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Materials for Turbomachinery in Hydrogen Applications

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ABSTRACT

Centrifugal compressors are commonly utilized for hydrogen compression in refineries for critical applications, and a potential “Hydrogen Economy” to lowering the carbon footprint on a worldwide scale will require compression of hydrogen to even higher pressures. Provided that the temperature is kept below 200°C (392°F), relatively standard materials that are currently utilized in hydrogen compression and transportation can be utilized at pressures up to 69 MPa (10 ksi). There is an extensive service history of centrifugal compressors which utilize carbon steel casings in a hydrogen environment, and API 941 has recognized 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 centrifugal compressor casing. Higher strength steels can be used for the rotating components provided that they have a maximum yield strength of 827 MPa (120 ksi). While this provides a method to compress the hydrogen for transportation and storage, the yield strength requirement limits the maximum performance of the compressor and results in the need for more compression stages or additional compressors to be utilized to achieve a desired storage or transportation pressure. Efforts are underway to find a material with a higher strength that it suitable for hydrogen compression.

INTRODUCTION

Among the most promising and developed technologies for lowering the carbon footprint on a world-wide scale is through the use of hydrogen. There is a great potential for utilizing hydrogen for energy storage and low-carbon emission hydrogen production which help reduce the carbon footprint, and technological advancements for renewable hydrogen are possible for both near term and long term goals. For hydrogen to develop its full potential, it will be required that hydrogen can not only be economically generated, but it will have to be transmitted through pipelines which make up the world’s current energy infrastructure. The hydrogen will be generated at atmospheric pressure, but efficient transportation and storage of the hydrogen can only be provided at higher pressures which will have to be performed by using a compressor. Hydrogen transmission through the existing natural gas pipelines will be the most economical methods of transporting hydrogen from sites where it can be generated to all locations where it is needed. Hydrogen may be blended with methane for small volume transmission while dedicated lines will be used for higher volume hydrogen transmission in future applications. Utilizing the existing natural gas infrastructure is a far more cost effective method compared storing hydrogen in containers for transportation by rail or vehicle. The safe production and compression of hydrogen will be imperative in supporting a future hydrogen economy. The European Commission on Hydrogen economy has been making plans for pipelines to transport Hydrogen throughout the continent by 2050. For effective storage and transportation of Hydrogen, the gas needs to be compressed to a pressure of 8.273 MPa (1,200 psi) which can be handled by carbon steel pipelines and pressure vessels.

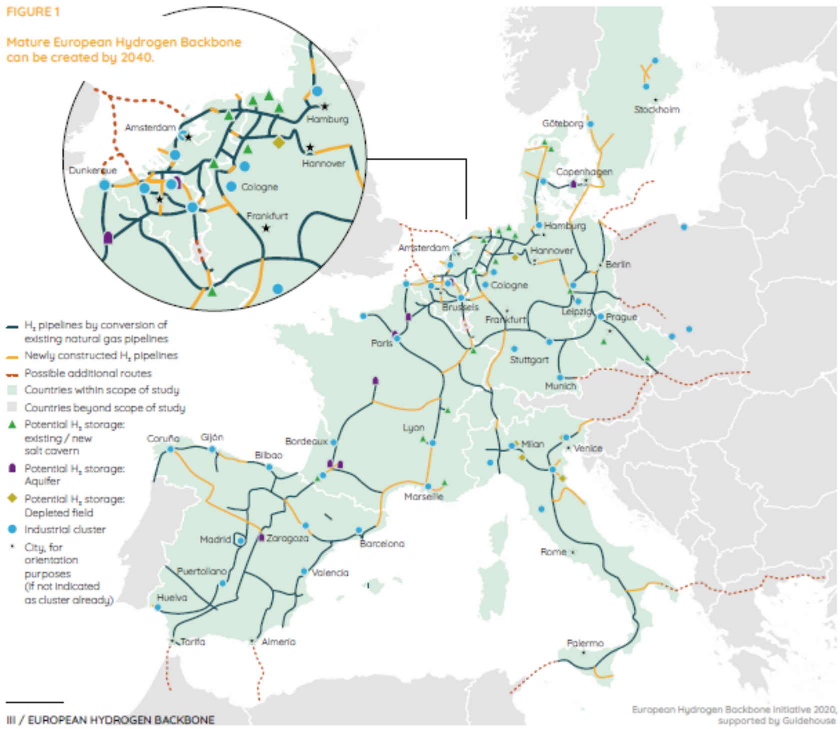


Figure 1: Plans for European Hydrogen Backbone by 2040 [1]

Hydrogen compressors have been utilized in a variety of refinery process in a number of applications. Typically their main purpose is to move feedstock through a reactor. The gas then goes through separators and then the recycle gas goes back through the compressor loop. The process gas in hydrogen recycle compressors is mainly hydrogen with small amounts of highly corrosive impurities that were not removed by the separators. Typically, the resulting discharge pressure of the hydrogen recycle compressors is less than 2.07 MPa (300 psi).

Hydrogen has been known to have a detrimental influence on metals, including iron based metals such as steels and other metals which have industrial significance. While the mechanical design strength of the material remains unchanged, the ductility of the material is what can be reduced. From a fracture mechanics or fit-for-service perspective, defects that are acceptable without the presence of hydrogen may become unstable in the presence of hydrogen. Hydrogen can also be responsible for cracking mechanisms within materials that are completely independent of an externally applied stress.

