Energy transition with hydrogen pipes: Mannesmann "H2ready" and the changeover of existing Gasunie natural gas networks

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Pure hydrogen will be one of the main energy carriers in the changeover of the primary energy supply to renewable energy sources. For the transport of large quantities of hydrogen gas, pipelines are the most viable solution both economically and ecologically. Since hydrogen/methane mixtures will also be used on the way to a hydrogen-based future, current and future investigations and considerations are concerned not only with pure hydrogen gas but also with these gas mixtures. In the field of hydrogen transport, the focus is also on the optimization of modern steel pipe materials for new installations as well as on the conversion and further use of existing pipeline networks. The present paper starts by presenting trends in the energy sector. Here, the emphasis is on quantity considerations. This is followed by a brief account of the current status and of activities regarding the necessary adjustments to the regulatory framework. These are based on technical qualification studies and further development work. This paper presents the key tests, their background and examples of findings. The first measures derived from these tests in the production of longitudinally welded steel pipes by Mannesmann Line Pipe GmbH using the high-frequency induction (HFI) process have resulted in modified pipes for the transport of hydrogen gas. We draw attention to the potential of cost-effective and safe new line pipes. The paper also turns to the further use of existing gas pipelines and their conversion to hydrogen. The current work on creating a changeover roadmap is discussed. Furthermore, the Dutch network operator N.V. Nederlandse Gasunie reports on its practical experience with the conversion of a natural gas pipeline to hydrogen transport.

Introduction

„In the Paris Climate Agreement COP21, which came into force on 11/04/2016, 196 states agreed under international law that global warming should be limited to well below 2 °C, if possible to 1.5 °C, compared to the pre-industrial era." [1] During the climate summit in September 2019, many states committed themselves to additional efforts, including about a third of 193 United Nations members who pledged to become climate-neutral by 2050, among them Germany and the Netherlands. Furthermore, 102 cities, 10 regions and even 93 corporations also endorsed this goal. Russia also officially joined the Paris Climate Agreement. Another 70 countries promised to raise their efforts in the fight against global warming from 2020. What measures will be taken remains to be seen.

One of the necessary steps is the phasing out of coal-fired power generation. This is planned for 2038 in Germany and by as early as 2030 in the Netherlands. In addition, the Netherlands will be discontinuing gas production of the Groningen field in the short term. Safety reasons are also important here, as production from the largest gas field has caused earth quakes in the Netherlands. If the power supply is to be provided by renewable energy sources, attention must be paid to the stability of the electricity grid, since wind and solar as the main suppliers of energy are not always available in unchanging quantities. An estimate is given in [2]. For 5,000 hours per year an oversupply of primary energy generated is forecast for Germany for the year 2050. In total this amounts to about 80 TWh. This contrasts with a shortfall of about 300 hours (about 3.3 TWh) in the energy required. One way to compensate for this volatility is to use hydrogen as an intermediate storage medium for excess energy. None of the other energy storage technologies is technically or economically capable of coping with the amount of energy and storage duration involved [3]. Hydrogen can then be used to fill the supply gap in times of primary energy shortfall. In addition, hydrogen is also capable of serving the heat market as a gas. Industrial applications such as carbon-neutral steel production also have a high demand for hydrogen.

At any rate, in future it will become necessary to transport hydrogen in large quantities to the consumer. Environmentally and economically, pipelines offer the best solution [4], so steel pipelines are currently the focus of attention in many areas. Various scientific studies have therefore been conducted to demonstrate the material's suitability for the transport and storage of hydrogen. The aim of current network operators is to transport hydrogen via the natural gas networks already in place and currently in use. Since the energy density („energy content") of hydrogen is lower than that of natural gas,

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1 GHG: GreenHouse Gas

the transport of pure hydrogen via the existing natural gas infrastructure reduces energy transmission capacity by about 20 to 25 % [5]. For this reason, modern line pipe steels are being tested in preparation for the laying of new lines and the replacement of old ones. The focus here is on investigations into the mechanical behavior of the steels on exposure to hydrogen gas. However, the effect of not only pure hydrogen gas is being investigated, but also mixtures of natural gas and hydrogen, as this is regarded as a transitional solution for the changeover to the hydrogen-based energy supply of the future. In addition, the effect of other gas components such as moisture or even minor constituents such as hydrogen sulfide H_2S are included in the analysis. When hydrogen stored as a reserve is extracted from a salt cavern, for example, hydrogen sulfide may be contained in the gas due to microbiological processes in the cavern. For the evaluation of a planned changeover of an existing (natural gas) pipeline, older steel grades are also being included in the studies. In addition to the above-mentioned material studies, such properties as surface quality, corrosion damage, mechanical prestressing and the condition of the welds are also being investigated to determine their suitability for changeover to the transmission of hydrogen gas. All these considerations regarding the characterization of steels and pipelines will then go toward new regulatory codes, so that a safe transition to a hydrogen-based energy supply is achieved.

The first part of this paper presents an overview of the tests that are currently the focus of scientific material investigations. A brief presentation is given of examples of findings from the tests, especially on modern line pipe steels from Mannesmann Line Pipe GmbH. Furthermore, the paper also summarizes the current state of the various standardization and regulatory activities in the transport of hydrogen via pipelines. The second part of the paper deals with the changeover of existing natural gas pipelines to hydrogen. For this purpose, the experiences of the Dutch network operator N.V. Nederlandse Gasunie are presented, taking the pipeline X-804 (Dow, Terneuzen-Yara, Sluiskill, 12.4 km-DN 400) as an example.

Trends in the energy sector

As of recently, green hydrogen (i.e. produced from renewable sources) has been regarded by everyone concerned in Germany as one of the main energy carriers and accorded a special role in the energy transition. The findings from the Gas 2030 dialogue process [6] attach such huge importance to hydrogen for the future of the climate that a National Hydrogen Strategy is currently being drawn up on behalf of the Federal Government. In addition, hydrogen offers industrial policy opportunities for Germany in the field of power-to-gas and downstream products, as well as in its general utilization outside the power industry. An increase in hydrogen imports and a deepening of offshore cooperation is expected. There is also a consensus that the gas infrastructure has to be adapted in order to accommodate more hydrogen in the future. This involves admixing hydrogen to natural gas as a bridging technology into the future, as well as component development and the achievement of „H_2-readiness“. The latter also aims at a common understanding throughout Europe and, if necessary, regulation of hydrogen networks. In future, it should therefore also be possible to import more carbon-free and carbon-neutral gases from other European countries. The necessary measures in the fields of planning, technology and regulations include the further development of the pipeline networks. The changeover of existing pipelines and the construction of new pipelines for the landfall and

