WELDING SOLUTIONS FOR THE TRANSPORTATION AND STORAGE OF GAS AND LIQUID HYDROGEN

BY NICOLA FARAONE

It is a matter of fact that hydrogen will be a key part of the global energy transition. In a world where energy consumption is projected to grow, the urgent need to drastically reduce CO_2 emissions is the main tailwind for the renewables energies as the sole way to meet the target.

Wind and solar energy have been demonstrated as reliable techniques for the production of CO_2 free energy. The main drawbacks of these energies is that wind and sun are not constantly available. This in turn causes issues during peak times when demand on the grid is high. There can also be a risk for wasting energy when the production is superior to the demand.

Hydrogen is the answer to guarantee stable energy production for renewables.

In fact, hydrogen is well known as a fuel and a feedstock, but it is also projected to become the most popular energy carrier in an integrated cycle connected to the energy produced from renewable sources.

For the reasons above, we will need pipelines and tankers for the hydrogen transportation, as well as tanks for the storage. Hydrogen transportation and storage can be in gaseous or liquid state. Each form brings challenges for the choice of materials used.

voestalpine Böhler Welding is developing and proving a suitable welding consumables portfolio matching the requirements for this new industry challenge that will be part of our future.

“By 2050, however, about five times the amount of hydrogen currently produced will be needed to achieve the climate targets.”

HYDROGEN PRODUCTION

Hydrogen is the most abundant element and the smallest molecule in the universe. It can be utilized as a fuel in turbines or in fuel cells. It is a fundamental feedstock for the petrochemical and urea industries.

The main technologies to produce hydrogen are:

- Methane reforming
- Coal gasification
- Water electrolysis

Depending on the production technology and source, hydrogen can be identified by different colors:

- grey hydrogen is not climate-neutral; coal and natural gas are used as the raw materials for production
- blue hydrogen is CO_2 neutral; it is grey hydrogen when CO_2 is separately captured and stored
- green hydrogen is produced from renewable energy
- turquoise hydrogen it is produced by pyrolysis of methane
- pink/red/purple hydrogen is produced from water electrolysis using energy from nuclear power plants
- yellow hydrogen is produced from water electrolysis using energy from solar power plants
- brown/black hydrogen is produced from brown/black coal
- white hydrogen is occurring from geological hydrogen sources (fracking)

Green hydrogen will further push the development of renewable energy as well as the spread of electrolyzers.

Blue hydrogen is interesting as well in the transition to 100% green hydrogen, considering that it is CO_2 neutral, and, for the time being, could guarantee higher production volumes and lower costs compared to the green hydrogen.

Steam reforming is today the most common method to produce hydrogen on a large scale (in particular for the petrochemical and chemical industry). The process uses natural gas that is preheated and the sulfur removed, then mixed with steam heated to the same temperature. The gas-steam mixture is heated and passed through reformer tubes, reaching temperatures of 850°C. Thanks to a catalyst, hydrogen and carbon oxides are formed.

voestalpine Böhler Welding has a full portfolio for the welding of reformers tubes:

Base Material type	Product name	EN ISO Classification	Welding Process
Alloy 800/800H/800HT	UTP 2133 Mn	3581-A, EZ 21 33 B 4 2	SMAW
Alloy 800/800H/800HT	UTP A 2133 Mn	14343-A, WZ 21 33 Mn Nb	GTAW
Alloy 800/800H/800HT	UTP A 2133 Mn	14343-A, GZ 21 33 Mn Nb	GMAW
Alloy HK, HP, HP Nb, HP MA	UTP 2535 Nb	3581-A, EZ 25 35 Nb B 6 2	SMAW
Alloy HK, HP, HP Nb, HP MA	UTP A 2535 Nb	14343-A, WZ 25 35 Zr	GTAW
Alloy HK, HP, HP Nb, HP MA	UTP A 2535 Nb	14343-A, GZ 25 35 Zr	GMAW
Alloy 35/45, 35/45 MA	UTP 3545 Nb	3581-A, EZ 35 45 Nb B 6 2	SMAW
Alloy 35/45, 35/45 MA	UTP A 3545 Nb	18274, S Ni Z (NiCr36Fe15Nb0.8)	GTAW
Alloy 35/45, 35/45 MA	UTP A 3545 Nb	18274, S Ni Z (NiCr36Fe15Nb0.8)	GMAW

ARC WELDING PROCESSES FOR THE HYDROGEN TRANSPORTATION AND STORAGE COMPONENTS

The main welded components for hydrogen transportation and storage will be pipelines and storage tanks (carrier, trailers, vessels etc).

