of pressurized hydrogen gas on ductile crack growth under constant displacement are determined. The fracture specimen (CT-specimen) receives a fatigue crack and is then charged with pure hydrogen for a time duration of 1000 h under a certain pressure (e. g. 100 bar) while mechanically loaded with a preset load level. Afterwards the specimen is broken and the fracture surface analyzed for potential crack growth via scanning electron microscopy (SEM).
A further method for testing K_{IH} is the constant load test. Here, the designated stress intensity is applied on the specimen with a weight and cantilever.

K_{IH} test specimens with bolts to apply constant displacement

Both methods are limited in their validity concerning the preconditions of linear elastic fracture mechanics if line pipe steels are tested. Nevertheless, K_{IH} is currently used for qualification of line pipe steels according ASME B31.12-2023.
As an alternative, codes and standards, as DVGW G463, refer to the standard fracture toughness value KJIC. This parameter is experimentally determined in pressurized hydrogen gas. It provides a characteristic limit material value. SZMF currently establishes an extended H2SteeLab, a new hydrogen test laboratory, where these and further test capacities will be realized.

PART 7:

BURST TESTS ON LINE PIPES UNDER HYDROGEN

Component behaviour under static/cyclic internal pressure

We perform burst tests to investigate relevant problems and integrity questions of components under pressurized hydrogen gas. The tests on pipes of various dimensions and conditions indicate the effects of the medium hydrogen on the burst behaviour.
One major challenge is that all safety relevant aspects are guaranteed, because hydrogen in combination with oxygen is a highly explosive mixture. A correct test procedure is mandatory and all parts of test equipment must operate perfectly according to the state of the art.

The analysis of the burst behaviour is realized with a full instrumentation with pressure sensors, clip gauges as well as recording with high-speed cameras. Fracture analysis allows a sound evaluation. We evaluate holistically the pipe behaviour under the ambient conditions and loading. In coordination with the clients, we determine test setup and parameters to provide results also with additional challenges, e. g. external influences as artificial defects. Important results concerning failure mode and fracture type already were obtained in burst tests under hydrogen.

The dimensional range of burst tests carried out under hydrogen up to outer diameters OD = 70 mm and wall thickness up to WT = 3,4 mm. The volumes were up to 1.7 litres. Burst pressures were up to 400 bar. Further tests are in planning to successively increase the dimensions and the test volume.

Example of a vessel prepared for burst test

SECTION 4

APPLICATIONS

Line pipes, pipe storage, high pressure tanks and lines, stainless steel tubes

PART 1:

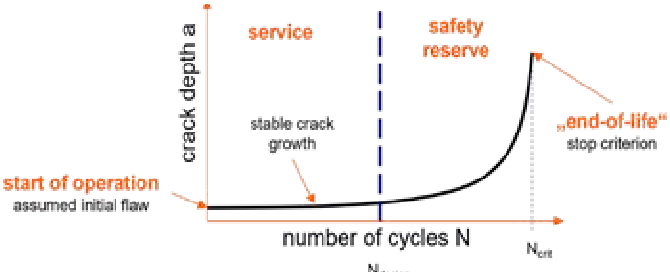
LINE PIPES

Line pipes for hydrogen transport

Together with the line pipe manufacturers of the Salzgitter group, SZMF has consolidated knowledge and experience with different mechanisms of hydrogen embrittlement for decades: On the one hand, these aspects have been extensively investigated for sour service line pipes concerning hydrogen induced cracking; on the other hand, individual pipelines or smaller distribution lines already have been used safely for the transport of gaseous hydrogen. However, generally existing hydrogen pipelines are designed for low gas pressures and small quantities of hydrogen. In a future hydrogen economy, the transport of much larger quantities of hydrogen will be required and the operating conditions for the hydrogen distribution system have to be adapted to higher gas pressures and gas flows – even compared to the natural gas network.