INFLUENCE OF HYDROGEN ON STEEL

In the presence of diatomic hydrogen (H_2), testing has indicated that the ductility of many steels decreases in comparison to the same type of testing performed under standard atmospheric conditions. This reduction in ductility is often called hydrogen embrittlement. Examples of this are shown in Figure 2 where the elongation of various materials is decreased with an increasing partial pressure of hydrogen [2].

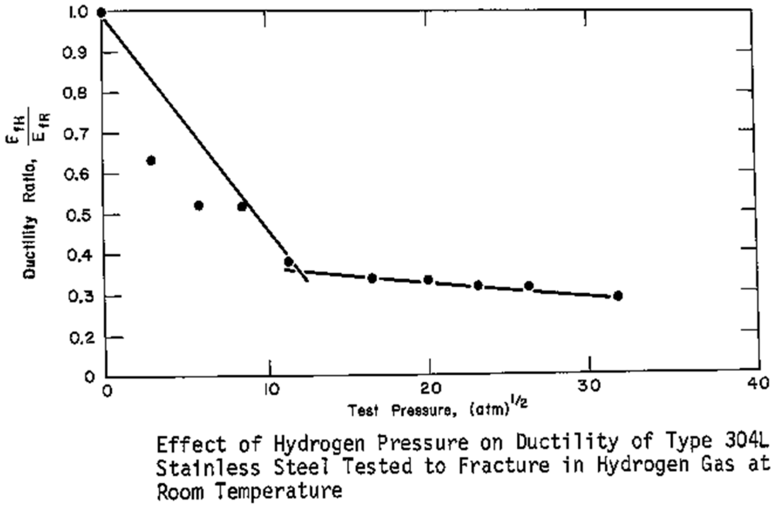


Figure 2A: Effect of Hydrogen Pressure on Ductility of 304L Stainless Steel Tested to Fracture in Hydrogen Gas at Room Temperature [2]

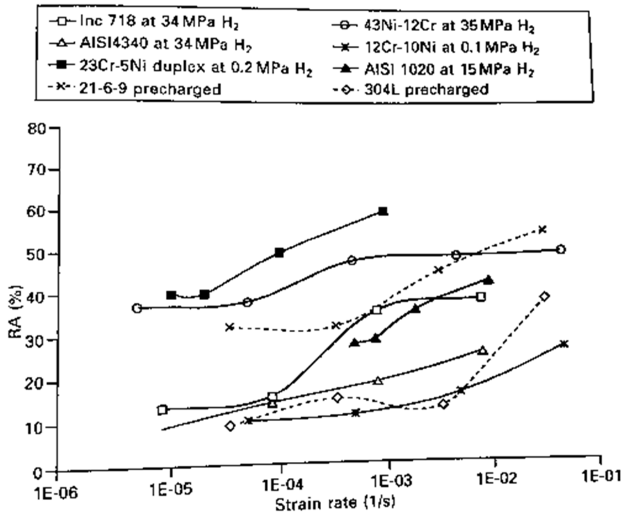


Figure 2B: Effect of strain rate on ductility in the presence of hydrogen upon various alloys[3]

The tensile strength and yield strength are not influenced by the presence of hydrogen, however, there is a reduction in the ductility of the alloy which is most noticeable at slower strain rates. At higher strain rates, the influence is not very noticeable. The reason for this reduction in ductility is that hydrogen can diffuse into the metal. Hydrogen has the smallest atomic size of any element, so it will have the highest diffusivity into a material and can settle at interstitial sites within the atomic arrangement of the alloy. Once hydrogen is in the metal lattice, the hydrogen proton settles at areas of high triaxial stress and it suppresses cross-slip of dislocations. By not allowing the dislocations within the material to move easily, this results in a resistance to movement and a lower tolerance for any type of plastic deformation. This is what creates the lower ductility of the material and can result in a brittle appearance of the failure. At slower strain rates, or a lower rate of plastic deformation, the ductility is reduced further in comparison to that of higher plastic deformation rate. At lower strain rates, the hydrogen will have more time to diffuse and settle at interstitial sites to block dislocation movements to create a further reduction in the ductility. At higher strain rates, the diffusion of the hydrogen into the material has less time to permeate the material ahead of the dislocation movement and the resulting ductility is less effective.

The influence of hydrogen on the ductility of steel can be seen by an examination of the fracture surface under a Scanning Electron Microscope (SEM). Ductile fractures caused by an overload tensile failure on carbon steel, low alloy steels and stainless steels will reveal a dimpled surface under higher magnification, which is the result of the material deforming prior to the failure. On the other hand, brittle failures will not show these dimples. The material will show a faceted surface, which is the result of the material not being able to deform prior to the fracture. An example of these fracture surfaces are shown in Figure 3. This sample of 13% Chromium – 4% Nickel stainless steel allow was allowed to fracture under a hydrogen environment. This fracture surface displays a mixed fracture surface, displaying locations of a ductile failure and other areas of a brittle fracture due to hydrogen embrittlement.

