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New hydrogen fuel lines from carbon steel tubes and their qualification for high-pressure hydrogen applications

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Abstract

Recent advancements in steel tube technology have led to the development of carbon steel tubes specifically designed for hydrogen fuel lines in mobile machinery or in automotive applications. These developments address the material and safety challenges associated with hydrogen as an energy carrier on the pathway to climate neutrality. Especially the development and proof of operational safety for carbon steel tubes made from new materials for high-pressure hydrogen is challenging.

This paper provides insights into qualification process of the BENTELER HYRESIST® Mobility tubes for high pressure hydrogen applications. These fluid line tubes developed by BENTELER Steel/Tube from a ferritic-pearlitic carbon steel are an economic alternative to austenitic stainless-steel tubes, which are the current state of the art for hydrogen fluid lines. The main content of this paper will be the properties of the new steel grade, the hydrogen testing and its results under high-pressure hydrogen conditions of this steel in general and as a hydrogen fluid line, as well in the context of the current hydrogen fluid lines regulations.

The general hydrogen compatibility of the new steel material was proven by a burst disk test with pressurized hydrogen. Additionally, tubes made from this steel underwent a testing procedure where the tube is subjected to a cyclic loading under high-pressure hydrogen at different temperatures, followed by a hydraulic burst test to proof lifetime safety. These dynamic investigations were carried out using processed tubes in combination with fittings as a prototype hydrogen fluid line. The methodology successfully demonstrated the general hydrogen compatibility of the BENTELER HYRESIST® Mobility tubes. Finally, the paper will conclude with an evaluation of this innovative solution for high pressure hydrogen lines in relation to the current state of the art.

Keywords. BENTELER HYRESIST® Mobility, hydrogen fluid lines, seamless cold-drawn precision tubes, carbon steel, high-pressure hydrogen, burst disk test, pressure cycling test.

1. INTRODUCTION

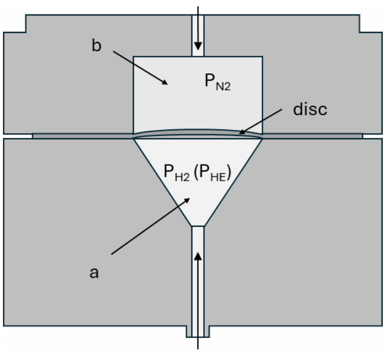
The practical evaluation and the prediction of hydrogen embrittlement in steels are despite numerous scientific studies a persistent problem. There is no generally accepted load-independent material criterion for the hydrogen sensitivity of steels under pressurised hydrogen. The reduction of area or elongation at fracture in the quasi-static tensile test is often used as a technological comparison value. It is often neglected that actual loads of real components under hydrogen typically occur by multiaxial loading and under dynamical load conditions. Occasionally, notched specimens are used, although the test result is critically dependent on the notch sharpness.

Fracture mechanics tests, such as determining the crack propagation rate as a function of the stress intensity factor, are effective methods for the investigation of hydrogen embrittlement resistance. However, these tests are not suitable for small and thin-walled tubes because the extraction of standard CT-samples is not possible because of the specimen size.

For the newly developed high-pressure tubes BENTELER HYRESIST® Mobility by BENTELER Steel/Tube a different testing approach was chosen. The tubes for hydrogen application made from a specially developed ferritic-pearlitic carbon steel are tested by an approach that is presented below. This approach is focusing at 70 MPa (700 bar), which is a pressure stage that is especially needed for automotive or other mobile machinery applications. It uses the burst disk test according to DIN EN ISO 11114-4 and a dynamical cycling internal pressure test, which is linked to a subsequent hydraulic burst-test. Moreover, the experimental method and its results are compared to the current automotive standards.