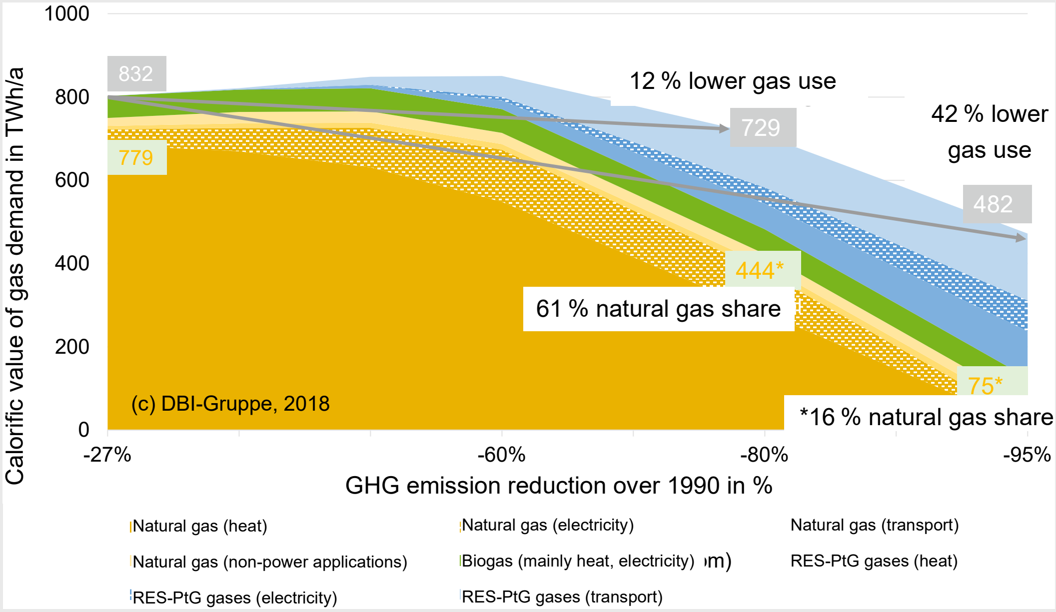

Figure 1*: Scenarios for trends in gas demand and GHG[1] emission reduction in Germany according to J. Nitsch [10]*

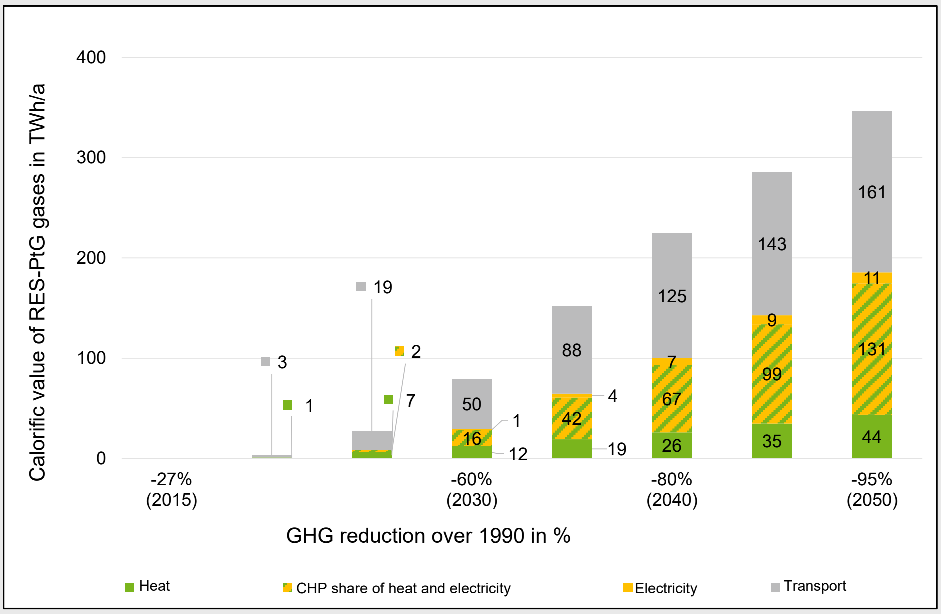

***Figure 2**: Scenarios for trends in RES-PtG gas use, broken down into sectors according to J. Nitsch [10]*

distribution of green hydrogen from power-to-gas plants on offshore platforms must also be part of this initiative.

Required quantities of hydrogen gas by 2050

For the primary production of the predominant share of renewable energy, the two main sources available are solar and wind. In [7] and [8], 33 GW of required or installed offshore wind capacity is predicted for Germany in 2050, 168 GW for onshore wind (4 times the current amount) and 166 GW for photovoltaic/sun (about 4.5 times the current amount). Overall, it is foreseeable that Germany, but also Europe, will be dependent on renewable energy imports of several 100 TWh/a if the energy supply is completely defossilized. Such energy quantities can only be transported in an ecologically and economically sensible way by resorting to gaseous or liquid energy sources. Hydrogen from renewable sources will form the energy basis [9].

Figure 1 shows how demand for natural gas, biogas and RES-PtG [2] gases from the various sectors can develop in Germany between today and 2050 in line with the 2 °C target of the Paris Agreement. For this purpose, relevant studies have been evaluated and the „CLIMATE 2050" scenario from [10] has been selected and graphically depicted.

As a result, trend scenarios for gas utilization in Germany show 60 %, 80 % and 95 % GHG reductions. The largest share of current gas demand (27 % GHG reduction) is claimed by natural gas with 779 TWh in 2015 (94 % of gas demand). However, with ever greater GHG emission reductions, this share will inevitably decrease. In the short term, i.e. up to a reduction to 60 % over 1990, natural gas can help reduce GHG emissions by substituting other fossil fuels such as coal. In the long term, however, this fossil natural gas will also be increasingly replaced by green gases (biogas, RES-PtG gases). For this reason, the total demand for gas will only decrease moderately despite ambitious GHG reduction targets.

Figure 2 shows the trend in demand for RES-PtG gases broken down according to their use in heat supply, electricity generation and transport. The share of combined heat and power generation in the electricity and heat supply is shown in addition.

A key finding with regard to the trend in gas demand up to 2050 and the 95 % GHG reduction is not only that overall gas demand will fall, but also that the use of gas will change significantly. This trend is shown in ***Figure 3***. In 2015, most of the gas was used to meet demand in the heating sector. If, however, a scenario is assumed in which a GHG reduction of 80 % is achieved, the projected gas use is distributed somewhat more evenly between the different areas of use, i.e. electricity, heating and transport. With a GHG reduction of 95 %, use specifically as a fuel increases even further, since the transport sector has the greatest potential for decarbonization.

In the 95 % GHG reduction scenario, if the total 347 TWh of renewably produced gases shown in Figure 3 is based entirely on hydrogen and an ideal efficiency of 1 in its use is assumed, the quantity of hydrogen gas will be about 10 million metric tons. With more realistic efficiencies, the amount of hydrogen gas will be much higher. More

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[2] Hydrogen or methanized hydrogen, RES-PtG: Renewable Energy Source – Power to Gas

concrete figures for the transport sector, for example, are reported in [4] for Europe. If a linear increase in current fuel consumption is assumed, the relevant demand for hydrogen (corrected for drive efficiency) across Europe will be 60.6 million tons in 2050 if all vehicles are based on H_2 drive technology. In [11], a quantity of roughly 33 million tons of H_2 per year (1,100 TWh/a) is estimated for all transport sectors, i.e. cars, trucks, trains and aircraft, in Germany alone. In the industrial sector, the following quantity can be roughly estimated using the example of steel production: Salzgitter AG as a steel producer has an annual crude steel capacity of around 5 million tons. Even with the most advanced, coal-based steel production processes currently in use in Salzgitter, around 8 million tons of carbon is emitted. Salzgitter AG's SALCOS project aims to replace coal with hydrogen as an energy source. A 25 % reduction in carbon emissions results in a hydrogen gas requirement of around 80,000 Nm³ per hour. This amounts to an annual demand of 63 metric kilotons. Accordingly, 232 kilotons per annum would be required for virtually carbon-free steel production, and this only for a „mid-sized" steel producer. [12] estimates an annual H_2 quantity for the entire German steel industry of approx. 2,500 kilotons.