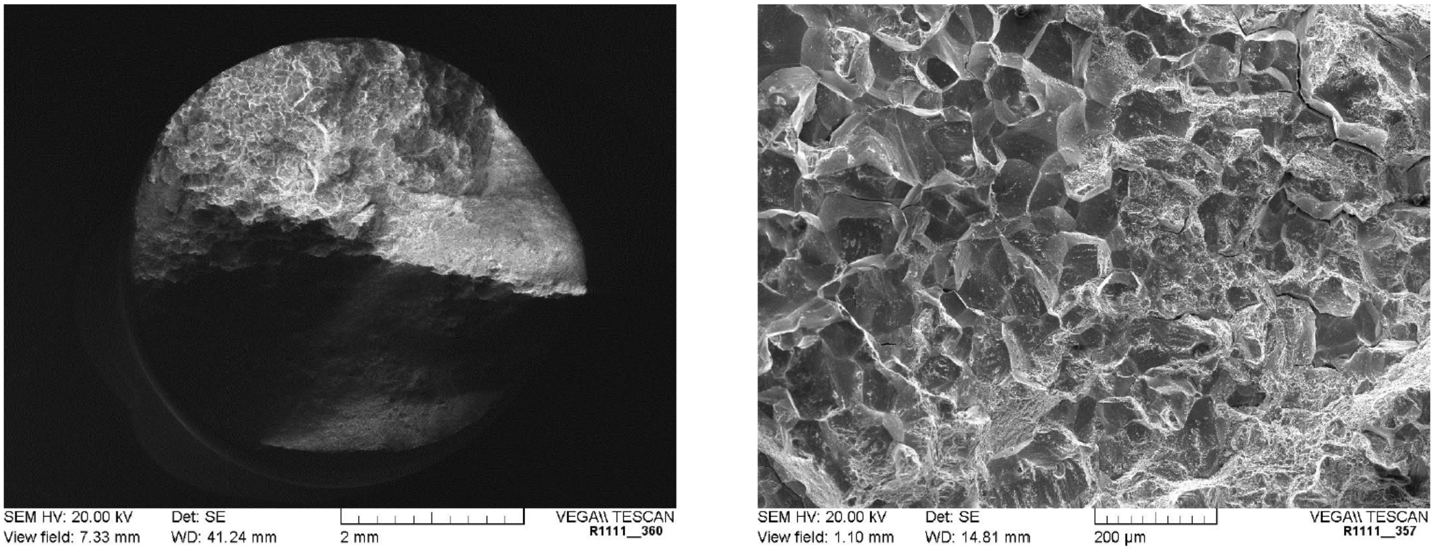


Figure 3: Tensile sample of 13% Chromium – 4% Nickel stainless steel fractured under a hydrogen environment as viewed in a Scanning Electron Microscope (SEM). The overall fracture surface is displayed on the left. A higher magnification view is given on the right which shows evidence of a faceted brittle fracture and a dimpled ductile fracture. [4]

HYDROGEN INDUCED CRACKING

A more detrimental influence on the embrittlement of steels is atomic hydrogen. Atomic hydrogen is generated either by the dissociation of diatomic hydrogen (H_2) at elevated temperatures and pressures or by a cathodic reaction that occurs in the environment or with the surface of the steel itself. The atomic hydrogen can permeate the steel even more readily than diatomic hydrogen. It is sufficiently small enough to settle at interstitial sites and does not allow dislocations to move, and the movement of the dislocations is really what provides the ductility to a metal. It 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, there are internal stresses built up in the material. If this continues, the internal pressure can build up sufficiently high to create a fracture within the material itself. This mechanism is referred to as Hydrogen Induced Cracking (HIC). This type of cracking has many different nicknames including stepwise cracking, hydrogen pressure cracking, blister cracking or hydrogen induced stepwise cracking. NACE TM0103 defines HIC as stepwise internal cracking that connect adjacent hydrogen blisters on different planes of the material or connected to the surface.

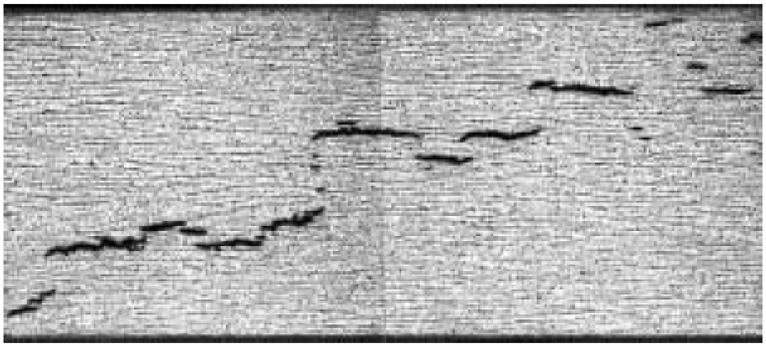


Figure 4: HIC in Carbon Steel under no Applied Stress [5]

The dangerous part of the hydrogen induced cracking mechanism is that it can occur with no applied external stress.