Current standards for high pressure gas pipelines such as ISO 3138, EN 1594 or API 5L [1, 2, 3] do not provide any specific information on hydrogen applications. Standards for hydrogen applications as EIGA IGC Doc 121/14 [4] focus on low strength and low pressure of the pipes. For higher strength steel grades, ASME Design Code B31.12 (2023) [5] provides the option of performing a lifetime assessment for hydrogen pipelines. This concept is based on a fracture mechanics approach. National standards, e. g. DVGW G463 [6], also follow the methodology of the ASME rules for hydrogen pipelines in their new revision.

Fracture mechanic lifetime assessment assumes an existing crack in the steel component, although of course it may not actually be present there. For this purpose, the initial crack size is assumed to be at the limit of detectability of non-destructive testing methods. Using crack propagation laws, the crack growth of the crack under cyclic loads can be calculated up to a critical crack size concerning a failure of the component. The critical crack size is linked to the toughness of the material. In fracture mechanic tests under realistic operating conditions (gas mixture and pressure) the toughness of the materials can be characterized by the parameters K_{IC} or K_{JIC}.



Lifetime assessment of a pipeline

According to ASME B31.12 (2023) an alternative qualification of the material without determining the toughness is possible by determination of the threshold stress intensity factor K_{IH}. This qualification value describes whether a crack propagates in the presence of a given mechanical load. It is determined in accordance with ASME BPVC Sec VIII Div. 3 KD-10 [7] or ASTM E1681 [8] and is required to be at least 55 $\text{MPa}\sqrt{\text{m}}$. For this purpose, three different heats, each with three positions of the pipe microstructure (base material, heat affected zone and weld metal), have to be tested with three samples each. This results in a large number of specimens to be tested.

However, the K_{IH} measurement only provides a characteristic material value if the crack propagates during the test and stops due to the associated decreasing load of the specimen. If there is no crack propagation, only the achievement of the minimum requirement of 55 $\text{MPa}\sqrt{\text{m}}$ according to ASME B31.12 is documented.

[1] *ISO 3183 (2019): Petroleum and natural gas industries - Steel pipe for pipeline transportation systems. Interna-tional Organization for Standardization, 2019-10*

[2] *EN 1594 (2013), Gas infrastructure — Pipelines for maximum operating pressure over 16 bar — Functional requirements. European Committee for Standardization, CEN, 2013-12*

[3] *API 5L 46th Edition: Line Pipe. American Petroleum Institute, 2018-05*

[4] *EIGA IGC Doc 121/14: Hydrogen Pipeline Systems. European Industrial Gases Association, 2014*

[5] *ASME B31.12 (2023), "ASME B31.12-2019 Hydrogen Piping and Pipelines" The American Society for Mechani-cal engineers, New York, USA*

[6] *DVGW G463 (2021), "Gashochdruckleitungen aus Stahlrohren für einen Auslegungsdruck von mehr als 16 bar; Planung und Errichtung ". Deutscher Verein des Gas- und Wasserfaches e. V., Bonn*

The K_{IH} determination is based on linear elastic fracture mechanics. According to ASTM E1681 a minimum specimen thickness is required for a valid test in order to keep the plastic zone at the crack tip small in relation to the specimen size. The required specimen size depends on the strength of the material and the applied stress intensity. The higher the K_{IH} and the lower the yield strength, the larger the specimen must be. Due to the usual line pipe wall thicknesses between 5 mm and 35 mm the minimum specimen thickness cannot be realized for line pipe materials. ASME BPVC Sec. VIII Div. 3 addresses this problem by defining a specimen thickness of > 85 % of the pipe wall for a valid K_{IH} value instead of the thickness criterion from ASTM E1681. This means that K_{IH} only represents the threshold value for the stress intensity of a pipe material with the given wall thickness. A transfer to other wall thicknesses is not possible.