These components are well-known and the welding processes involved in the manufacturing will be the same that we already see in industries as Oil & Gas and petrochemical.

In particular, the following processes will mainly be used:

» GTAW mainly for root passes and filling passes for low thickness components

» GMAW for filling passes

» SMAW in particular for the pipelines

» FCAW for high productivity and out-of-position welding

» SAW for heavy wall vessels for CGH_2 (compressed gas hydrogen) storage and for the manufacturing of the longitudinal seams in welded pipes

WELDING CHALLENGES FOR THE HYDROGEN TRANSPORTATION AND STORAGE COMPONENTS

In the welding industry, hydrogen is rarely used. There are sometimes small additions in shielding gases for GTAW and GMAW processes and in the rutile and cellulosic flux covered electrodes.

The reason is that hydrogen is often a detrimental element in the weld joints, creating severe defects in (e.g. cracks).

Hydrogen can reach the weld pool through the residual humidity in the coverings of electrodes or fluxes, but there are also potentials risk (especially in the O&G industry) associated to the presence of the hydrogen in the process. For example, Sulfide Stress Corrosion Cracking (SSCC) and High temperature hydrogen attack (HTHA) are potential causes of failures in the Oil & Gas industry.

The main defects caused by the hydrogen in the weld joints can be:

» Worm holes

» Porosity

» Fish eye phenomena

» Hydrogen assisted cold cracking (HACC)

» Hydrogen assisted cracking (HAC)

» Hydrogen induced cracking (HIC)

The above mentioned are undesired phenomena associated with residual quantities of hydrogen present in the weld metal.

The future challenge for construction in the hydrogen industry is to guarantee safe service condition in 100 % hydrogen environment (including some potential residual detrimental elements as the electrolytes).

In particular, the main task for the materials and welding engineers will be the assessment of the potential hydrogen embrittlement on steels.

Hydrogen molecules can attack the surface of the steel (absorption), separate into atomic hydrogen (dissociation) and migrate as hydrogen atoms into the steel (absorption).

Then the hydrogen may affect the metallic materials resulting in specific issues:

1 – Hydrogen embrittlement: the absorption of the hydrogen atoms into the steel has a direct consequence on the reduction of ductility and toughness of the steel. In general, the susceptibility to hydrogen embrittlement increases as the material strength increases.

2 – Property changes at low temperatures: tensile properties of the austenitic stainless steels increase at sub-zero temperatures, while elongation and impact properties reduce.

In the table below, the material compatibility for compressed gas hydrogen or liquid hydrogen applications.

Material	Gas Hydrogen	Liquid Hydrogen	Comment
Carbon steel	Acceptable	Not acceptable	Not suitable for cryogenic service
Austenitic SS	Acceptable	Acceptable	/
Nickel Alloys	Not acceptable	Acceptable	High risk for hydrogen Embrittlement
Aluminum Alloys	Acceptable	Acceptable	/

THE ROLE OF THE AMMONIA IN THE HYDROGEN ECONOMY AND THE RELATED WELDING CHALLENGES

Hydrogen will be an important feedstock in the fertilizers industry. In this case, the hydrogen that is used for ammonia production is often defined green ammonia (NH_3).

In green ammonia projects, the core welded components, in addition to the ones for the process equipment for the production of the carbamate, are the pressure vessels used to store the H_2 produced by renewable energy (wind or solar).

The big challenge for the materials and welding engineers is to guarantee a safe compressed gas hydrogen storage at high pressure (up to 200 bars). Moreover, in order to reduce the wall thicknesses for the vessels and to increase the operating pressure, high strength steels may be selected, with a higher potential risk of hydrogen embrittlement compared to the mild steels.

Green Ammonia can play an important role in the hydrogen industry not only as a feedstock for the chemical industry, but also as the energy carrier for the hydrogen transportation.