Hydrogen Induced Cracking is most critical on components which are processed in a single direction, such as rolled plate and pipe. The inclusions form along planes within the steel. These inclusions are elongated due to the mechanical processing, and the stress intensities at the corners of the inclusion are relatively high. When the hydrogen pressure builds up within these cracks, they can extend a crack which then links up with an extending crack on a different plane of the material and create a through-thickness crack that goes throughout the thickness of the material. This all occurs with no applied external stress. There is a test for the resistance of material to Hydrogen Induced Cracking (HIC) testing per NACE TM0284 which is titled "Standard Test Method –

Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen Induced Cracking". This testing involves the creation of atomic hydrogen though a corrosion mechanism developed by a solution containing Hydrogen Sulfide and NaOH solution as shown below in Figure 5.

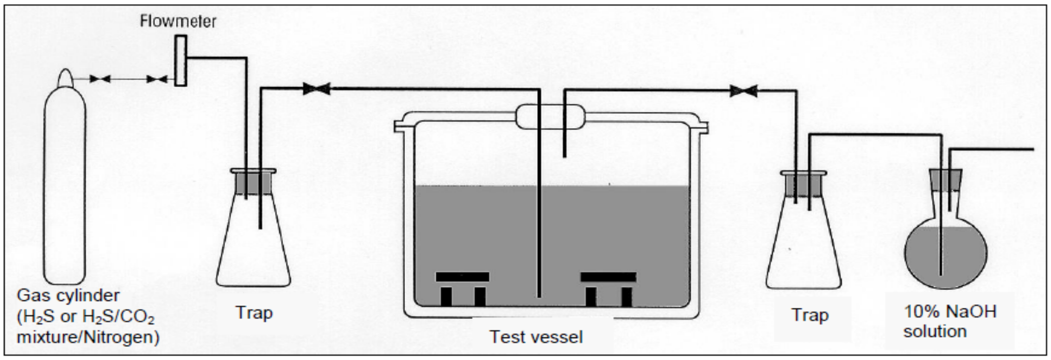


Figure 5: Schematic Diagram of NACE TM0284 Testing for HIC

Samples are cut through an entire cross-sectional sample of a plate or a piping which are separated by an inert glass rod in the testing solution. As it is impractical to test a full thickness plate in some circumstances as in the case of a compressor casing, this type of arrangement allows for a full test of the material cross-sectional thickness. These illustrations are provided in Figure 6.

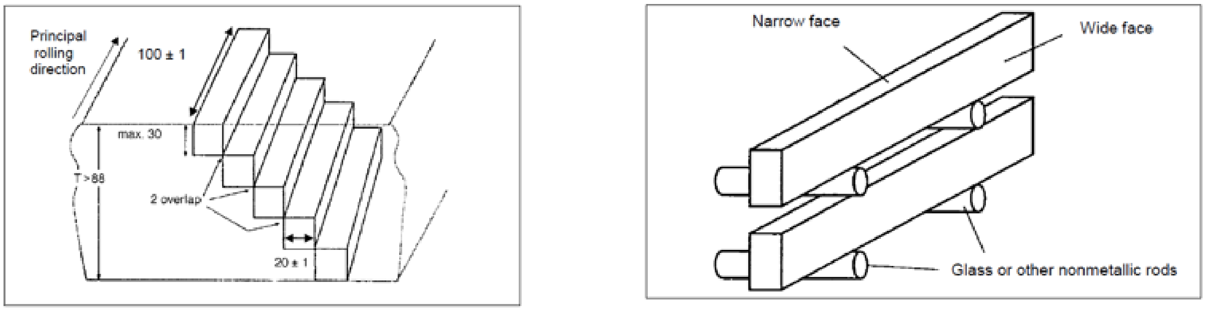


Figure 6: Cross-Sectional Samples and Setup within the test cylinder for NACE TM0284 Testing

The results of this testing are measure through the cracks that are developed within the material at any location. The samples are polished and observed through a metallograph to review the extent of the cracking. Various ratios of the length of cracks, thickness of cracks and the amount of stepwise linking of the cracks are measured as shown in Figure 7.

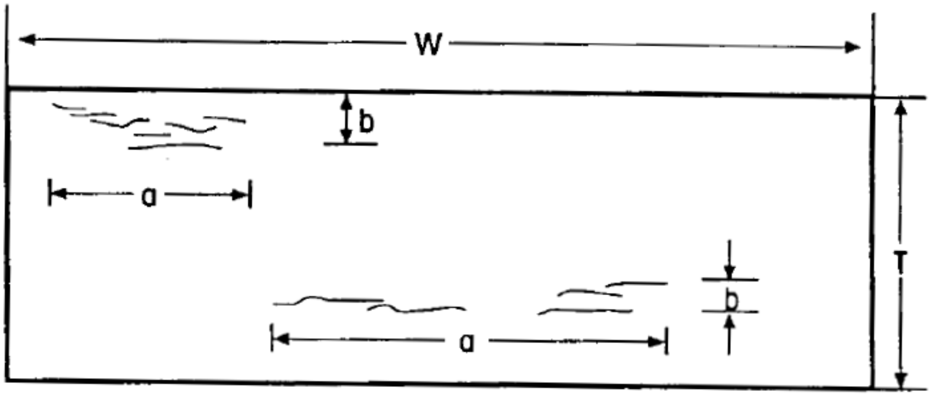


Figure 7: Illustration of crack dimensions used in evaluating test samples from NACE TM0284