State of standardization activities on hydrogen gas transmission lines

State of current standards/codes

On the way to the fully decarbonized future of energy supply with a hydrogen-based supply infrastructure, the admixture of hydrogen to fossil natural gas will have to be a transitional solution – at least until a sufficient volume of hydrogen is available from renewable primary energy sources for a complete switch to a 100 % supply of green hydrogen in all areas of demand. In the pipeline network sector, we examine two scenarios: on the one hand, the changeover of existing pipelines for current natural gas transport to hydrogen or hydrogen/natural gas mixtures. And, on the other hand, the use of newly laid pipeline systems. This of course includes not only pipes, but also the fittings, valves, etc. belonging to the pipeline system. The focus of this paper is on line pipe steels.

For the changeover of existing pipelines for natural gas-hydrogen mixtures, the current scope of the DVGW[3] codes applies to the possible admixture of currently up to 10 vol. % hydrogen. In connection with the objectives of the DVGW Roadmap Gas 2050, the transformation of gas supply in Germany along the entire value chain, including the use of gas from the current structure, to a targeted largely climate-neutral system in 2050 is currently being considered [13]. In this context, an increase of this admixture limit to 20 vol. % hydrogen by 2030 is being discussed. Furthermore, the complete changeover from subnetworks to pure hydrogen should represent the appropriate step towards meeting the above-mentioned necessary climate policy goals. At the same time, it will also help to avoid the technical and economic problems that arise with the gradual admixture of hydrogen (in excess of 10 vol. %) and the associated fluctuation in gas composition.

The main focus of the conversion roadmap is on the necessary modification measures, which are broken down according to operating strategy / capacity planning, measurement technology, customers' hydrogen tolerances, safety policy, maintenance strategies, communication, legal issues and pipeline materials. For the qualification roadmap (admixture of 10 vol. % hydrogen), resort can be made to the DVGW's existing technical codes for issues relating to the maintenance strategy and legal aspects. From a safety point of view, the change in the explosion hazard zones due to the addition of hydrogen is to be checked and, based on this, the safety concept modified. Current investigations of the DVGW also show that, in terms of measurement technology on the transport level, only the process gas chromatographs need to be modified or replaced. The suitability of the pipeline materials for hydrogen is being established in ongoing investigations, e.g. as part of the HYPOS project „Pipeline

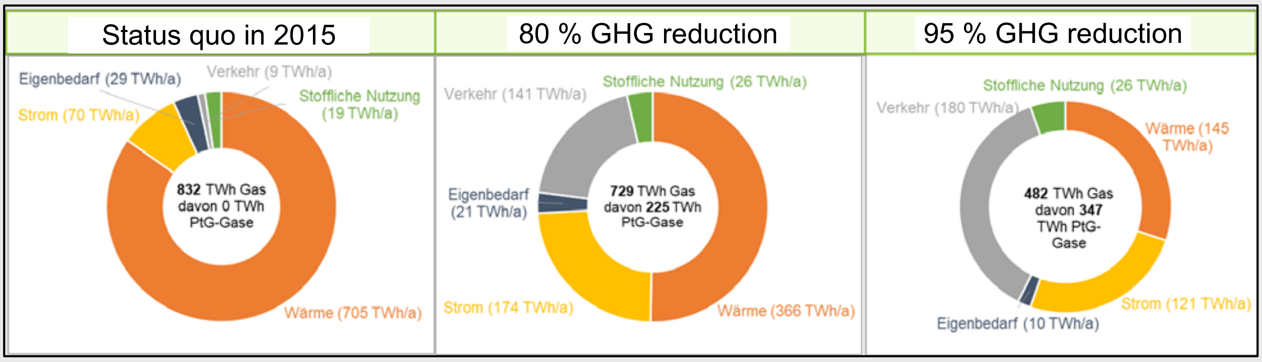

***Figure 3**: Scenarios for trends in gas use according to sectors in Germany (primary energy consumption, calorific value)*

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[3] Deutscher Verein des Gas- und Wasserfachs e.V. [German Technical and Scientific Association for Gas and Water])

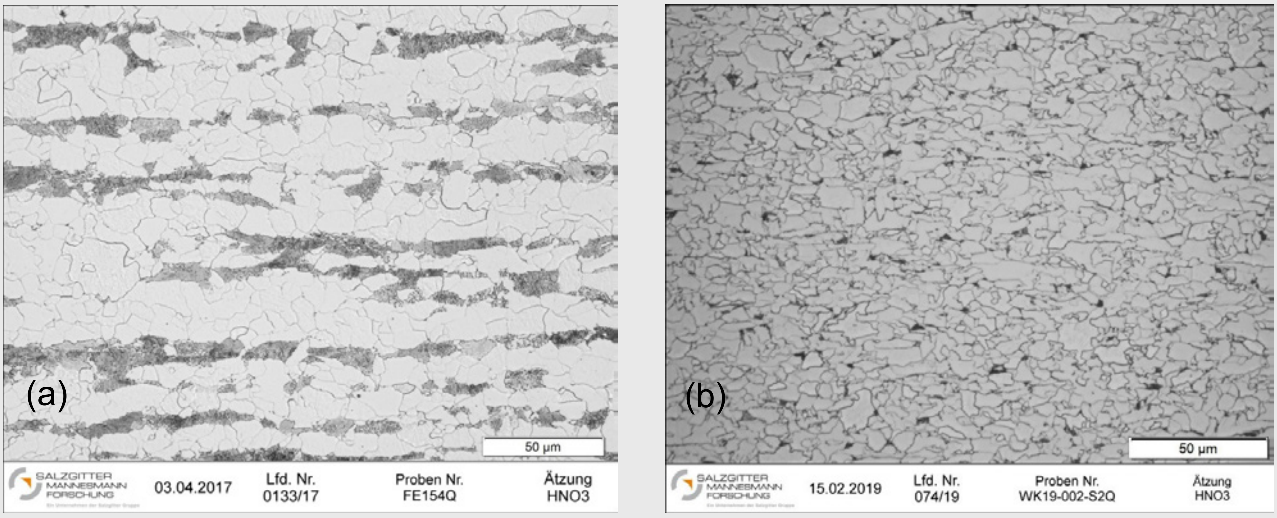

***Figure 4**: Microstructures of Materials 1 (a) and 2 (b)*

Integrity Management for the Further Use of the Existing Natural Gas Infrastructure for Hydrogen“ (H_2-PIMS). However, use is generally assumed to be uncritical at 10 vol. %, although this is called into question by dynamic crack propagation investigations. In [14], for example, it was found that the increase in the crack propagation rate due to exposure to hydrogen is almost independent of the hydrogen concentration in the natural gas and is almost fully effective even below 10 vol. %.

