UNDER PRESSURE

Derrick Bauer, Ebara Elliott Energy, considers the challenges associated with the compression and transportation of high-pressure hydrogen through existing pipelines.

As one of the most promising technologies for lowering the carbon footprint on a global scale, hydrogen holds great potential for energy storage and low-carbon emission production. Technological advancements for renewable hydrogen production are currently being developed to meet near-term and long-term energy and emissions goals. To develop its full potential, however, hydrogen will have to be economically generated, and it will also have to be transmitted through the natural gas pipelines which make up the world's current energy infrastructure.

The US Infrastructure Investment and Jobs Act of 2021, and the related Inflation Reduction Act of 2022, provide for investments, policies, and incentives to accelerate clean energy initiatives, including billions for clean hydrogen. Likewise, plans to transport hydrogen throughout Europe by 2050 are already in development by the European Commission on Hydrogen.

Safe production and storage will be imperative in supporting a future hydrogen economy. As investment and progress toward production of zero and low-carbon hydrogen accelerates, efforts to solve significant technical challenges are underway.

One such challenge is the detrimental effect that hydrogen has on some industrial metals, including iron-based metals such as steels. While hydrogen does not change the mechanical design strength of these metals, it can reduce its ductility. From a fracture mechanics or fit-for-service perspective, defects that are acceptable without the presence of hydrogen may become unstable in its presence. Hydrogen can also be responsible for cracking mechanisms within metals that are completely independent of an externally applied stress.

Hydrogen embrittlement

The most efficient and economical method for transporting hydrogen will be transmission through existing pipelines. Hydrogen will be generated at atmospheric pressure, but efficient transportation and storage can only be provided at higher pressures, which will require compression. For effective storage and transportation, hydrogen needs to be compressed to a pressure of 8.273 MPa (1200 psi) which can be handled by carbon steel pipelines and pressure vessels.

In the presence of diatomic hydrogen (H_2), testing indicates that the ductility of many steels decreases in comparison to the same type of testing performed under standard atmospheric conditions.[1] This reduction in ductility is also known as hydrogen embrittlement. Because hydrogen has the smallest atomic size of any element, it can diffuse into the metal and settle at interstitial sites with the atomic arrangement of steel alloys. Once hydrogen is in the metal lattice, the hydrogen proton settles in areas of high triaxial stress, suppressing cross-slip of dislocations. This leads to an early failure and brittle appearance of the failure.

Atomic hydrogen has an even more detrimental influence on the embrittlement of steels than diatomic hydrogen. Atomic hydrogen is generated either by the dissociation of diatomic hydrogen at elevated temperatures and pressures, or by a cathodic reaction that occurs in the environment or on the surface of the steel itself. Atomic hydrogen can permeate steel alloys more readily than diatomic hydrogen and is sufficiently small to settle at interstitial sites, preventing dislocations from moving. The movement of the dislocations is really what provides the ductility to a metal.[2]

Atomic hydrogen can also settle into a void within the metal and react with another atomic hydrogen atom, combining to form a H_2 gas pocket contained within the material. As the pressure builds due to the formation of more hydrogen, internal stresses build up in the material. If this continues, the internal pressure becomes sufficiently high to create a fracture within the material itself. This mechanism is referred to as hydrogen induced cracking (HIC). This type of cracking is also called stepwise cracking, hydrogen pressure cracking, blister cracking, or hydrogen induced stepwise cracking.

NACE TM 0103 defines HIC as stepwise internal cracking that connects adjacent hydrogen blisters on different planes of the material or on the material surface. HIC is most critical on components which are pressed in a single direction, such as rolled plate and pipe. The danger of the HIC mechanism is that it can occur with no applied external stress.

There are methods to help improve the material's resistance to HIC. The first is with the steel melting practices. Reducing the level of contaminants such as sulfur and phosphorus has a significant influence by minimising the inclusions where hydrogen can settle and link up. Heat treatment minimises alloying segregation to prevent interfaces where hydrogen will link up, providing the highest fracture toughness by increasing the material's resistance to fracture.

At higher pressures and temperatures, H_2 will dissociate into atomic hydrogen which can cause problems by permeating the steel. It can preferentially react with carbon and degrade the steel. API 941 provides guidelines for steels in 'Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants'.[4] This specification states that carbon steel has been successfully utilised for hydrogen pressure vessels up to 69 MPa (10 000 psi) and temperatures up to 221°C (430°F), provided that weldments are stress relieved. The heat affected zone (HAZ) of a weldment can have a higher hardness at a localised area, so these welds must be stress relieved in order to make sure that they are not susceptible to hydrogen embrittlement.

At higher temperatures, hydrogen can permeate the steel and preferentially react with the carbides contained within the steel to form methane. The methane gas cannot escape the steel, developing a high internal pressure which can exceed the fracture toughness of the steel locally, causing blistering or fissures, again with no applied external stress acting upon the material. The addition of elements which help to form a more stable carbide, notably chromium and molybdenum, helps to avoid internal fissuring by minimising the reaction with the hydrogen. While this can help prevent internal fissuring at higher temperatures in comparison to that of carbon steel, these steels still have limitations for hydrogen service.