Within industry standards such as API 617, there are no minimum conditions indicating when testing for resistance to Hydrogen Induced Cracking is required. When the corrosion of steel occurs under a wet hydrogen sulfide environment, atomic hydrogen can be absorbed which can lead to this type of cracking mechanism. There are many variables including the partial pressure of hydrogen sulfide and the amount of moisture within the process gas. Testing for Hydrogen Induced Cracking resistance is not a standard included for centrifugal compressor casings, although it can addressed within the customer specifications. Fortunately, there are methods to help improve the material's resistance to HIC in the presence of hydrogen sulfide. The first method involves the melting practice of the steel. Improving the cleanliness of the material has a significant influence. Keeping the level of impurity contents low, such as Sulfur and Phosphorus, will minimize the inclusions where hydrogen can settle and link up. Figure 8 shows a photomicrograph of Manganese Sulfide inclusions within the steel. These are elongated cracks with sharp crack tips that create a high stress intensity when hydrogen builds up within these locations. The heat treating can be performed to minimize alloying segregation to prevent interfaces where hydrogen will also link up. The heat treatment can be performed to provide the highest fracture toughness, basically increasing the material's resistance to fracture. An example of the resulting microstructures are shown in Figure 9.

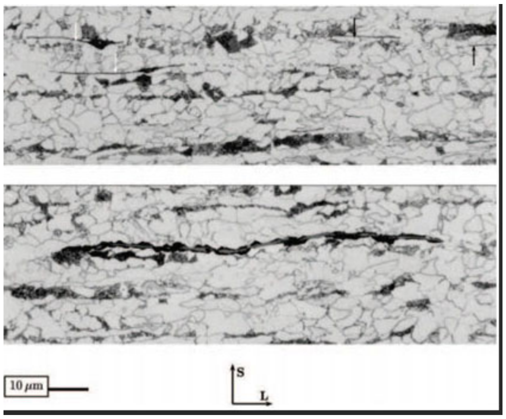
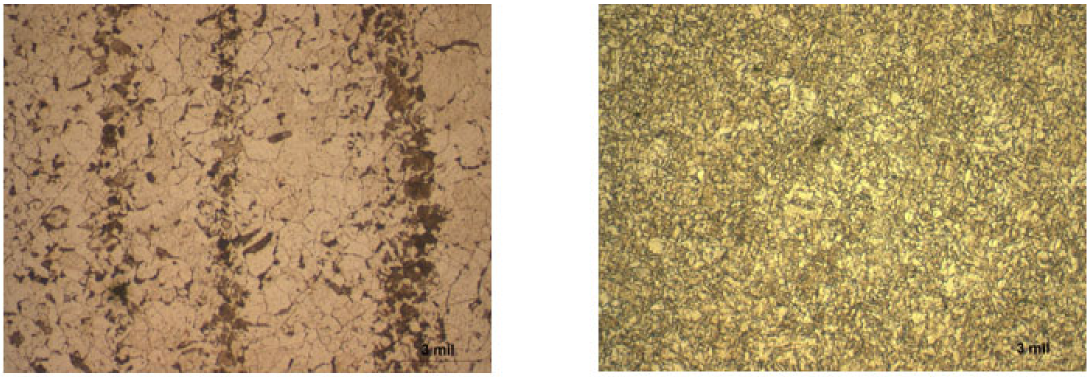


Figure 8: Manganese Sulfide inclusions within a carbon steel [6]



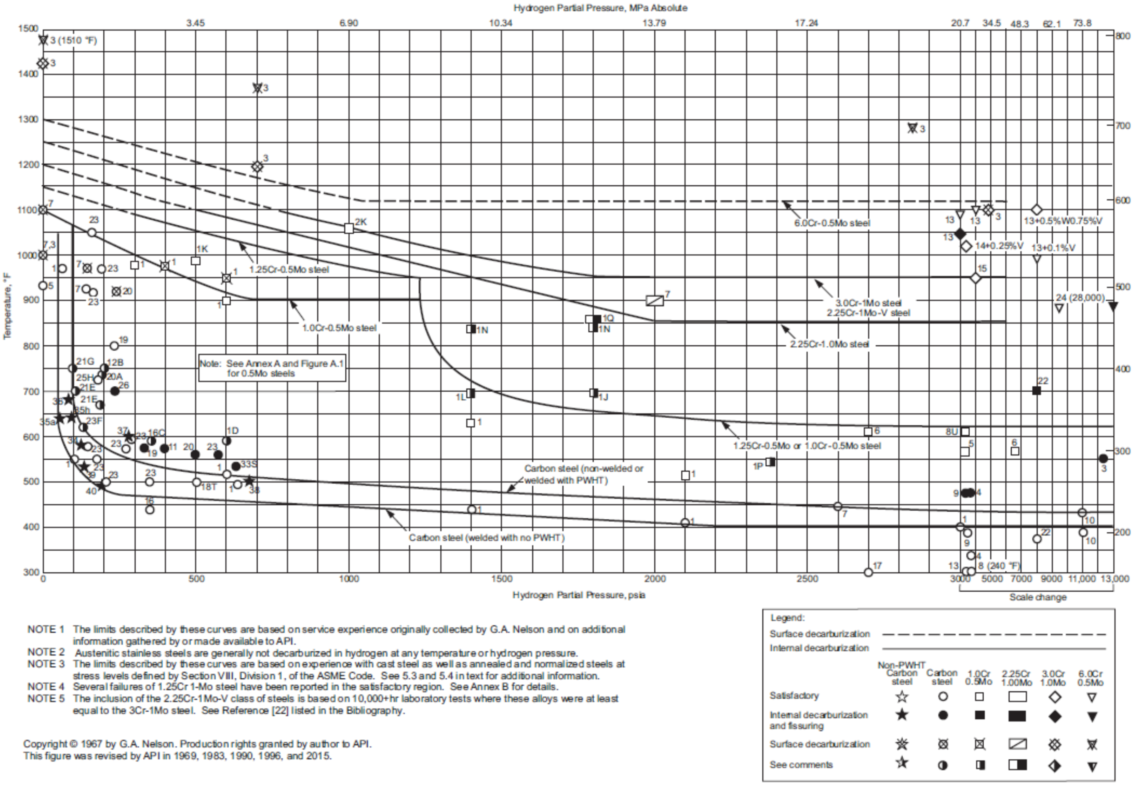
Double Normalized ASME SA516 Grade 60 Plate