Hydrogen forms explosive mixtures at concentration of 4-74% and the use of ammonia as intermediate energy vector will reduce this potential risk. After transportation, the ammonia can be transformed again in H2 before use or it can be used as a feedstock as well as fuel in turbines to produce CO_2 free electricity.

The welding engineers need to find the optimal solution for the ammonia storage tanks and carries, considering the potential risk of stress corrosion cracking related to condensed ammonia in anhydrous state. For this reason, materials with ultimate tensile strengths of maximum 70KSi (485 MPa) are often selected and need to be carefully welded with the proper filler material in order to control the tensile and the hardness properties in the weld joint.

voestalpine Böhler Welding has the required experience and the suitable portfolio for ammonia storage tanks construction.

CONSTANT LOAD TEST ON BÖHLER WELDING FILLER MATERIALS

The suitability of welded components (pipes, tanks etc.) to the hydrogen embrittlement can be assessed using different tests. Among others, we can mention:

» Constant load test (e.g. in acc. to ISO 16573 part 1)

» Slow strain test (e.g. in acc. to ISO 16573 part 2)

» Fracture mechanics test

» Small punch test

» Permeation test

» Dynamic test.

In order to verify the hydrogen embrittlement resistance of the filler materials suitable for the construction of the pressure vessels for gas hydrogen storage, voestalpine Böhler Welding performed the constant load test on a selection of welding products.

The constant load test performed under 100 % hydrogen is more representative of this operating condition than other tests designed to demonstrate the HIC (hydrogen-induced cracking) resistance in the H_2S service (e.g. EN 10229 or NACE TM 02/84).

voestalpine Böhler Welding tested under the constant load test a selection filler materials for the main processes used in pressure vessel and pipeline construction in order to verify the resistance to hydrogen embrittlement.

The constant load test permits estimates of the maximum diffusible hydrogen content at which a material does not fail due to hydrogen embrittlement under a constant load.

The following welding processes and consumables have been selected.

Product name	AWS	EN ISO Classification	Welding Process
BÖHLER FOX EV 60	A5.5, E8018-C3H4R	2560-A, E 46 6 1Ni B 42 H5	SMAW
Diamondspark Ni1 RC SR	A5.29, E81T1-Ni1M-JH4	17632-A, T 50 6 1Ni P M21 1 H5	FCAW
Union S 3 Si - UV 418 TT	A5.17, F7A8-EH12K	14171-A, S 46 6 FB S3Si	SAW

TIG process has not been included in this testing campaign, considering this is mainly for root pass/tack welding (high dilution condition will not be represented by the all weld-metal constant load test).

FCAW has been preferred to GMAW because of the better usability, especially for out-of-position welding.

The mechanical properties of the selected filler materials, matches, also under the usual post weld heat treatment conditions, the requirements of the mild steel that may be selected for this application (e.g. P355 NL1)

Property	Requirement in acc. to EN 10028 for P355 NL1 steel
R_{p02}	> 355 MPa
R_m	> 490 MPa
A	> 22 %
Impact energy (transverse)	> 27 J @ -40 °C

The following testing conditions have been applied:

» High pressure hydrogen at 100 bar

» Temperature at 80 °C

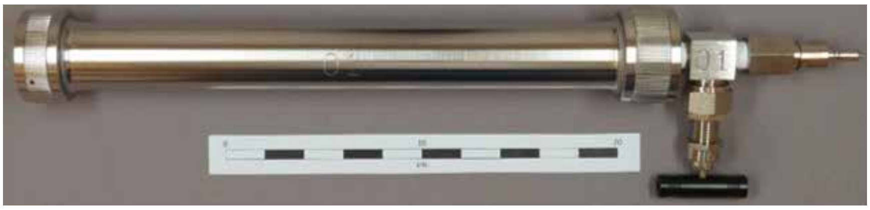
» Load equal to the yield strength of the material

» 4 weeks testing time for every specimen

» Dry (no electrolyte presence) and wet (200g/l NaCl electrolyte) conditions

The higher the temperature and the pressure, the tougher the testing condition.