2. HYDROGEN COMPATIBILITY TESTS USING THE BURST DISC TEST

The evaluation of the hydrogen embrittlement resistance of steels can be carried out using the burst disc pressure test developed by Fidelle et al. [1-5], in accordance with DIN EN ISO 11114-4 [7]. In this test, a disc-shaped specimen is clamped and subjected to continuously increasing gas pressure until bursting or crack initiation occurs (Fig. 2.1). The embrittlement effect of hydrogen (H_2) is quantified by comparing the burst pressures under hydrogen (P_{H2}) and helium (P_{HE}), with helium serving as an inert reference gas. The ratio P_{HE}/P_{H2} is used as a measure of the material's susceptibility to embrittlement. It should be noted that this ratio depends on the pressure increase rate, which must be kept constant during each test.



a) Underside of the disc is loaded with P_{H2}
b) Top side of the disc is loaded with P_{N2}

The disc is loaded with $\Delta P = P_{H2} - P_{N2}$

Figure 2.1. Principle of the burst disk testing according to DIN EN ISO 11114-4 [7]

Based on extensive measurements on steels that have proven successful in practice or have failed under hydrogen exposure, Fidelle identified a burst pressure ratio of $P_{HE}/P_{H2} = 2$ as a critical value, which was adopted by DIN EN ISO 11114-4. The ratio of P_{HE}/P_{H2} is also known as hydrogen embrittlement index (HEI). For materials with values of the HEI < 2, no component failure due to hydrogen embrittlement is expected.

A key advantage of this approach is that the strength and the ductility of the material are reflected in the test result. The loading conditions are particularly favourable for the effect of pressurized hydrogen and resemble those in pressure vessels or hydrogen-carrying fuel lines.

2.1. Experimental boundary conditions

According to DIN EN ISO 11114-4 (method A), the test disc must meet specific properties and dimensions. It must be flat and the surface is produced either by grinding or machining to ensure an appropriate surface finish. The dimensions are as follows: The diameter measures 58 mm, the thickness 0,75 mm and the flatness deviations is less than 1/10 mm with a surface roughness Ra < 1 µm.

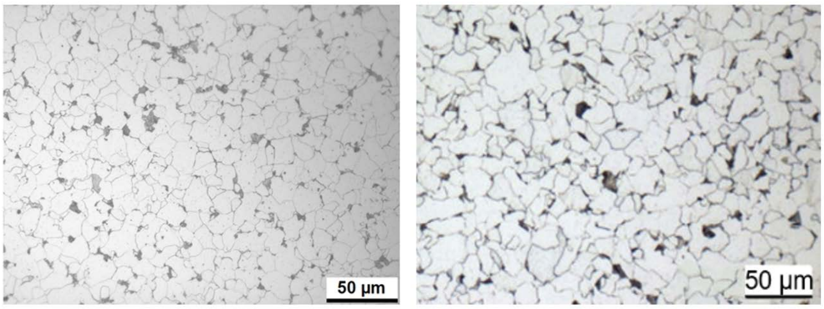
If an evaluation of the steel at an operating pressure exceeding 30 MPa is required, a disc thickness greater than 0,75 mm shall be used. Due to the hydrogen pressure of 70 MPa in automotive fuel lines, the test discs had thicknesses ranging from 1,49 to 1,52 mm. Tests were conducted using hydrogen (purity > 99.9995 mol-%) and helium (both gases with H_2O < 3 µl/l), with pressure increase rates evenly distributed between 0,3 and 40 MPa/min. For complete material evaluation, 15 tests (six with helium and nine with hydrogen) as specified in DIN EN ISO 11114-4, method A, are considered sufficient. For disc thicknesses above 0,75 mm, the burst pressure Pr´ must be systematically corrected to account for deviations from the test of a disc with standard wall thickness. The corrected burst pressure Pr´ is determined by the following equation (2.1):

$$Pr' = \frac{Pr \cdot 0{,}75}{e_m}, \text{where } e_m \text{ is the mean disc thickness} \qquad (2.1)$$

Corrected burst pressures are shown as a function of the pressure ramp rate. The pressure ramp rate is calculated by dividing the actual burst pressure by the test time and is expressed in MPa/min. For each hydrogen test, the ratio Pr'_{He}/ Pr'_{H2} is determined, where Pr'_{He} is the theoretical helium burst pressure associated with the same pressure increase rate as the hydrogen test (obtained by regression from the corrected helium burst pressure), and Pr'_{H2} is the corrected hydrogen burst pressure. The ratios Pr'_{He}/ Pr'_{H2} shall be represented in relation to the pressure increase rate. The hydrogen embrittlement index (HEI) of a material is the maximum of these ratios. A material with an index not exceeding 2,0 is considered hydrogen compatible.