Customers’ hydrogen tolerance, and particularly that of CNG filling stations, aquifer reservoirs and certain branches of industry (e.g. glass or steel producers), must be viewed critically. Without these gas consumers, the qualification of pipelines can already be carried out relatively quickly and easily today. In the event of a changeover to pure hydrogen, the measurement technology can be simplified, since the gas composition remains constant. As far as the safety design and maintenance strategies are concerned, it is possible to build on the experience (e.g. EIGA IGC Doc 121/14) of hydrogen networks in the chemical industry, which, however, do not deviate greatly from the DVGW codes. A challenge that has to be clarified with the authorities is the current legal situation since, depending on the application, decisions have to be taken in accordance with the High-pressure Gas Pipeline Ordinance (GasHDrLtgV) or the Technical Rule for Pipeline Systems (TRFL), and this may involve different follow-up measures (e.g. monitoring and leakage system). According to current opinions, an extension of the GasHDrLtgV and the DVGW code is advisable in order to limit these follow-up measures and thus facilitate a more user-friendly changeover process. However, the issue of safety must not be neglected. Ultimately, the existing pipeline materials still have to be tested for their general susceptibility to hydrogen, with the experience and investigations of the chemical industry and from the current project providing support here in the assessment of a pipeline‘s condition.

Revision of codes

At present, a growing number of codes are being revised and redrafted with regard to the use of line pipe for the transport of pure hydrogen gas and the admixture of hydrogen to natural gas. In the latter case, it is currently still unclear which limit for the admixed quantity (e.g. 5 %, 10 % or 20 %) will be applied. It is also possible that there will be different solutions, depending on the system technology on the transport route or the final application. Initial indications of this are given in [15].
In Germany, the DVGW is dealing with the topic in extensive design activities. Several worksheets are undergoing review and revision, for example:

- » Worksheet G 463: High pressure gas steel pipelines for a design pressure greater than 16 bar – Construction
- » Worksheet G 466: High pressure gas steel pipelines for a design pressure greater than 16 bar – Operation and maintenance
- » Instruction Bulletin G 501: Airborne remote gas detection

TC234 at CEN is focusing on amending the following standards:

- » EN 1594: Gas infrastructure – Pipelines for maximum operating pressure over 16 bar – Functional requirements
- » EN 16348: Gas infrastructure – Safety Management System (SMS) for gas transmission infrastructure and Pipeline Integrity Management System (PIMS) for gas transmission pipelines – Functional requirements
- » EN 1918: Gas infrastructure – Underground gas storage

***Table 1**: Chemical compositions of the two materials*

Material	C	Si	Mn	P	S	Al	Cu	Cr	Ni	Mo	Nb
Material 1	0.169	0.201	1.373	0.017	0.0041	0.05	0.033	0.052	0.053	0.013	0.022
Material 2	0.048	0.281	0.898	0.007	0.0007	0.035	0.017	0.038	0.044	0.013	0.034

***Table 2**: Mechanical properties of the two materials*

Material	$R_{p0,2}$ in N/mm²	$R_{t0,5}$ in N/mm²	$R_{p2,0}$ in N/mm²	R_m in N/mm²	$R_{t0,5}/R_m$ in %	A in %	Z in %
Material 1	379	381	428	523	73	33	70
Material 2	460	465	494	524	89	31	81

In North America, the ASME (American Society of Mechanical Engineers) has been revising its code B31.12: Hydrogen Piping and Pipelines, and released the new version in December 2019. While it is still unclear at German and European level which essential material investigations on the effect of compressed hydrogen gas should be included in the codes, ASME B31.12 is much more precise. Which investigations are discussed or referred to in B31.12 will be explained in the next chapter.

Material investigations on the effect of compressed hydrogen gas on line pipe steels – importance of the tests and examples of results

The process and effect of possible hydrogen embrittlement in metals has been extensively described in literature [1, 16-20]. Three major tests are currently being discussed for the material characterization and design of line pipes.

Slow-strain-rate tensile test

In the slow-strain-rate tensile test [4], a tensile specimen is subjected to quasi-static loading. The test procedure is the same as that in a conventional tensile test but with a significantly reduced strain rate. This gives the hydrogen sufficient time to diffuse into the specimen material and to segregate at critical microstructure points (e.g. at the tip of a crack). Once the material's yield strength has been reached and the specimen undergoes plastic deformation, the constant increase in specimen elongation gives rise to a bare metal surface which enables the absorption of hydrogen atoms. The formation of a bare metal surface is necessary because the natural oxide layer on the specimen surface almost completely prevents the splitting of the hydrogen molecules into atomic hydrogen and the absorption of hydrogen atoms into the steel. The test results make it possible to quantify the effect of hydrogen on the basic strength characteristics.

To evaluate the suitability of pipelines for the transport of pure hydrogen as well as natural gas with a hydrogen admixture, Mannesmann Line Pipe GmbH, with the help of Salzgitter Mannesmann Forschung GmbH (SZMF), has investigated the resistance to hydrogen-induced corrosion on current Mannesmann Line Pipe materials in various steel grades. The investigations succeeded in proving that even pipes of higher strength classes from Mannesmann Line Pipe showed no increased susceptibility to hydrogen-induced corrosion when exposed to pure compressed hydrogen [e.g. 1, 21, 22]. It is not only the tensile strength and chemical composition that are important for the susceptibility of the materials to hydrogen-induced corrosion. The material's microstructure dependent on the production route also has a major effect on the suitability of the material for transporting hydrogen.

The effect of hydrogen on the ductility characteristics of elongation at break and reduction of area as a function of the material's microstructure was tested with slow-strain-rate tensile tests on two materials of API 5L [23] grade X52 [5]. The two materials differ significantly in their production routes. Material 1 was normalized in the hot rolling mill during production, while Material 2 was thermomechanically rolled. The latter material was produced to the specifications of Mannesmann Line Pipe's internal Technical Standard for „H2ready" hydrogen transport pipes [25]. ***Figure 4*** shows the differences in the microstructure. A ferritic-pearlitic microstructure with pronounced segregation lines can be observed in the micrographs of Material 1. The former austenitic grain size was defined as 10 according to DIN EN ISO 643 [26]. The microstructure of thermomechanically rolled Material 2 is much finer (former austenitic grain size of 11) and more homogeneous than that of Material 1 without pronounced lines of segregation. ***Table 1*** shows the chemical composition of the two materials, and ***Table 2*** the mechanical properties.

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[4] SSRT Test = Slow-Strain-Rate Tensile Test, also known in the literature as the Constant Extension Rate Tensile Test (CERT Test)

[5] Corresponds to an L360 conforming to DIN EN ISO 3183 [24]

To determine the susceptibility to hydrogen-induced corrosion, slow-strain-rate tensile tests were carried out on round bar tensile test specimens under realistic conditions of 80 bar total pressure. The test media were 100 % hydrogen and nitrogen as the reference medium. The specimens were tested at a strain rate of 2.0 x 10^{-6} s^{-1} under single-direction loading until fracture. To evaluate the ductility, the reduction of area after fracture and plastic elongation were determined and the fracture surfaces of the specimens were evaluated fractographically. The relative reduction of area after fracture Z_{rel} is calculated from the ratio of the specimens' reduction of area after fracture in hydrogen Z_{H2} and in nitrogen Z_{N2}, and the relative plastic elongation E_{PR} from the ratio of the specimens' plastic elongation after fracture in hydrogen E_{PH2} and in nitrogen E_{PN2}.