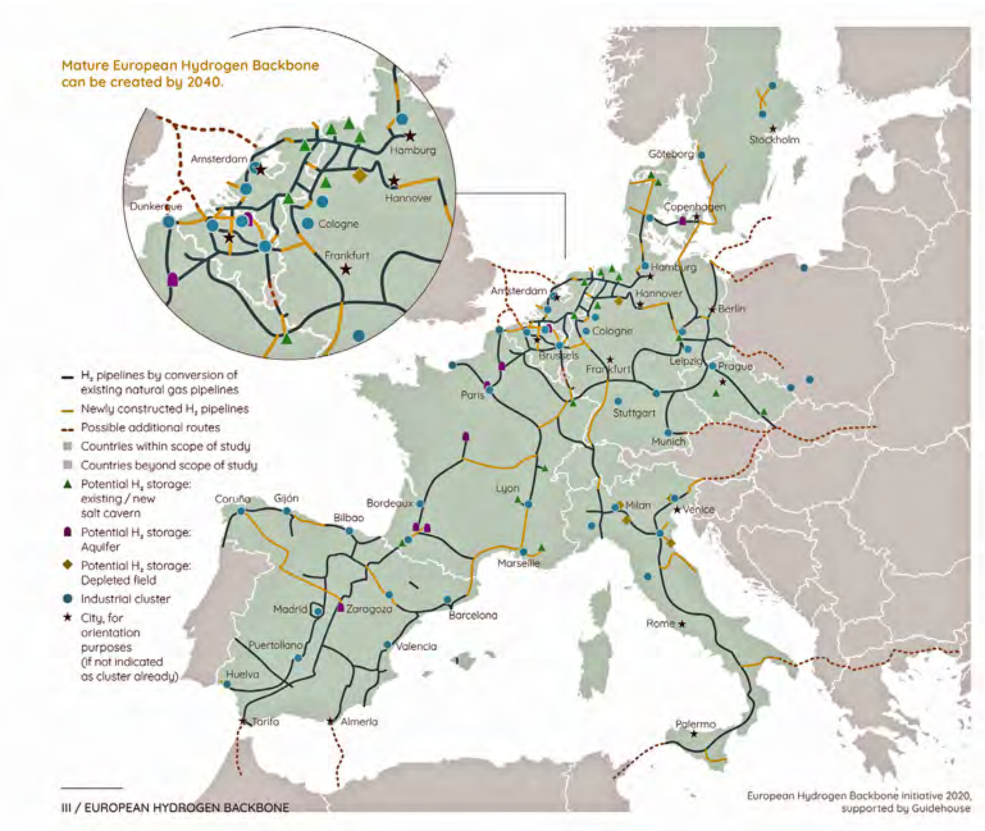

Figure 1. Plans for European Hydrogen Backbone by 2040 (with permission from the European Hydrogen Backbone Initiative).[3]

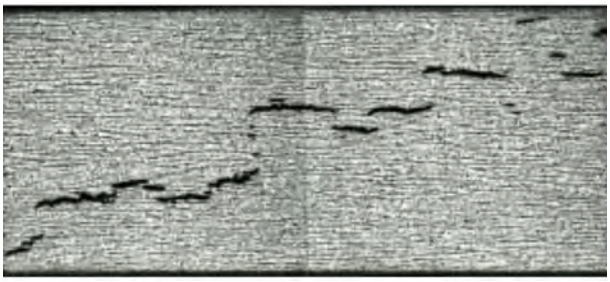

Figure 2. HIC in carbon steel under no applied stress.[5]

Figure 3. Centrifugal compressor shaft.

Compressors in hydrogen service

Hydrogen generation through any process is performed at atmospheric pressure. For improved efficiency and effective transportation through pipelines, the hydrogen must be compressed to a higher pressure. For centrifugal compressors, the requirements for rotating equipment in hydrogen service are found in API 617, which states the following:

"Materials that have a yield strength in excess of 827 MPa (120 psi) or hardness in excess of Rockwell C 34 are prohibited for use in hydrogen gas service where the partial pressure of hydrogen exceeds 689 MPa (100 psi gauge) or the hydrogen concentration exceeds 90 molar percent at any pressure."[6]

This restriction applies to all materials within a centrifugal compressor without exception. This does not have much of an influence on the casing materials which are typically carbon steel. However, the yield strength limit does influence the rotating components such as the impellers and shaft. As noted in API 941, carbon steels have been utilised at higher pressures successfully, and are commonly used for hydrogen pressure vessels. Centrifugal compressors typically operate at temperatures well below 200°C (392°F) in hydrogen service, and in many cases, high-temperature attack does not need to be considered. Carbon steel can be used for the pressure-containing casing of a centrifugal compressor and also the internal stationary components such as the diaphragms and volutes.