2.2. Specimen preparation

Since it is not possible to extract a disc with a diameter of 58 mm directly from a small thin-walled tube, a forged specimen of the same material was first cut out from a continuously cast billet. To eliminate the dendritic cast structure, the material was forged at about 1100 °C into a round bar of 58 mm diameter. Following the cutting of 2 mm thick discs from the round bar, both sides were grinded to achieve thicknesses of 1,49-1,52 mm and fulfill the surface roughness requirements according to DIN EN ISO 11114-4. Through a subsequent heat treatment, a ferritic–pearlitic structure was established, comparable to the microstructure of a cold-drawn tube with a small wall (fig. 2.2). For both microstructural conditions, a grain size class of 10 was identified, together with comparable hardness values of approximately 125 HV1, which correspond to an estimated tensile strength of about 400 MPa. Consequently, the burst disc specimens exhibit microstructural characteristics and mechanical properties analogous to those of hydrogen fuel lines manufactured from the same material.



Tube, grain size class: 10 Disc, grain size class: 10

Figure 2.2. Comparison of microstructure between tube (left) and disk (right)

2.3. Results

The burst disc pressure tests were carried out in accordance with DIN EN ISO 11114-4 (Method A). Fig. 2.3 shows the corrected hydrogen and helium burst pressures as a function of pressure rise rate, as well as the resulting burst pressure ratios. All burst pressure ratios are significantly below the critical value of 2,0. According to DIN EN ISO 11114-4 (Method A), the hydrogen embrittlement index (HEI) of a material corresponds to the maximum value of this ratio, which in this case is 1.16. Based on this HEI, the examined tube material can be considered compatible with hydrogen at a pressure of 70 MPa.

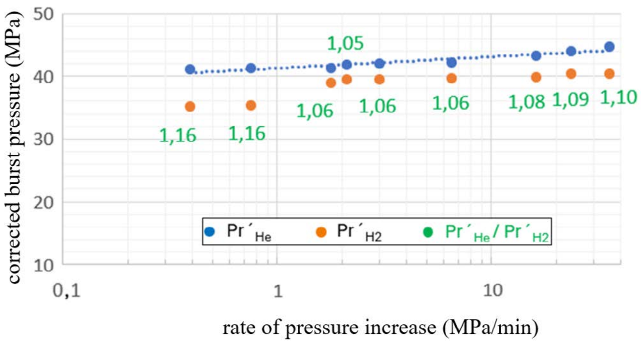


Figure 2.3. Corrected hydrogen and helium burst pressures as a function of pressure rise rate

3. CYCLIC PRESSURE TESTING OF HIGH-PRESSURE TUBES

To evaluate the potential sensitivity of steels to hydrogen in practical applications, it is essential to characterize their cyclic behaviour. The aim is to prevent the failure of components due to real world conditions, which could otherwise have severe consequences. To guarantee the durability of steel components exposed to hydrogen, fatigue tests under maximum loading conditions and varying temperature conditions are recommended.

The tested components consist of the hydrogen-carrying tube (seamless cold-drawn, outer diameter: 6.35 mm, wall thickness: 1.675 mm) with an outside corrosion protection layer and with tube fittings at both ends. The corrosion protection coating was realized as BENTELER ZISTA®SEAL and BENTELER ZISTAPLEX®. ZISTA®SEAL is a flexible chromiumVI-free zinc coated tube with a thin sealer as a top coat, offering good corrosion protection, even after tube processing. ZISTAPLEX® is a tube with a flexible duplex coating consisting of chromium (VI)-free zinc coating with an additional red coloured organic coating, offering high corrosion protection, even after tube processing. The tube fittings also play a key role in the functional and practical design of hydrogen fluid systems, as they must ensure gas-tightness under high hydrogen pressure and stability against mechanical impacts. Moreover, a 316L stainless steel tube of the same size with identical tube fittings was used as a reference.