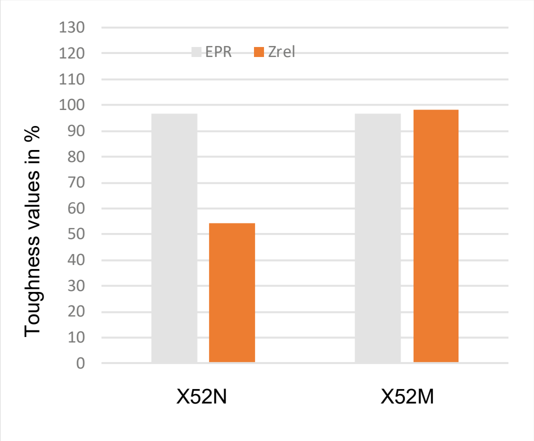

***Figure 5**: Toughness values of the two materials in hydrogen at 80 bar*

$$Z_{rel} = \frac{Z_{H2}}{Z_{N2}} \cdot 100\,\% \qquad (1)$$

$$E_{PR} = \frac{E_{PH2}}{E_{PN2}} \cdot 100\,\% \qquad (2)$$

The determined toughness values E_{PR} and Z_{rel} of the specimens are shown in ***Figure 5***, and the determined tensile curves in ***Figure 6*** and ***Figure 7***. In hydrogen, the tensile strength and uniform elongation were not affected in any of the specimens.

For both specimens of Material 1, the investigations in hydrogen show a steeper drop of the tensile curve in the range of very high strains compared to the tensile curves measured in the inert medium. The toughness characteristics of these specimens show a relative reduction of area after fracture with mean values of 54.2 %. Fractographic evaluation under the scanning electron microscope shows an increased brittle fracture area on the fracture surface of the tensile specimens (see ***Figure 8***). These effects are not observed in the test results of Material 2. With a relative reduction of area of 98.4 % and a relative elongation at break of 96.7 %, this material shows good resistance to hydrogen-induced corrosion.

Static crack propagation tests

The slow-strain-rate tensile test disregards the presence of notches or cracks. To investigate material behavior in the presence of cracks on exposure to hydrogen, crack propagation tests are performed. In static crack propagation tests to ASTM E 1681 [27], notched compact tensile specimens (***Figure 9***) are initially subjected to vibrational loading until a crack forms in the notch root. The pre-cracked specimens are then electrolytically charged with hydrogen. Usually, a much higher volume concentration of hydrogen is achieved in the specimen than by charging with hydrogen gas. Together with the stress increase

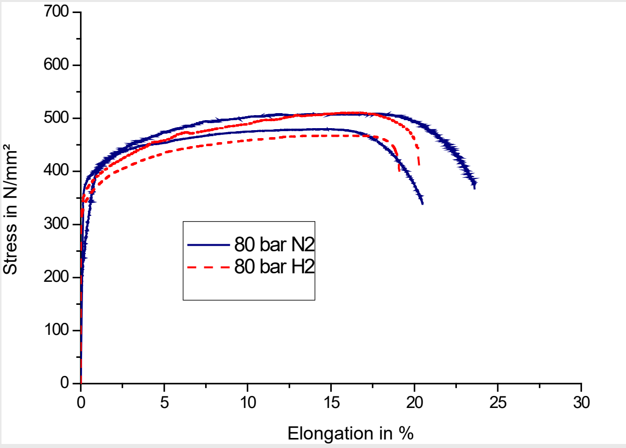

***Figure 6**: Stress-strain curves of SSRT tests measured on Material 1*

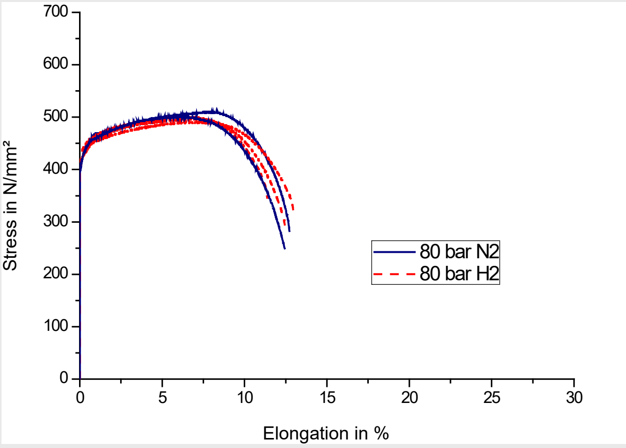

***Figure 7**: Stress-strain curves of SSRT tests measured on Material 2*

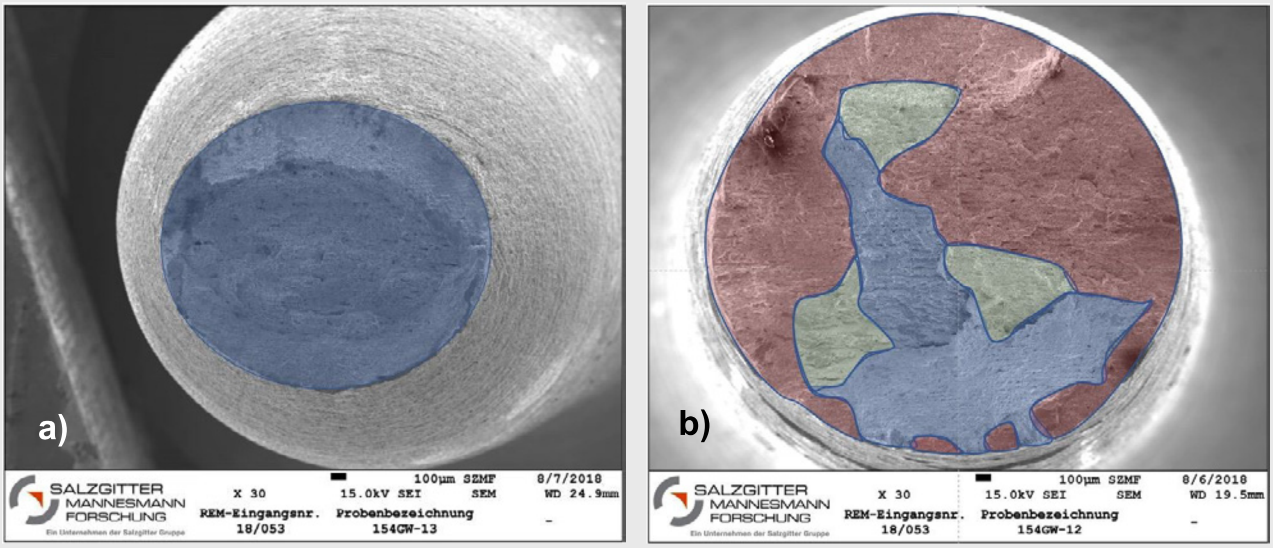

Figure 8: *Typical fracture surface of Material 1 after the slow-strain-rate test in the scanning electron microscope. Blue: ductile fracture. Red: brittle fracture. Green: mixed surface. Test media nitrogen (a) and hydrogen (b)*

at the crack at the root of the notch, this produces the most critical condition possible. These specimens are then subjected to a constant static load. The time to specimen failure is evaluated. By testing at different loads, a lower crack toughness limit value can be determined at which the specimens no longer break. This can be compared with suitable tests in inert media, e.g. air, to determine a reduction factor. A typical test set-up with a result curve is shown in ***Figure 10***.