Normalized + Accelerated Cooled + Tempered ASME SA516 Grade 60 Plate

Figure 9: Microstructure of ASTM A516 Grade 60 Plate After Heat Treatments

API 617 – 8th Edition does not require any specific HIC testing to be performed and it does not address the material's resistance to Hydrogen Induced Cracking. It is relatively common for customer specifications to require this testing when they hydrogen sulfide concentration is over a certain value, however, there is no industry standard minimum value for when this type of testing is required. It should also be noted that steel plate manufacturers will not guarantee that the material will pass the most stringent acceptance criteria on a Hydrogen Induced Cracking test.

At higher pressures and temperatures, H2 will dissociate into atomic hydrogen which can cause problems by permeating the steel. It can preferentially react with carbon and degrade the steel. Additions of Chromium and Molybdenum can be utilized to help prevent this at higher temperatures in comparison to that of carbon steel, however, these steels still have limitations for their service. API 941, titled Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants, provides guidelines for steels that are suitable based upon the operating temperature and the hydrogen partial pressure as shown below in Figure 10.



NOTE 1 The limits described by these curves are based on service experience originally collected by G.A. Nelson and on additional information gathered by or made available to API.

NOTE 2 Austenitic stainless steels are generally not decarburized in hydrogen at any temperature or hydrogen pressure.

NOTE 3 The limits described by these curves are based on experience with cast steel as well as annealed and normalized steels at stress levels defined by Section VIII, Division 1, of the ASME Code. See 5.3 and 5.4 in text for additional information.

NOTE 4 Several failures of 1.25Cr 1-Mo steel have been reported in the satisfactory region. See Annex B for details.

NOTE 5 The inclusion of the 2.25Cr-1Mo-V class of steels is based on 10,000+hr laboratory tests where these alloys were at least equal to the 3Cr-1Mo steel. See Reference [22] listed in the Bibliography.

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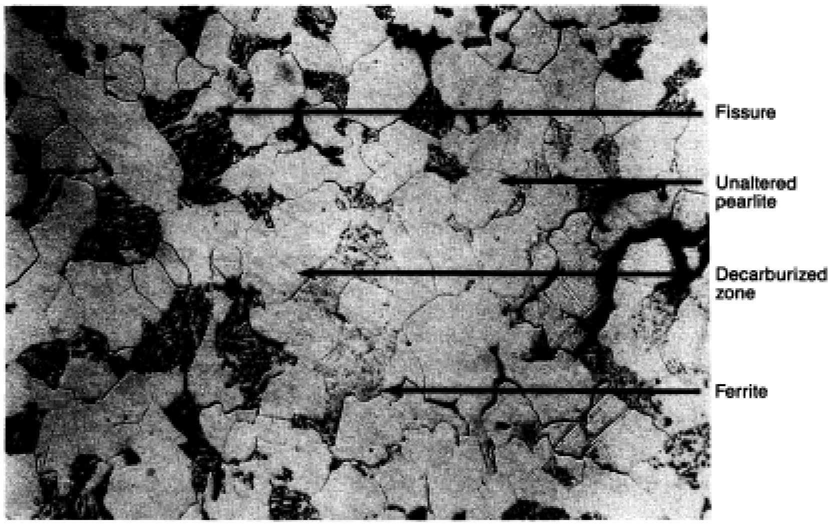
This figure was revised by API in 1969, 1983, 1990, 1996, and 2015.

Figure 10: Diagram from API 941 – Operating Limits for Steels in Hydrogen Service to Avoid Decarburization and Fissuring [5]

API 941 states that carbon steel has been successfully utilized for hydrogen pressure vessels up to 69 MPa (10,000 psi) and temperatures up to and including 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 localized area, so these welds should be stress relieved in order to ensure that they are less susceptible to hydrogen embrittlement. At higher temperatures above 250 C (480 F), the hydrogen can permeate the steel and preferentially react with the carbides contained within the steel to form methane. The pressure of the developed methane gas can not escape from the steel and becomes trapped within pockets, developing a high internal pressure which can exceed the fracture toughness of the steel locally and cause 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, help to avoid internal fissuring by minimizing the reaction with the hydrogen. In steam turbines, 2.25Cr-1Mo are used for components operating at elevated temperature to avoid graphitization of the carbides during long term exposure to the temperatures. The photomicrograph provided below in Figure 11 illustrates the microstructural damage that can occur within steels at elevated temperatures in hydrogen service.