To proof the validity of the K_{IH} value within the linear-elastic fracture mechanics the CMOD value (Crack Mouth Opening Displacement) can be used. According to ASTM E1681, the CMOD ratio, measured at unloading and loading of the sample, must be 90 % or above. The K_{IH} tests carried out in SZMF on line pipe materials indicate the presence of a plastic zone at the notch tip with CMOD values < 80 %. The conditions for the application of linear-elastic fracture mechanics are not met in the K_{IH} measurement on modern line pipe materials with high toughness.

In order to determine valid break-off criteria for the lifetime assessment, the actual fracture toughness K_{IC} of the material can be used instead of the critical stress intensity. The fracture toughness can be determined according to test standards ASTM E399, ASTM E1820 or ISO 12135 [9, 10, 11]. The fracture toughness K_{IC} in pressurized hydrogen is determined by testing a notched specimen with monotonically increasing load until fracture. However, for determining the fracture toughness a primarily brittle material behaviour is required. Pipeline steels are characterized by their ductility, which must be considered when determining the characteristic values. In the case of ductile materials, elastic-plastic fracture mechanics can be used to determine the K_{JIC} value. This method has great potential for a realistic determination of characteristic values for pipeline design: Actual material characteristic values can be determined, and test times can be saved compared to a 1,000-hour immersion test like the K_{IH} test. However, complex testing technology is required to determine this characteristic value, which is currently only available in a few testing laboratories. We are currently working on the construction of such a testing facility.

Depending on accessibility, need and significance, all test methods have their justification. In case that boundary conditions for valid tests cannot be met, test methods and test conditions for the qualification of line pipes should be defined in alignment with the line pipe operator.

For the design of pipelines, it is important that the yield strength and tensile strength of the materials are not affected by hydrogen. This can be demonstrated by slow strain rate tensile testing (SSRT) under pressurized hydrogen. Typical behaviour of line pipe materials tested at 100 bar hydrogen pressure. The linear elastic range of the stress-strain curve, the yield strength and the tensile strength are not affected by hydrogen. Only in the range of higher strain (above tensile strength) the stress-strain curves show an earlier fracture of specimens tested in hydrogen than specimens tested in a reference medium. This effect leads to reduced ductility values like reduction of area and fracture elongation. Tensile specimens after SSRT testing in hydrogen usually show less necking and secondary cracks in the necked area. These high strains, at which the effect of hydrogen is observed, are not realistic for the operating conditions of pipelines.

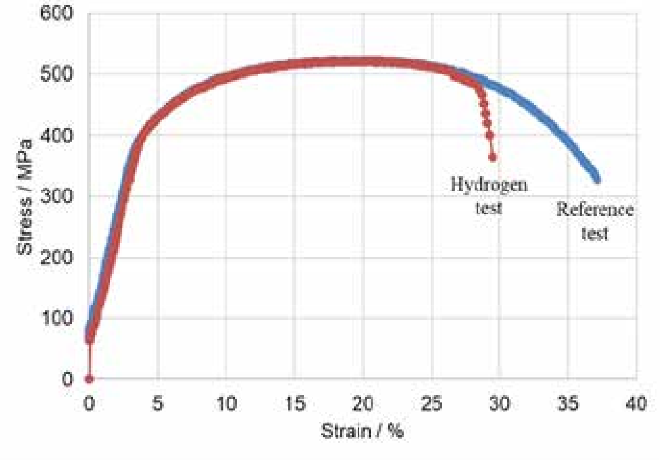
[7] *ASME BPVC (2013), "ASME BPVC Section VIII Division 3 (2013) Alternative Rules for Construc-tion of High Pres-sure Vessels". The American Society for Mechanical engineers, New York, USA*

[8] *ASTM E1681-03 (2013), "Standard Test Method for Determining Threshold Stress Intensity Factor for Environ-ment-Assisted Cracking of Metallic Materials". ASTM International, West Conshohoken, USA*