In this pictures you can see the autoclave equipment used:

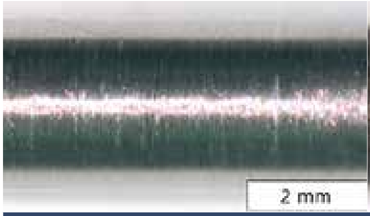
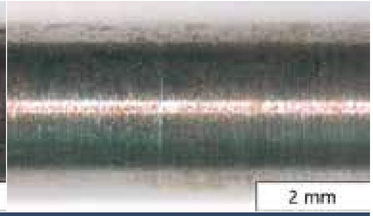
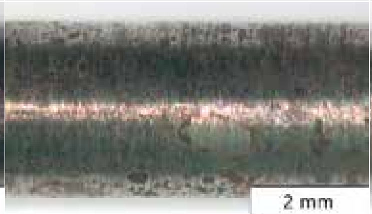
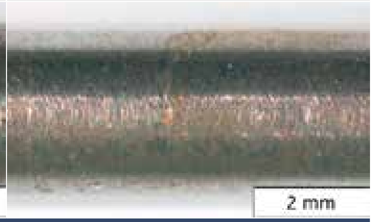
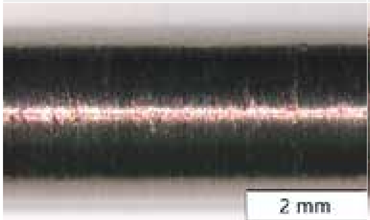
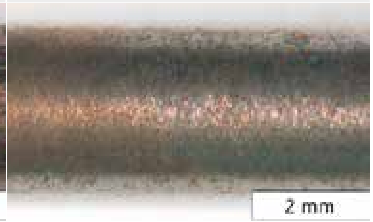


Courtesy of Montanuniversität Leoben

In the table below there are summarized the results of the test for each welding consumable.
The hydrogen content shall be intended in the specimen after completion of the test.

pH_2 @ 80 °C [bar]	Electrolyte NaCl [g/l]	Sample exposure	Fracture	Hydrogen content [ppm]
		SMAW Böhler FOX EV 60		
100	0	Gaseous	NO	0.09
100	200	Gaseous	NO	0.17
100	200	Electrolyte	NO	0.12
		FCAW diamondspark Ni1 RC SR		
100	0	Gaseous	NO	0.10
100	200	Gaseous	NO	0.09
100	200	Electrolyte	NO	0.09
		SAW Union S3Si (wire) and UV 418 TT (flux)		
100	0	Gaseous	NO	0.16
100	200	Gaseous	NO	0.19
100	200	Electrolyte	NO	0.11

Samples surface condition after testing:

<table>
<tr><th colspan="3">SMAW Böhler FOX EV 60</th></tr>
<tr><td>Gaseous</td><td>Gaseous 200 NaCl</td><td>Electrolyte 200 NaCl</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><th colspan="3">FCAW diamondspark Ni1 RC SR</th></tr>
<tr><td>Gaseous</td><td>Gaseous 200 NaCl</td><td>Electrolyte 200 NaCl</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><th colspan="3">SAW Union S3Si (wire) and UV 418 TT (flux)</th></tr>
<tr><td>Gaseous</td><td>Gaseous 200 NaCl</td><td>Electrolyte 200 NaCl</td></tr>
<tr><td></td><td></td><td></td></tr>
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It is possible to observe no fracture on all the all weld metal specimens in both dry and wet conditions.

The results confirm the low tendency to hydrogen embrittlement under H_2 gas environment of these Böhler Welding products.

BÖHLER WELDING FILLER MATERIALS FOR LIQUID HYDROGEN APPLICATIONS

Similar to natural gas, gaseous hydrogen can be liquefied by cooling at cryogenic temperature. For hydrogen, the liquefaction temperature is -253 °C.

In liquid state, hydrogen can be stored and transported in tanks that requires a lower volume compared to the gaseous state. This is a very important property when the hydrogen cannot be transported using pipelines (e.g. overseas).

Obviously, the metallic materials for the liquid hydrogen tanks manufacturing must be carefully selected, considering the operating temperature below -253 °C.