Dynamic crack propagation tests

Dynamic crack propagation tests complete the characterization of the materials exposed to compressed hydrogen gas. The test is described in various ASTM standards [27,

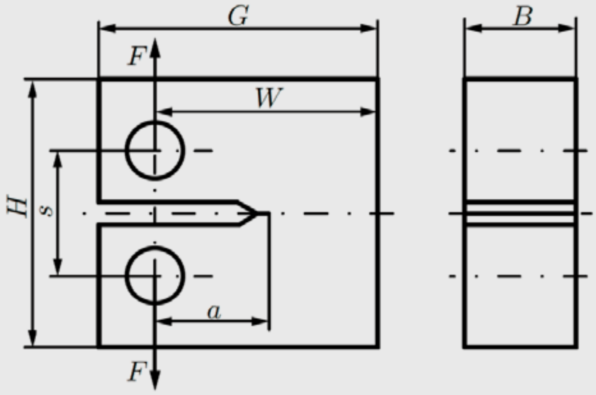

Figure 9: *Geometry of the CT specimen according to ASTM E 399 [28] (example)*

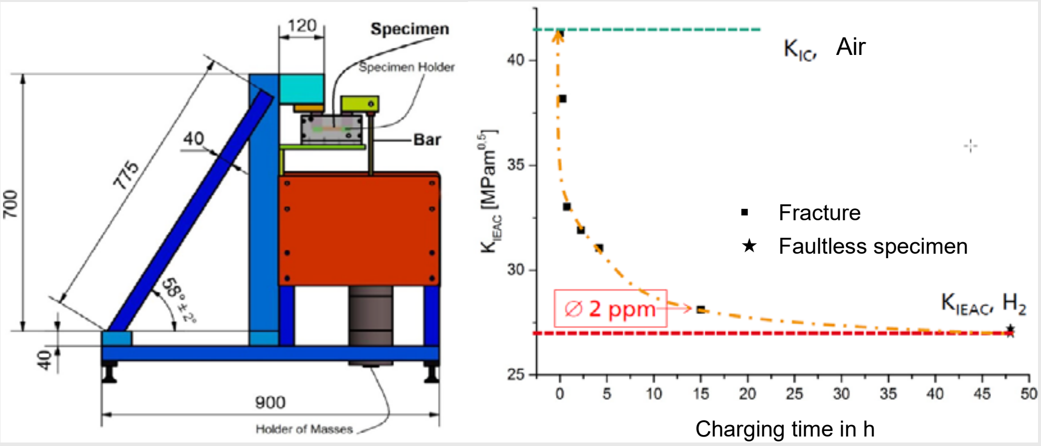

Figure 10: *Test set-up for a static crack propagation test (schematic) and a typical result curve from a complete test series [29]*

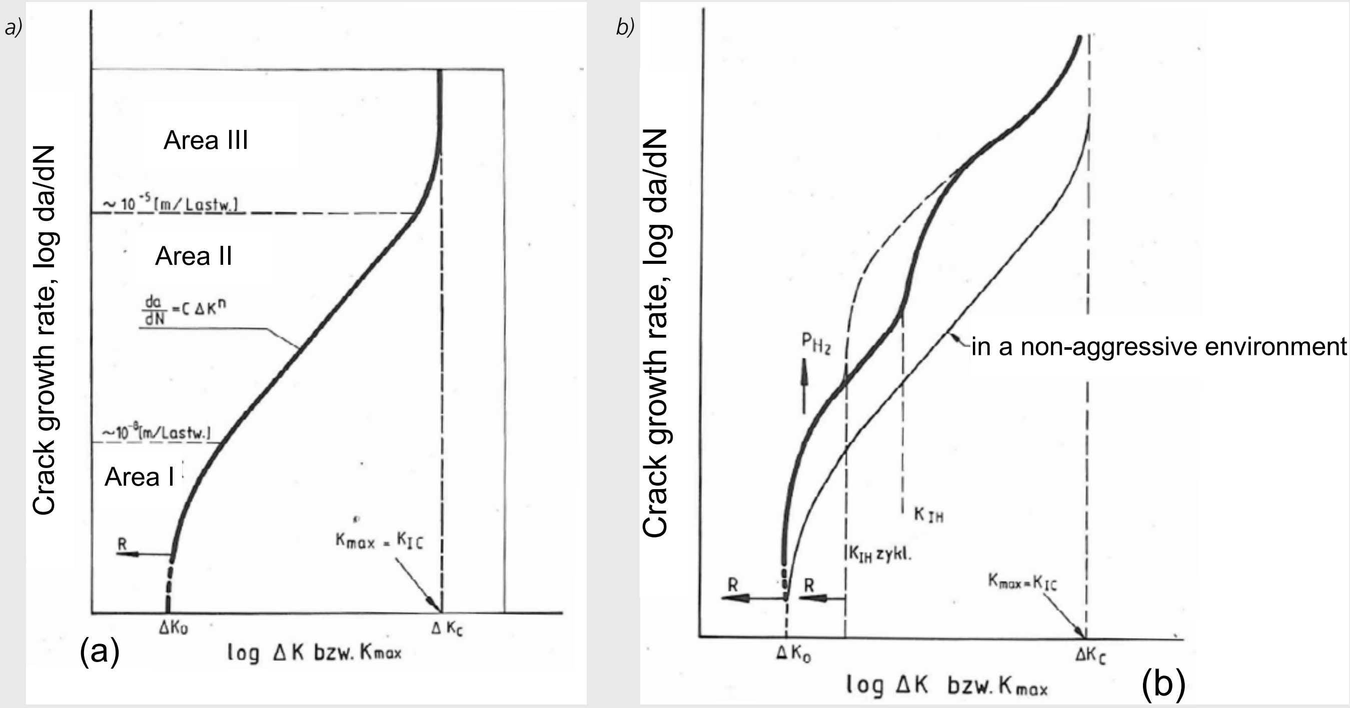

Figure 11: *Fatigue crack growth in air (a) and in the presence of hydrogen (b) [32]*

28, 30, 31]. Unlike the static tests, a fatigue (dynamic) load is applied here. The crack propagation per cycle is measured. The known relationship between the crack growth rate $^{da}/_{dN}$ and the amplitude of the stress intensity factor ΔK (test medium air) is shown schematically in ***Figure 11*** (a). Only from the threshold value ΔK_0 onwards does crack growth become detectable. This value depends largely on the stress ratio and less on the material being tested. It is worth mentioning that when a crack forms under cyclic loading, critical plastic deformation can take place locally in areas of high stress concentration (notches, cracks, surface flaws), even though the total deformation is still within the material's elastic range [32]. After a brief phase of crack initiation (area I), the crack growth rate decelerates in area II. This constant crack growth can be described by the Paris equation given in the figure. In area III, accelerated crack growth then sets in again up to supercritical crack growth and failure thus arises when the critical stress intensity K_{IC} is exceeded. The effect of hydrogen on the curve and thus on crack growth in hydrogen was investigated in [33] and [34] on low-alloy steels, for example. In both studies it was found that an increase in the crack growth rate was always detectable with different hydrogen contents and gas pressures. A typical change in the curve is shown schematically in ***Figure 11*** (b). Crack acceleration due to hydrogen occurs in all areas of the curve. The threshold value ΔK_0 remains unchanged however. Fatigue tests in hydrogen on API 5L grade X80[6] showed a significant reduction in crack resistance and an increase in crack growth rate by a factor 10 [35]. The time factor plays a decisive role here. At high frequencies it is difficult to induce a corrosion reaction in a hydrogen atmosphere. Here the time is too short for the hydrogen to penetrate the material via a bare metal surface possibly exposed by cracking of the oxide layer during loading and/or to diffuse in the material's microstructure to the tip of the crack. Therefore, very low frequencies of load change are to be selected in the test. In [36], pressure fluctuations with frequencies below 0.03 Hz are held responsible for hydrogen-induced fatigue cracking in gas pipelines. However, new findings contradict the commonly held doctrine that crack growth continues to increase with decreasing load frequency [37]. For some metallic materials, there seems to be a lower limit value for the frequency.