Notes:
1. Service conditions were 65,000 hours in a catalytic reformer at a temperature of 790°F (421°C) and a hydrogen partial pressure of 425 pounds per square inch absolute (2.93 megapascals).
2. Magnification: × 520; nital etched.

Figure 5—C-0.5Mo Steel (ASTM A 204-A) Showing Internal Decarburization and Fissuring in Hydrogen Service

Figure 11 – Internal Decarburization and Fissuring of Steel in Elevated Temperature Hydrogen Service [5]

MATERIALS FOR COMPRESSORS

When hydrogen is generated through any process such as electrolysis from water, this will be performed at atmospheric pressure. For improved efficiency and effective transportation through pipelines, the hydrogen will have to be compressed to a higher pressure through the use of a compressor. While the previous section discussed Hydrogen Induced Cracking and conformance to NACE specification, there are additional requirements included in API 617-8th Edition for centrifugal compressors that directly address rotating, highly stressed components such as impellers. In API 617-8th Edition Paragraph 4.5.1.11, it states the following:

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

This restriction is applied to all materials within a centrifugal compressor, there are no exceptions. On the casing materials which are typically carbon steel, this does not really have much of an influence. The yield strength limit does influence the rotating components such as the impellers and the shaft. As previously mentioned in API 941, carbon steels have been utilized at higher pressures successfully and are commonly used for hydrogen pressure vessels. Centrifugal compressors typically do 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 utilized for the pressure-containing casing of the centrifugal compressor and the internal stationary components such as the diaphragms and volutes.

The alloys typically utilized for the rotating components are low alloy steels or martensitic stainless steels. The rotating compressor shaft is usually a low alloy steel such as UNS G43400 (4340 steel), and the impeller are commonly a martensitic stainless steel such as UNS S41000 (410 stainless) or UNS S17400 (17-4 PH stainless steel). 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 centrifugal compressor impellers are often “closed” impellers, containing both a hub and a cover with a complicated blade geometry. These impellers have typically been manufactured through welded construction which requires a thermal stress relief to reduce the hardness of the hard heat affected zone (HAZ). Centrifugal compressor impellers have been increasingly manufactured from 1-piece methods due to advancements in 5-axis machining and plunge Electrical Discharge Machining (EDM). Even with 1-piece construction on impeller, weld repairs to correct machining errors such as tool gouges or service damages are necessary. The alloys utilized for the highly stressed rotating components can be heat treated to meet the 827 MPa (120 ksi) maximum yield strength requirement per API 617.

Figure 12: Picture of centrifugal compressor rotor

Other components (such as stationary seals, o-rings) within the compressor need to be considered as well. 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 a PAI material. The O-ring materials are usually an FKM material which has a "1" rating in hydrogen gas. At lower temperatures below 200°C (392°F), special considerations are not normally necessary for these components.

Similar to NACE requirements, the piping material is carbon steel per ASTM A106 and weldments should be stress relieved to avoid localized 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 is often used to minimize this type of cracking. The good news is that this cracking is often detected immediately during non-destructive inspection of the component such as liquid penetrant inspection or magnetic particle inspection prior to assembly.

Hydrogen recycle gas compressors have been commonly utilized in refineries, and they provide an excellent baseline for materials that can be used for compressors in hydrogen service. This is used in a purifying process in refineries where H2 recycle stream combines with makeup gas in the reactors. The process gas is over 90% H2, however, the discharge pressure is usually less than 70 bar (1,000 psi). When following the guidelines within API 617 for the materials, there have not been any documented failures attributed to hydrogen embrittlement.

EVALUATION OF HIGHER STRENGTH MATERIALS

There is an effort by a number of companies to find higher strength materials that are not subjected to hydrogen embrittlement. There is no industry-recognized standard set as a fit-for-service testing and the development is of the 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 test materials in the presence of a corrosion cell which generates atomic hydrogen. Nickel based alloys such as Inconel 718 material has demonstrated a resistance to hydrogen embrittlement even with a yield strength exceeding 827 MPa (120 ksi), however this has only been demonstrated in laboratory testing and there is no service data to support this claim. Titanium alloys with their combination of high strength and low density would ideally be promising. This would be a significant benefit for rotating equipment, however, Titanium can readily form hydrides which are a brittle phase. Alpha phase titanium will readily react in a hydrogen environment. The Beta phase has a slower reaction at temperatures below 300°C (572°F), however, 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 can not 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.