The typical choice for this application is stainless steel, due to its good toughness properties given by the austenitic structure at sub-zero temperature.

voestalpine Böhler Welding has a strong heritage in the production of stainless steel filler materials and in particular, for critical applications at cryogenic temperatures.

A comprehensive portfolio of controlled ferrite products is available and we are able to guarantee the requested impact properties for the liquefied natural gas applications.

In the ASME BPV Code, Section VIII div.1. In the part UHA-51 is defined the rules for impact testing base metals, heat affected zones and base metals, depending on the MDMT (minimum design metal temperatures) for pressure vessel constructed from high alloy steels.

The typical requirement is for the weld metal 0.38 mm of lateral expansion at -196 °C.

Welding Process	Consumable Type	Product name
SMAW	308L	**Böhler FOX EAS 2 LF**
FCAW	308L	**FOXcore 308L T1 LF**
GTAW	308L	**Thermanit JE 308L Cryo**
SAW	308L	**Thermanit JE 308L Cryo - Marathon 504**
SMAW	316L	**Böhler FOX EAS 4 LF**
FCAW	316L	**FOXcore 316L T1 LF**
GTAW	316L	**Thermanit GE 316L Cryo**
SAW	316L	**Thermanit GE 316L Cryo - Marathon 504**
GMAW	316LSi	**Thermanit GE 316L Si Cryo**

Also available and well established in the market is a welding consumables portfolio that guarantees outstanding properties at cryogenic temperatures even lower than -196 °C, under our product names Böhler ASN 5 and Thermanit 18/17 E Mn.

Product name	AWS	EN ISO Classification	Welding Process
BÖHLER FOX ASN 5	A5.4, E317L-15 (mod.)	3581-A, E 18 16 5 N L B 2 2	SMAW
Thermanit 18/17 E Mn	A5.9, ER317L(mod.)	14343-A, Z 18 16 5 N L	GTAW
Thermanit 18/17 E Mn	A5.9, ER317L(mod.)	14343-A, Z 18 16 5 N L	GMAW
Thermanit 18/17 E Mn - Marathon 104	A5.9, ER317L(mod.)	14343-A, Z 18 16 5 N L	SAW

In the table below some impact toughness results for the wire Thermanit 18/17 E Mn welded in GTAW and GMAW processes.

Process	d [mm]	Gas	KV @ -196°C [J]			L.E. @-196°C [mm]			KV @ -269°C [J]			L.E. @-269°C [mm]		
GTAW	1.6	Ar	93	81	86	1.06	0.98	1.07	88	82	81	1.03	0.87	0.89
GTAW	2.4	Ar	78	85	84	0.91	1.06	1.06	79	92	80	0.76	1.03	0.91
Process	**d [mm]**	**Gas**	**KV @ -196°C [J]**						**KV @ -269°C [J]**					
GMAW	1.2	M12	69		74		84		80		79		84	
GMAW	1.2	M13	82		84		82		82		83		83	
GMAW	1.2	M22	45		42		50		44		46		45	

When the MDMT is colder than -196 °C (-320 °F), as for the liquid hydrogen applications (where the MDMT is below -253 °C), the part UHA-51 sets some rules for the permissible welding processes (SMAW, FCAW, GMAW, SAW, PAW and GTAW) and for the toughness testing (for both PQRs qualifications and filler materials pre-use testing).

Specific requirements for the ferrite content and impact properties (e.g. 0.53 mm of lateral expansion at -196 °C) are defined when type 308L and 316L filler metals are welded in GTAW, GMAW and FCAW process.

voestalpine Bohler Welding is further improving is portfolio in order to meet the ASME requirements.

CONCLUSIONS

Thanks to its multi-purpose usage as fuel, feedstock and energy carrier, hydrogen will play a primary role in the reduction of the carbon footprint and new investments in terminals, pipelines, carriers will be necessary to support this economy.

voestalpine Böhler Welding is actively working to support its partners in this path to the reduction of emissions, investing in new product developments and testing in order to be one step ahead in this emerging market.

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Working for voestalpine Böhler Welding since 2014 with a focus on the welding consumables for the power and process industry.

Currently involved also in the welding applications related to the hydrogen storage and transportation.

voestalpine Böhler Welding
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