In addition to the above-mentioned observation in [14] that the increase in the crack propagation rate on exposure to hydrogen is almost independent of the hydrogen concentration in the natural gas, [38] also reports that the hydrogen pressure is negligible here. Even at low hydrogen (partial) pressures, the effect of hydrogen damage on the crack propagation rate of API 5L line pipe steels is almost total. Likewise, dependence was found not on the material's minimum yield strength, but rather on the material's microstructure.

When designing a pipeline for the transport of hydrogen, there are two possibilities, assuming the existence of a

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[6] Corresponds to an L555 to DIN EN ISO 3183

crack: either the degree of pipeline utilization is calculated so that no measurable and hence no critical crack growth occurs, or the number of operating cycles is calculated so that any growing crack does not exceed the critical value within the pipeline's planned service life. To ensure this, there have so far been two basic approaches. One is to reduce the degree of pipe utilization, e.g. by reducing the line pressure or by suitably increasing the wall thickness or strength class. In ASME B31.12, for example, this is achieved in Design Option A by means of a so-called Materials Performance Factor, i.e. a reduction coefficient. This depends on the mechanical properties of the pipe and the design pressure. The other (Design Option B) envisages using fracture mechanics considerations and tests to determine limit values for the load intensity in hydrogen gas, which are then used for calculating the degree of utilization. In the new revised version of ASME B31.12, the mechanism of hydrogen-enhanced fatigue is also considered. On the basis of several tests on different pipeline grades [38], a single upper envelope has been defined. ***Figure 12*** shows a representative comparison of the envelope with the findings obtained on X52. This curve forms the „worst-case" basis of the newly implemented simplified model for the conservative design of pipelines exposed to compressed hydrogen gas.

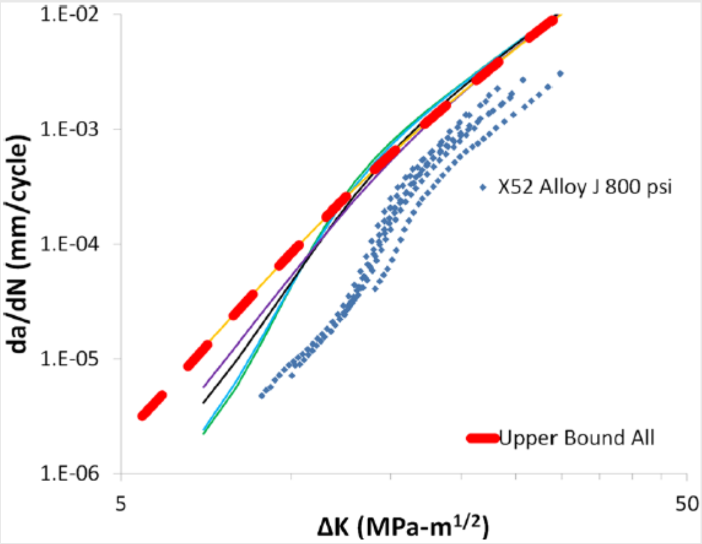

Figure 12*: Comparison of the envelope with the results obtained on X52 [38]*

From earlier static investigations (tensile test), an inverse relationship is known to exist between the strength and the negative effect of hydrogen on ductility (hydrogen embrittlement). Since only this effect was considered in the design of parameters in, for example, ASME Standard B31.12, this resulted in limitations for steel grades above API 5L X52 with minimum yield strengths greater than 360 MPa. In contrast, more recent investigations have shown that hydrogen-induced crack propagation under fatigue loading does not depend on material strength [39]. From this it was concluded that the design constraint for higher-strength steels is overly conservative and not justified. Thus, the approval of steels with yield strengths up to 485 N/mm² (API 5L X70[77]) is capable of reducing material and installation costs by about 25 % regardless of reductions [40]. As a result of this study, the new version of ASME B31.12 will no longer include these restrictions relating to higher-strength steels between X52 and X70.

Conversion of a Dutch natural gas pipeline to hydrogen

In 2018 Gasunie converted an existing gas pipeline for the transport of natural gas to hydrogen. The gas composition varies from 70 to 100 % hydrogen, the rest being natural gas with a maximum of 1 % CO. To achieve this, limited modifications were undertaken on the existing pipeline and the full integrity and safety situation was reassessed. This document specifically addresses the effect on the service life of the pipes used and the welds by means of which these pipes were joined.

One of the challenges in the production of a pipe and its laying on site is the welding of the joints. Welding is a process in which there are in fact always irregularities. However, as long as these do not compromise integrity, they are considered acceptable. There are various standards for this, such as EN ISO 3183 [24] for the longitudinal welds of pipes and EN 12732 [41], which is also applied in DVGW GW 350 [42], for on-site girth welds. Both standards contain acceptance criteria which allow an irregularity in the welded joint. This means that, with these irregularities, there is no danger to integrity at design pressure and in the given pipe-laying conditions. However, these irregularities may grow due to pressure changes in the pipeline. For a pipeline transporting natural gas, we, at Gasunie, assume there will be no significant growth in the irregularities permitted by the standard, despite the continuous load caused by pressure changes. If growth is taking place, it can be assumed to be less than 0.01 µm per load change.

When hydrogen or natural gas with a percentage of hydrogen is transported, the resistance of the steel to crack propagation may change if atomic hydrogen can penetrate the steel lattice. For this to happen, molecular hydrogen first has to be split into atomic hydrogen. In a steel transport pipeline, this can take place on a non-corroded, clean steel surface. This may be the case if there is a permissible irregularity in the pipe, such as a groove open on the inside of the pipe. In this case it is important to know how crack growth occurs under hydrogen conditions. In various international projects, extensive information has been gathered on the rate of steel crack growth under hydrogen conditions. By using these values in a fracture

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[7] Corresponds to an L485 conforming to DIN EN ISO 3183