Low-alloy steels or martensitic stainless steels are typically used for the rotating components. The rotating compressor shaft is usually a low alloy steel such as UNS G43400 (4340 steel), and the impellers are commonly a martensitic stainless steel such as UNS S41000 (410 stainless) or UNS S17400 (17-4 PH stainless). These are used because of their high yield strength, where more corrosion resistant alloys such as austenitic stainless or even duplex stainless steels do not have the yield strength for the rotating components. The materials used for the high-stressed rotating components can be heat treated to meet the 827 MPa maximum yield strength requirement per API 617.

Other components within the compressor must also be considered. Shaft seals can be an abradable mica-filled PTFE material, or they can be a rub-tolerant material such as a carbon-filled PEEK or PAI material. The O-ring materials are usually an FKM material which has a '1' rating in hydrogen gas. At temperatures lower than 200°C (392°F), special considerations are not normally necessary for these components. The piping material is carbon steel per ASTM A106.[7]

Weldments should be stress relieved to avoid localised areas with a high hardness that could lend themselves to hydrogen embrittlement. Hydrogen in weldments has been a known problem as liquid metal has a higher affinity for hydrogen, so low hydrogen electrodes and pre-heating are often used to minimise this type of cracking. The good news is that this cracking is often detected immediately.

Hydrogen recycle gas compressors are commonly used in refineries, and they provide an excellent baseline for materials that can be used for compressors in hydrogen service. They are used in a purifying process in refineries where the H_2 recycle stream combines with makeup gas in the reactors. The process gas is over 90% H_2. However, the discharge pressure is usually less than 70 bar (1000 psi). When following the API 617 guidelines for the materials, there have not been any failures attributed to hydrogen embrittlement. Most failures in these compressors are caused by a carryover of ammonium chloride into the compressor, which is extremely corrosive, causing fouling which chokes the flow path, and corrosion pitting even on stainless steel materials. The corrosion pits act as great initiation sites for fatigue cracks, and the rotating components see many cycles of alternating stress due to the nature of the operation.

The search for higher-strength materials

There is an ongoing effort to find higher strength materials that are not subject to hydrogen embrittlement. There is no industry recognised standard for fit-for-service testing, and the development of materials and testing conditions are reviewed on a case-by-case basis. Much of this is performed through slow strain rate tensile testing in a high-pressure hydrogen chamber. Another approach is to test materials in the presence of a corrosion cell which generates atomic hydrogen.

Metals other than steels that are under consideration for hydrogen compression include titanium alloys, nickel-based alloys such as Inconel 718, and aluminium alloys. Titanium alloys are promising due to the combination of high strength and lower density. This would be ideal for rotating equipment, however, titanium can readily form hydrides which are a brittle phase. Alpha phase titanium will readily react with a hydrogen environment. Beta phase titanium has a slower reaction at temperatures below 300°C (572°F), but the beta phase has a high solubility for hydrogen. The absorbed hydrogen can raise the ductile-to-brittle transition temperature of the alloy as dislocation slip systems cannot operate effectively with hydrogen atoms at interstitial sites. In alpha-beta titanium alloys, the beta phase allows for a rapid diffusion of hydrogen to all boundaries of the alpha phase which reacts to form hydrides.

Nickel-based alloys have the ability to achieve yield strengths well above the 827 MPa (120 ksi) yield strength limit. Even with a higher density in comparison to steel, these alloys can achieve a higher strength-to-weight ratio. Nickel based alloys such as Inconel 718 have been shown to be susceptible to hydrogen embrittlement in high-pressure hydrogen atmospheres. This has only been demonstrated in laboratory testing and there is no service data to back up this claim. Aluminium alloys can experience hydrogen environment embrittlement (HEE) in a hydrogen environment in the presence of moisture. Dry H_2 does not typically show any effects upon aluminium and aluminium alloys; however, HEE can occur in the presence of liquids or liquid vapour. Aluminium is not typically utilised for hydrogen environments due to the need to keep all potential liquids out of the system.

Conclusion

Provided that the temperature is kept below 200°C (392°F), relatively standard materials currently used in hydrogen compression and transportation can be used at pressures up to 10 ksi (69 MPa). There is an extensive service history at refineries for centrifugal compressors under these conditions, and API 941 recognises that standard carbon steel can be used at these conditions. Carbon steel is used for the pressure-containing components such as the process piping and the compressor casing. Higher strength steels can be used for the rotating components under a maximum yield strength of 120 ksi (827 MPa), which provides a method to compress the hydrogen for transportation and storage. This yield strength limit provides limits for the amount of compression that can be achieved, perhaps resulting in the need for more compression stages or the number of compressor units that will be required. Efforts are underway to find a material with a higher strength that is suitable for hydrogen compression. With carbon steel being suitable for transportation of hydrogen to a maximum temperature and pressure of 221°C (430°F) and 69 MPa (10 000 psi), existing natural gas pipelines can be used. Higher pressure pipelines will require materials with more stable carbides to avoid degradation during service.

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