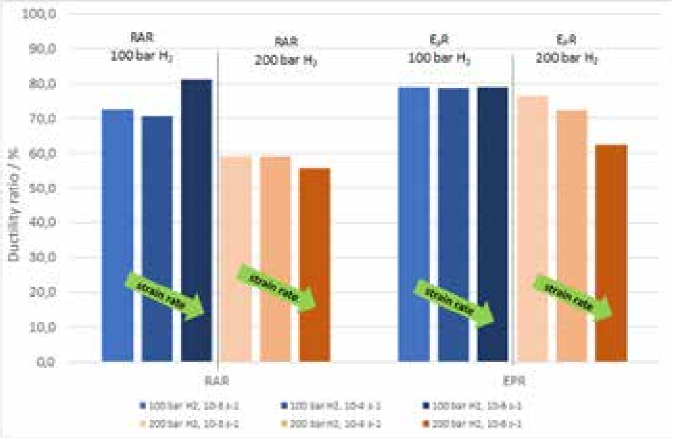
[9] *ASTM E399-12e3 (2012), "Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc for Metallic Materials". ASTM International, West Conshohoken, USA*

[10] *ASTM E1820-20e1 (2020), "Standard Test Method for Measurement of Fracture Toughness". ASTM Interna-tional, West Conshohoken, USA*

[11] *ISO12135:2016 (2016), "Metallic Materials – Unified method of test for the determination of quasistatic frac-ture toughness". ISO, Genf, Schweiz*



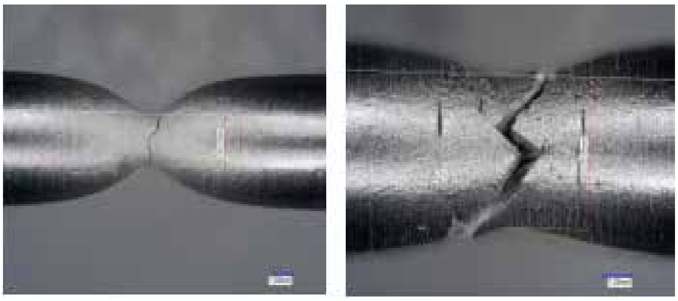
Exemplary stress strain curve of a line pipe sample tested with SSRT



Ductility values of a line pipe material depending on Strain rate and hydrogen pressure

Slow strain rate testing is a suitable test method for comparing different steels and optimizing materials. However, the test results depend on the hydrogen pressure applied in the test and the strain rate of the specimen. In investigations by SZMF, as well reduction of area as plastic elongation at fracture showed decreased values at a test pressure of 200 bar compared to the test pressure of 100 bar. An influence of the strain rate was only determined at severer test conditions of 200 bar. In particular, the fracture elongation decreased with decreasing strain rate. At the test pressure of 100 bar, which is more relevant in line pipe applications, this correlation was not visible. For a comparison of line pipe materials, it is therefore advisable to increase the sensitivity of the test and to switch to severe test conditions with higher hydrogen pressure and lower elongation rate (e. g., 200 bar and 10^{-6} s^{-1}). A test with a higher strain rate (10^{-5} s^{-1} or 10^{-4} s) is sufficient for testting material behaviour under the usual operating conditions of 100 bar for line pipes.

Flagship Project TransHyDE
SPONSORED BY THE
Federal Ministry of Education and Research
Funded by the European Union
NextGenerationEU



SSRT specimens after testing, left: tested in nitrogen, right: tested in hydrogen

[5] BMBF Leitprojekt TransHyDE, Verbundvorhaben Sichere Infrastruktur, Laufzeit 2021 – 2025. www.wasserstoff-leitprojekte.de/leitprojekte/transhyde

PART 2:

PIPE STORAGE

Buffer storage for pressure cycles

Pipe storage facilities are established for storing natural gas as buffer for balancing fluctuations in demand or supply shortage. Pipe strings are welded from steel pipes with overall volumes of 5.000 – 10.000 m^3. The operating pressures are usually up to 100 bar.