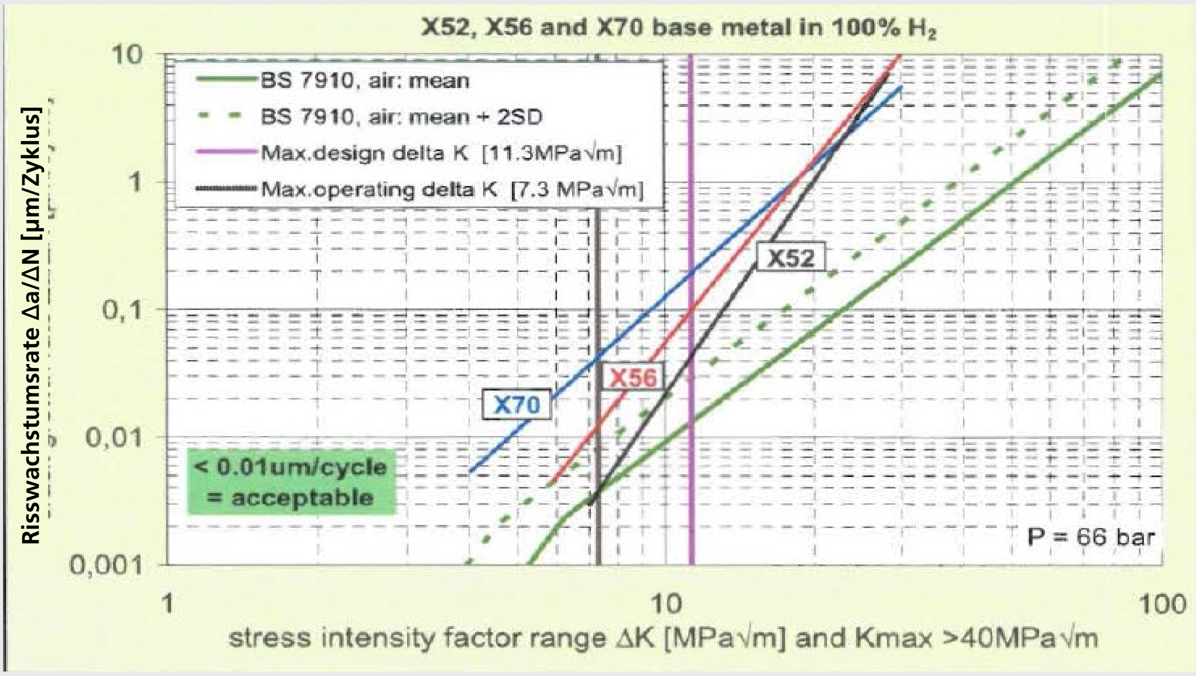

Figure 13*: Crack growth rates in 100 % hydrogen [43]*

mechanics analysis of the known, acceptable irregularities, it is possible to calculate the load cycles/pressure cycles at which the maximum acceptable growth of irregularities is not exceeded. For this, the above-mentioned limit of 0.01 µm/cycle for natural gas is applied as the limit for acceptable growth. ***Figure 13*** below shows the crack growth rate for a number of pipeline steels, obtained in the Naturalhy project [43].

From the figure, the threshold value for the permissible ΔK for crack growth of 0.01 µm/pressure change is to be determined. The factor ΔK for the evaluation of a threshold load is known from the theory of fracture mechanics. Gasunie has used this method to determine for the existing gas pipeline whether any crack growth on exposure to hydrogen does not result in a higher value than for natural gas. The calculations were carried out in accordance with BS 7910:2013+A1:2015 [44]. The following procedure was adopted:

- Hydrogen crack resistance under continuous load
- Determining the pressure fluctuations (magnitude Δp and number N) during the envisaged service life
- Determining the threshold load (ΔK) of a known flaw (3 at 50 mm) in a pipeline
- Determining the rate of crack growth
- Determining the crack growth of the assumed irregularity
- Determining whether the crack growth results in an impermissible flaw size within the envisaged service life.

The following initial values were assumed when calculating the flaw size: Starting from a flaw in the height of a weld bead, a flaw height of 3 mm was adopted for evaluation. Most permissible flaw lengths are 25 mm. However, since non-destructive testing does not always show the full flaw length, 50 mm was adopted as the maximum length. The results of the calculations are summarized in ***Table 3***. On the basis of this calculation, it can be stated that the integrity range for this pipeline carrying up to 100 % hydrogen is no different from that for a natural gas pipeline for the flaw test in the pipes or girth welds. But all this has been known for some time the following statement was already made in 1978: „The biggest technical problem in transporting hydrogen gas under high pressure is the possibility of the low fatigue growth of existing cracks or crack-like flaws in the pipe body or in the weld“ [45].

Summary and outlook

It is now generally accepted that hydrogen will be one of the main energy carriers in the conversion of the primary energy supply to renewable energy sources. As consumers in all sectors such as transport, heating and industry gradually adapt to a pure hydrogen technology, fossil natural gas, methane from the remethanization of stored carbon monoxide/dioxide, and natural gas/hydrogen or methane/hydrogen mixtures will form a bridge technology for many years to come. Since pipelines are the most economic and ecological solution for the transport of large quantities of hydrogen, current investigations in the transport and storage sector are aimed on the one hand at converting and reusing existing pipeline networks and on the other hand at optimizing modern

***Table 3**: Crack formation force ΔK and stress range Ds, (flaw assumption: 3 mm height and 50 mm length in the longitudinal direction of the pipe weld or girth weld in pipes measuring in 48" x 14.1 mm, at a pipeline pressure of 66 bar*

Pressure fluctuation in bar	Flaw orientation	Stress in N/mm²	Stress change in N/mm²	Stress intensity ΔK in N/mm².√m	Flaw growth in 100 years in mm
6.6	Girth weld	292	29	3.4	0.37
	Longitudinal weld	150	15	1.7	0.37

steel materials for new installations. The focus here is on hydrogen/gas mixtures and, of course, pure hydrogen. The experiments currently being discussed for material qualification and their background, as well as the main standards adjustments for a hydrogen infrastructure, have been presented in this paper.

Mannesmann Line Pipe GmbH's main focus is currently on the development and the verification of the suitability of steel grades for new pipelines. In internal and sponsored projects, extensive tests have been carried out with a wide variety of old and new materials. These are described in this and earlier publications. On the basis of the findings and the experience gained, the current „H2ready" strategy for pipes for the transport of hydrogen gas has the following essential features. By avoiding surface irregularities such as notches or shoulders on the inside of the pipe, it is possible to prevent local stress increases under internal pressure. This reduces, firstly, the probability during operation of the creation of bare metal surfaces, which represent a potential point of attack for the diffusion of hydrogen into the material. Secondly, critical crack growth is thus prevented, which could otherwise start before the material's yield point is reached and result in premature component failure. A reduced carbon content, or carbon equivalent, improves weldability and thus results in lower hydrogen penetration. The reduction of phosphorus and sulfur contents as undesirable accompanying elements results in lower segregation and fewer internal irregularities during steel production, and thus ultimately in fewer internal points of attack for hydrogen. An optimum microstructure has just as positive an effect on a material's resistance to hydrogen attack. At Mannesmann Line Pipe, this is achieved by using thermomechanically (TM) rolled material. Due to the modified process, a limitation of the maximum values for yield point and tensile strength can be ensured both in the starting material and during pipe production. This in turn results in a harmonization of the degree of utilization under internal pressure, and thus in the prevention of local overloading. Investigations carried out to date in compressed hydrogen gas also suggest that higher-strength pipeline grades above API 5L X52 are suitable for use as transport pipelines. Higher strength enables the use of higher transport pressures or thinner pipe walls. This in turn yields a reduction in the consumption of resources and energy during production. „H2ready" pipes from Mannesmann Line Pipe are therefore clean, safe and cost-effective.

This paper also covers aspects of the continued use of existing gas pipelines and their conversion to hydrogen. Current work on the preparation of a conversion roadmap is discussed. Furthermore, the Dutch network operator N.V. Nederlandse Gasunie reports on its practical experience with the changeover of a natural gas pipeline to hydrogen transport. Here, the emphasis is especially on crack propagation issues. By means of fracture mechanics approaches it has investigated when a potential irregularity can cause a crack and whether the crack grows to an unacceptable flaw size within the intended service life. The design of pipeline operation has been based on conservative calculations.

Current and future investigations and activities are devoted to the completion of technical investigations and the further optimization of new line pipe materials, as well as the operation of old lines converted for hydrogen transport. The aim is to minimize the conservatism of current criteria in order to operate hydrogen transmission pipelines as economically and ecologically as possible, taking all safety issues into account.

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