3.1. Mechanical and microstructural characterisation of the tube

The mechanical properties of the high-pressure hydrogen tubes made of BENTELER carbon steel are listed in Table 3.1. The seamless cold-drawn and normalized BENTELER HYRESIST® Mobility (BHM) series-tube has a ferritic-pearlitic structure with a grain size class of 10 (see fig. 2.2 above).

Table 3.1. Mechanical characteristics of the high-pressure hydrogen tubes (BHM1) with outer diameter: 6.35 mm and wall thickness: 1.675 mm

	Yield Strength $R_{p0.2}$ (MPa)	Ultimate Tensile Strength R_m (MPa)	Elongation A (%)
BENTELER HYRESIST® Mobility 1	≥ 250	≥ 370	≥ 35

3.2. Experimental Procedure and Results

For cyclic tests with hydrogen internal pressure, respectively three high-pressure tubes with a length of 100 mm and with fittings on both tube ends (Fig. 3.1) were subjected to cyclic ageing with up to 50,000 pressure cycles at three different temperatures of +20, -40 and 60 °C. In one cycle of 20 to 30 seconds, the hydrogen pressure in the tube was increased from 0 to 87.5 MPa and then decreased back to 0 MPa. The maximum value of 87.5. MPa is equivalent to a nominal working pressure of 70 MPa (700 bar) multiplied by a safety factor of 1.25, according to EC79 or ISO 19887. The pressure test gas was hydrogen with a purity of >99.999 mol-% (hydrogen 5.0).

Following this cyclic ageing, hydraulic pressure tests were conducted until failure of the tubes. The determined burst pressure was compared with that of a non-preloaded reference tube to assess the effects of cyclic ageing under a pressurised hydrogen atmosphere. This hydraulic burst pressure tests were carried out at 20 °C and the results are shown in Table 3.2. No significant difference between the burst pressures of the tube samples preloaded with hydrogen and the reference samples (without hydrogen contact) can be observed. This proves the excellent hydrogen resistance of the BHM1 steel tube.

Table 3.2. Results of cyclic internal pressure tests and burst pressure tests

Temperature (°C)	Pressure cycles	Burst pressure (MPa)
BHM1 – *Reference without hydrogen*		
20	0 (reference)	330,0
BHM1 – cyclic loading with hydrogen		
20	10.000	339,7
-40	10.000	332,5
-60	50.000	329,3
Stainless steel (1.4404) – reference without hydrogen		
20	0 (reference)	350,0
Stainless steel (1.4404) - cyclic loading with hydrogen		
20	10.000	338,5
-40	10.000	343,3

Having a closer look at the results, it is remarkable that the BHM1 tube has a slight increase in burst pressure under the influence of hydrogen at 20 and -40 °C. At -60°C, the burst pressure is reduced by only 0.2%. While the burst pressures of the austenitic stainless-steel tube decrease by 3.3% under the same conditions (20 and -40°C, no testing at -60°C). Summarized, the BHM1 high-pressure tube even shows a very slightly higher resistance to high-pressure hydrogen embrittlement than the stainless-steel tube made of 316L (1.4404).

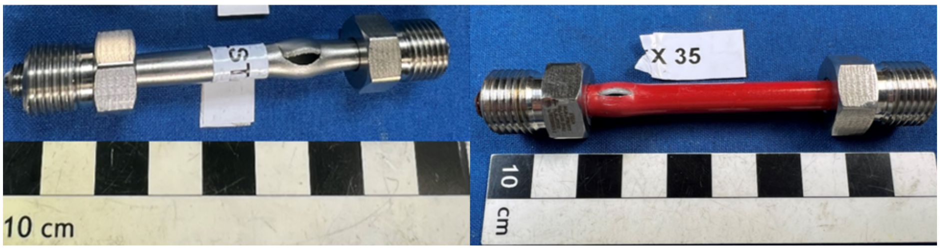


Figure 3.1. Test components after the hydraulic burst pressure test, 316L stainless steel (left) and BHM1-tube (right), each with tube fittings on both ends

4. TESTING APPROACHES AND STANDARDS

To provide a comprehensive context for the present work, the following paragraphs introduce an alternative testing approach which is under development for small sized tubes (4.1). Furthermore, the current standards for automotive applications are summarized (4.2).