While underground gas storages as caverns balance seasonal fluctuations, e. g. by filling redundant gas in the summer season and withdrawing gas during the heating period, pipe storages can compensate weakly or daily consumption peaks. Pipe storages are integrated in the transport infrastructure. They are installed overground or laid 1 – 2 m below the ground surface.

Pipe storages gain significance in the frame of energy transformation towards green hydrogen and the associated expansion of renewable energies, for buffering pressurized hydrogen gas obtained by electrolysis of green energy.

Storage pipes must be designed similar to pressure vessels by ensuring integrity for the various load scenarios during their service lifetime. Most relevant for storage pipes are the verification against static load (strength) and fatigue loads (fatigue strength) from internal pressure cycles that result from filling and emptying. For example if a service time of 40 years is envisaged and filling cycles twice a day, round about 30,000 pressure cycles need to be sustained. This applies to the pipes, the girth welds and all other storage elements, such as end caps and feed lines.

In case of hydrogen concepts exist for the lifetime assessment. The German national guideline AD 2000 provides in AD 2000-S2 [2] a fatigue assessment via fatigue strength curves (S-N-curves) based on fatigue class categories. The influence of pressurized hydrogen gas environment is taken into account by safety factors.

The design code ASME B31.12 (2023) [3] requires a lifetime assessment based on fracture mechanics. German national rules follow these concepts, e. g. G463 [4]. The fracture mechanics assessment assumes an initial crack at a critical position of high operating stresses. The crack size is presumed to be at the detection limit of non-destructive test methods. Fatigue crack growth laws allow the calculation of crack growth under cyclic loads up to a critical crack size. The crack growth material parame-ters can either be determined experimentally under pressurized hydrogen environment, or the codes [3] standardized parameters can be applied, which usually are conservative. The critical crack size is linked to the materials fracture toughness, which also needs to be experimentally determined. An additional safety factor must be con-sidered in the design.

In the national flagship project H2Mare and its subproject H2Wind [5] longitudinal welded pipes are investigated as storage pipes for hydrogen pipe storage. Together with partners Siemens Energy and Fraunhofer Institutes Salzgitter Mannesmann Forschung GmbH explores design aspects and the material behaviour in pressurized hy-drogen gas in numerous test series. Focus are the fatigue performance, welding technologies for the girth welds and permeation measurements. The material and pipe component behaviour will be tested experimentally in full-scale tests under realistic loading cycles in a demonstrator test.

Laying of pipe strings for natural gas storage [1]

SPONSORED BY THE

Wasserstoff Leitprojekte
Grün. Groß. Global.

Federal Ministry
of Education
and Research

---

[1] Erdgasröhrenspeicher, www.mannesmann-grossrohr.com
[2] AD 2000-Merkblatt S 2, Berechnung auf Wechselbeanspruchung, Juli 2012
[3]ASME B31.12 (2023): Code for Pressure Piping, Hydrogen Piping and Pipelines. American Society of Mechanical Engineers, 2019
[4] DVGW G 463 (2021): Gashochdruckleitungen aus Stahlrohren für einen Auslegungsdruck von mehr als 16 bar; Planung und Errichtung. Deutscher Verein des Gas- und Wasserfaches e.V., 2021-10
[5] BMBF Leitprojekt H2Mare, Verbundvorhaben H2Wind: Autarke Offshore-H2-Elektrolyse, Laufzeit 2021 – 2025. www.wasserstoff-leitprojekte.de/leitprojekte/h2mare

PART 3:

HIGH-PRESSURE TANKS AND LINES

Mobile applications

Previous hydrogen-powered cars store the gaseous hydrogen at 700 bar in type IV tanks. These tanks consist of a plastic liner wrapped in carbon fibres. The production is complex and therefore is a cost driver for the storage system. The poor CO_2 balance and the lack of recyclability of the used carbon fibres also contradict the environmentally friendly claim of hydrogen-powered vehicles. The integration of the large-volume tanks into the available installation space of the car is difficult and often leads to cost-driving structural changes to the chassis. In the future, tank solutions will have to fit into the underbody area of a BEV (Battery Electric Vehicle) platform without design changes.

High-pressure storage tanks made of high-strength steel tubes are a solution. Steel as a material is inexpensive, climate-neutral in the long term, infinitely recyclable and can be mass-produced. This sustainable product is therefore fully in line with the circular economy of Salzgitter AG's Strategy 2030. The challenge here lies in the material design and the manufacturing conditions to minimise the disadvantage of the steel's high weight by achieving the highest possible material strength and at the same time ensuring hydrogen compatibility and component suitability.

The Commission Implementing Regulation 2021/535 [1] on technical specifications for the type-approval of vehicles and vehicle parts is in force in the European Union since July 2022. For metallic materials, it requires hydrogen compatibility in accordance with DIN EN ISO 11114-1 [2] and -4 [3] tested at application conditions, unless the material corresponds to the established steels and strength classes for pressurized gas cylinders in DIN EN ISO 9809-1 [4]. If quenched and tempered steels with a tensile strength above 950 MPa are to be used for the storage of pressurized hydrogen, the hydrogen compatibility must be verified in accordance with DIN EN ISO 11114-4 or SAE J2579 [5] for the operating pressure of 700 bar at -40 °C. In addition, UN Regulation No. 134 [6] applies to pressurized hydrogen storage systems, which specifies an application-related test for qualification. This includes hydraulic burst tests and pressure cycle tests to ensure a service life of 15 years for the cylinders. A hydraulic follow-up test ensures performance reliability despite various impairments to the storage system and a pneumatic follow-up test with hydrogen simulates road use under extreme environmental conditions.

Together with Robert Bosch GmbH and Mannesmann Precision Tubes GmbH, Salzgitter Mannesmann Forschung GmbH is developing a functional prototype of a high-pressure storage system with cylinders made of seamless high-strength precision steel tubes in the publicly funded project HySteelStore [7]. The production of precision steel tubes for this demanding application is being optimised and the reliability and safety of the storage system is being demonstrated in accordance with the requirements of UN Regulation No. 134.

Cylinders made from seamless high-strength precision steel tubes

Supply lines and injection lines for hydrogen-powered vehicles and trains are pressure-bearing components. They guarantee safe filling of the storage tank and the supply of the fuel cell or the hydrogen combustion engine with gaseous hydrogen. The working pressure is up to 700 bar in the high-pressure range (connections in the tank system) and up to 200 bar in the medium pressure range (anode lines, injection lines).
Nowadays, austenitic stainless steels are predominantly used for these applications These include, among others, the steels with material numbers 1.4401, 1.4404, and 1.4435, which are mentioned in the standard SAE J 2579 [8] and listed as hydrogen-resistant. With appropriately designed materials, these conventional concepts can be supplemented or partially replaced by precision steel tubes made of carbon steel, creating a market innovation with significant cost advantages.
For stainless steels, high contents of cost-intensive elements such as nickel, chromium, and molybdenum increase the price, while the low strength leads to thick wall thicknesses for high pressures (up to 700 bar), which increases the component costs and overall weight.
Precision steel tubes made of low-alloy carbon steel have lower alloying costs and higher strength, resulting in more affordable and thinner-walled components. Optionally, corrosion protection

can be enhanced through zinc and zincnickel coatings. Precision steel tubes also offer good processability (forming, welding, soldering, etc.), allowing optimised designs.

To demonstrate suitability of pressurized hydrogen components, application-specific safety approval of precision steel tubes for mobile applications is necessary, based on the EU Regulation (EC) No. 79/2009 [9]. This regulation was repealed for pressure lines in June 2022, but often quoted as a reference and is still permissible for the approval of components for hydrogen applications under Regulation (EU) 2019/2144 [10], because no direct replacement is yet available.