4.1. Perspective on hydrogen service life testing of tubes and tube materials

As an alternative to the component testing described above, research is currently working on further efficient qualification procedures to assess the service life of tubes made of new materials under the influence of pressurized hydrogen.

In the project *hydrogen lightweight tube* (funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), funding code 03EI3070A) the use of longitudinally welded lightweight tubes for hydrogen use is qualified. The tubes are manufactured from strip steel, which was developed based on innovative material concepts. Regarding hydrogen qualification, the project is characterised by the development and testing of efficient test methods for hydrogen compatibility, especially for tubes with small outer diameters and thin walls.

Since the influence of hydrogen can lead to a significant reduction in fatigue life in the high-cycle fatigue range [6], an evaluation of cyclically stressed tube will be performed by life-time experiments, commonly referred to as “Wöhler”- tests. The required lifetime of the tube to be qualified in this project is below 10^6 cycles and falls within the time-dependent fatigue region of the “Wöhler”-curve. For this purpose, a test method is being developed with which the necessary material tests (low cycle fatigue) can be carried out quickly and cost-effectively in a specially adapted autoclave under pressurized hydrogen.

A second testing method using the C-ring technique, which enables easy sample production from thin sheets and tubes, is tested for the fatigue strength characterisation of products and materials under pressurized hydrogen. The project includes adapting this solution to the specific tube geometry and extending it for fatigue tests under pressurized hydrogen. This offers an additional quite simple method to characterize the fundamental hydrogen compatibility under pressurized hydrogen loading. This innovation enables targeted, geometry-specific material qualification and, in the future, cost-effective further developments and implementation into simple quality assurance measures.

4.2. Automotive standards for hydrogen compatibility testing of components

For the North American market, the applicable standard is ANSI HGV 3.1 – "Fuel system components for compressed hydrogen gas powered vehicles". In Europe, until July 2022, EC/EG 79/2009 was applied for the type approval of hydrogen-powered vehicles, together with the associated regulation EU 406/2010, which specified a detailed test sequence for high-pressure lines consisting of four tests. This sequence included an initial corrosion test, a cyclic gas pressure endurance test, a hydraulic pressure cycle test, and a final external leakage test. These tests were widely used and can still be considered state of the art. [8, 9]

The current applicable European regulation for type approval of hydrogen vehicles primarily refers to UN Regulation No. 134 (UN GTR 134), which, however, is vague regarding the test requirements for high-pressure hydrogen fluid lines. The incomplete description of the state of the art in the European regulatory framework has been addressed by the international standard ISO 19887-1: *Gaseous Hydrogen — Fuel system components for hydrogen-fuelled vehicles - Part 1: Land vehicles*. It has been developed based on the ANSI HGV 3.1 and is being published in October 2024 for hydrogen land vehicles. It's translated European derivatives might follow. Hydrogen rail vehicles are excluded in Part 1, but Part 2 of ISO 19887 for rail vehicles is under development. [8,10]

The qualification framework defined in HGV 3.1 and ISO 19887-1, contains a durability assessment of hydrogen fluid line assemblies by a multi-stage verification regime that integrates endurance (continuous operation), overpressure resilience, and post-cycling leak integrity evaluation.

The endurance test reproduces the thermomechanical and hydrogen-assisted degradation processes expected in operational vehicle environments, thereby serving as an accelerated surrogate for long-term service exposure. Most significant characteristic of this continuous operation test is the completion of the endurance cycling up to a maximum pressure of 875 bar of firstly hydrostatic pressure and secondly hydrogen pressure cycles for each 50 000 cycles at different temperatures (-40 °C, room temperature and +85 °C). The maximum pressure is set according to the specific pressure class of the application as defined in the normative pressure classification tables of both standards, starting from H25 (250 bar) up to H70 (700 bar). Maximum test pressure is calculated with a factor of 1.25 to 875 bar for a nominal working pressure (NWP) of 700 bar.

After the endurance test the assembly undergoes a hydrostatic strength test using an overpressure that exceeds the nominal working pressure by at least a factor of 2.5, enabling the detection of subcritical defects, microstructural degradation, and plastic deformation phenomena that may have accumulated during cyclic loading. The final stage comprises a leakage assessment performed at defined pressure conditions to evaluate the integrity of all sealing interfaces, welded joints, and mechanical connections. The compliance with the mentioned acceptance criteria in combination with additional tests like corrosion resistance, automotive fluid exposure and a bending test (for the proof of material ductility) ensures that the fluid line assemblies retain its structural reliability, hydrogen compatibility, and leak-tightness throughout the simulated design service life.

The requirements for high-pressure hydrogen fluid lines of ISO 19887-1 are aligned with ANSI HGV 3.1, except that the material selection for high-pressure components is not limited to non-corrosive austenitic stainless steels. This opens the possibility for the series use and qualification of material innovations such as e.g. the hydrogen fluid lines from carbon steel tubes, which is presented in the previous chapters of this article. [8, 10]

5. CONCLUSION

In summary, it can be stated that the presented test series successfully demonstrates the hydrogen compatibility of the high-pressure tubes BENTELER HYRESISIT Mobility. This enables the qualification of components made from these tubes, e.g. as a hydrogen fluid line assembly. According to current regulatory requirements, several standards govern the commercialization of hydrogen vehicles, covering both fuel cell and hydrogen combustion technologies.

In these standards, in addition to demonstrating the basic material compatibility under hydrogen exposure, component tests for fuel lines are required. These tests essentially replicate the expected operating conditions of the components over their service life. Both verifications were provided in a modified form within the experiments presented.

The technological neutrality regarding the material selection for hydrogen fuel lines of ISO 19887-1 enables the possible future use of innovations such as the high-pressure fuel line tubes (BENTELER HYRESIST® Mobility). These tubes are made of carbon steel specifically developed for the application in hydrogen fuel systems, other hydrogen mobile machinery or similar stationary applications. Altogether this innovation is supporting the cost-efficient development of hydrogen-powered vehicles and further hydrogen applications.

6. REFERENCES

[1] J. P. Fidelle, R. Broudeur, C. Roux, Effect of Hydrogen on Behavior of Materials, AIME Conf. Jackson Lake, USA. publ. AIME (1976) 507.

[2] J. P. Fidelle, R. Bernardi, R. Broudeur, C. Roux, M. Rapin, ASTM STP 543 (1974) 221.

[3] J. P. Fidelle, R. Broudeur, C. Pirrovani, C. Roux, ASTM STP 543 (1974) 34.

[4] J. P. Fidelle, L. R. Allemand, J. M. Deloron, C. Roux, MCchanique Electricitt, No. 229 (1969) 1.

[5] Colloque sur “Les Essais de Disque sous Pression”, Ivry, 29. 5. 1975, organist par INSTRUMENTS SA et le Commisariat l'Energie Atomique

[6] Michler, T. et al., Int. J. Fatigue 96 (2017) 67

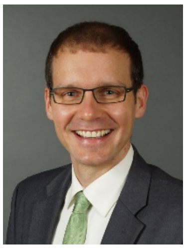
[7] DIN EN ISO 11114-4:2017 - Ortsbewegliche Gasflaschen - Verträglichkeit von Werkstoffen für Gasflaschen und Ventile mit den in Berührung kommenden Gasen - Teil 4: Prüfverfahren zur Auswahl von Stählen, die gegen Wasserstoffversprödung unempfindlich sind.

[8] ANSI/CS HGV 3.1 - Fuel system components for compressed hydrogen gas powered vehicles.

[9] EC/EG 79/2009 - Verordnung Nr. 79/2009 des Europäischen Parlaments und des Rates über die Typgenehmigung von wasserstoffbetriebenen Kraftfahrzeugen mit der zugehörigen Durchführungsverordnung EU 406/2010.

[10] ISO 19887-1 - Gaseous Hydrogen — Fuel system components for hydrogen-fuelled vehicles - Part 1: Land vehicles.

Biographies



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