The requirements of the standards DIN EN ISO 11114-1 [2], -4 [3], and ANSI/CSA CHMC [11] include burst disc and slow strain rate tests. Additionally, a defined test sequence of salt spray tests, pneumatic and hydraulic pressure cycle tests are necessary. This ensures the operational safety of pressure-bearing lines throughout their entire service life. Furthermore innovative, resource-saving material alternatives can be certified for decarbonizing mobile applications.

Salzgitter Mannesmann Forschung GmbH supports Mannesmann Precision Tubes GmbH in this development and application-specific products are being developed for this purpose. Established dimensions, such as those of diesel injection lines, are also being considered to continue utilizing well-known manufacturing processes and common interfaces with metallic sealing connections according to ISO 2974 [12] and ISO 8535-1 [13].

Pressure lines made from seamless precision steel tubes

References:

[1] Commission Implementing Regulation (EU) 2021/535 of 31 March 2021 laying down rules for the application of Regulation (EU) 2019/2144 of the European Parliament and of the Council as regards uniform procedures and technical specifications for the type-approval of vehicles, and of systems, components and separate technical units intended for such vehicles, as regards their general construction characteristics and safety. 31. March 2021

[2] DIN EN ISO 11114-1:2020-08 Gas cylinders - Compatibility of cylinder and valve mate-rials with gas contents - Part 1: Metallic materials. August 2020

[3] DIN EN ISO 11114-4:2017-09 Transportable gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 4: Test methods for selecting steels re-sistant to hydrogen embrittlement. September 2017

[4] DIN EN ISO 9809-1:2020-02 Gas cylinders - Design, construction and testing of re-fillable seamless steel gas cylinders and tubes - Part 1: Quenched and tempered steel cylinders and tubes with tensile strength less than 1100 MPa. February 2020

[5] Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles J2579_201806. 15.06.2018

[6] Regulation No 134 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV) [2019/795]. 17.05.2019

[7] Project „Metallic hydrogen high-pressure storage system for mobile fuel cell appli-cations 2025+“ as part of the National Innovation Programme Hydrogen and Fuel Cell Technology (NIP) funded by the Federal Ministry for Digital and Transport (BMDV). The funding guideline is coordinated by NOW GmbH and implemented by Project Management Jülich (PtJ). Duration 2020-2024

[8] SAE J 2579:2018-06-15 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

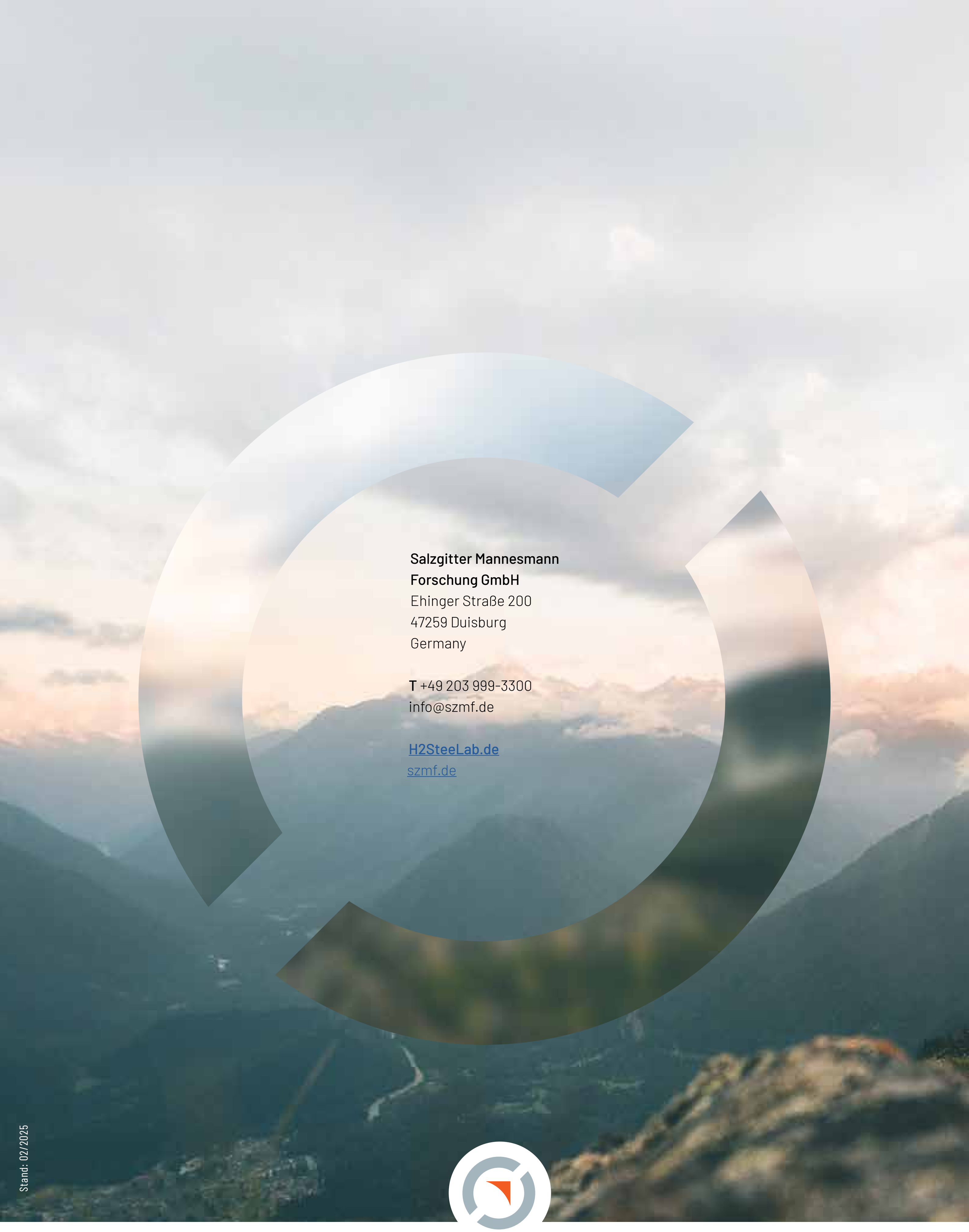
[9] Regulation (EC) No 79/2009 of the European Parliament and of the Council of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC

[10] Regulation (EU) 2019/2144 of the European Parliament and of the Council of 27 November 2019 on type-approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles, as regards their general safety and the protection of vehicle occupants and vulnerable road users, amending Regulation (EU) 2018/858 of the European Parliament and of the Council and repealing Regulations (EC) No 78/2009, (EC) No 79/2009 and (EC) No 661/2009 of the European Parliament and of the Council and Commission Regulations (EC) No 631/2009, (EU) No 406/2010, (EU) No 672/2010, (EU) No 1003/2010, (EU) No 1005/2010, (EU) No 1008/2010, (EU) No 1009/2010, (EU) No 19/2011, (EU) No 109/2011, (EU) No 458/2011, (EU) No 65/2012, (EU) No 130/2012, (EU) No 347/2012, (EU) No 351/2012, (EU) No 1230/2012 and (EU) 2015/166

[11] ANSI/CSA CHMC 1-2014 Test methods for evaluating material compatibility in compressed hydrogen applications – Metals

[12] ISO 2974 2018-03 Diesel engines — 60° female cones for high-pressure fuel injection components

[13] ISO 8535-1:2016 Diesel engines — Steel tubes for high pressure fuel injection pipes — Part 1: Requirements for seamless colddrawn single-wall tubes



Salzgitter Mannesmann
Forschung GmbH
Ehinger Straße 200
47259 Duisburg
Germany

T +49 203 999-3300
info@szmf.de

H2SteeLab.de
szmf.de

Stand: 02/2025

SALZGITTER
MANNESMANN
FORSCHUNG
A Member of the Salzgitter Group