Aluminum alloys can experience Hydrogen Environment Embrittlement (HEE) in a Hydrogen environment in the presence of moisture. Dry H2 does not typically show negative influence upon the mechanical properties of Aluminum and Aluminum alloys, however, hydrogen environment embrittlement can occur in the presence of liquids or liquid vapor. If a pure aluminum oxide (Al_2O_3) layer is not present, the atomic hydrogen can be directly generated by the interaction of moisture with the aluminum. The absorption of the atomic hydrogen by the aluminum alloy can lead to cracking similar to HIC in steels, and this mechanism is referred to as Hydrogen Environmental Embrittlement. Aluminum can only be utilized for hydrogen environments in the absence of moisture to avoid this embrittlement mechanism. Surface treatments such as anodizing can be used to help create a more complete aluminum oxide barrier on the surface of the aluminum alloy, and surface coatings can be utilized to act as a barrier that does not allow moisture to directly contact the aluminum.

For the ease of transportation of hydrogen, hydrogen can be mixed with hydrocarbons and introduced into existing natural gas pipelines. The key benefit to blending hydrogen with hydrocarbons is that it can allow the transportation of hydrogen within existing pipelines without the need for new dedicated pipelines, however, the hydrogen would have to be separated from the hydrocarbon gas at the source. Ammonia, chemical symbol NH_3, has also been included in this discussion as it is a good carrier of hydrogen. The ammonia would have to be used directly within a fuel cell or be processed at the source to generate hydrogen. When hydrogen is blended with a hydrocarbon gas or when transported as ammonia, standard carbon steel piping material can be successfully utilized. Ammonia is not generally corrosive to carbon steel as it can have a corrosion rate under 0.05 mm/year (0.002 inches/year) if liquid water is kept out of the system. Carbon steel pipelines or storage tanks can be effectively utilized for ammonia transportation.

COATINGS FOR HYDROGEN APPLICATIONS

As previously discussed, diatomic hydrogen does not present a corrosion concern for many common materials utilized in hydrogen compressors and transportation. When the guidelines set by API 617 – 8th Edition have been followed for controlling the maximum yield strength, all grades of steels including carbon steel, low-alloy steel and stainless steels have proven to be suitable in these applications without the need to apply a functional coating. Aluminum alloys in hydrogen gas, assuming moisture is not present, and Nickel-based alloys have also had successful service applications in hydrogen gas. With any alloy, the yield strength limit of 827 MPa (120 ksi) still applies to the critical compressor components. The yield strength limit controls the maximum spin speed that can be achieved by the impeller, and thus limits the amount of compression that can be achieved at each compressor stage. Unfortunately, there is no coating that can be applied which will allow the use of higher-strength materials to be used for these compressor components. In all cases, the base material itself must be suitable for the hydrogen environment and it can not rely on a functional coating to make it suitlable for the application.

In order for a functional coating to be effective, it must act as a barrier between the substrate and the environment. By not allowing the environment to contact the coated surface, any potential corrosion or embrittlement reactions will be avoided. Because hydrogen is an extremely small molecule, there are no materials or coatings that will prevent the eventual permeation of hydrogen throughout coating and eventually contact the base material. High-strength alloys with a yield strength over 827 MPa (120 ksi) and Titanium alloys with a high strength-to-weight ratio can not rely on a functional coating in this environment. In the cases where atomic hydrogen is generated due to a corrosion reaction within the process, the application of coatings are even less effective. Atomic hydrogen is simply a proton which is smaller than the lattice spacing between two atoms, so there are no known materials available today that will prevent permeation under these conditions. Since hydrogen will permeate through any coating and coatings can be compromised due to mechanical damage or possible adhesion issues, the base material of all compressor components must be suitable for the hydrogen environment.

For hydrogen recycle compressors, there is a surprising need for the use of coatings to prevent impeller failures as this is a highly corrosive service. Most failures in these compressors come from a carryover of ammonium chloride into the compressor. During the reforming process, hydrogen reacts with impurities to form ammonia and hydrochloric acid, and these two substances react to from ammonium chloride. The ammonium chloride carryover is highly corrosive and creates corrosion pitting even on stainless steel materials. The rotating components are exposed to a high number of cycles of alternating stress due to the nature of the operation. The corrosion pits act as great initiation sites for high cycle fatigue cracks. Additionally, the ammonium chloride deposits on the surfaces creating fouling issues by restricting the flow path of the compressor. An example of the ammonium chloride deposits and the resulting corrosion pitting damage are shown in Figure 13.

Figure 13: Ammonium Chloride Deposits and Corrosion Pitting on a Hydrogen Recycle Compressor

Most of the commonly available coatings for compressor applications are intended for preventing foulant build-up in hydrocarbon service. These coatings include an aluminum filled ceramic base layer for corrosion protection, a bond layer and a topcoat of a polytetrafluoroethylene (PTFE or Teflon) topcoat which provides a non-stick coating. An example of this is given in Figure 14. There have been variations to this type of coating throughout the industry, most of which involve the application of a different type of topcoat to make a more effective anti-stick coating for hydrocarbon deposits.

Figure 14: Picture of a coated centrifugal compressor rotor (left) and a photomicrograph of the coating layers (right)

Testing for resistance to ammonium chloride fouling and corrosion involves the development of a coating which provides a better anti-stick properties in comparison to PTFE topcoats and does not allow the permeation of the ammonium chlorides below the topcoat of the coating. The ammonium chloride will chemically react with the base layer of these coatings and remove the topcoat in the adjacent areas, starting a reaction that causes the coating to be removed. Efforts to provide a more suitable coating for hydrogen recycle compressors have resulted in testing methods being developed for ammonium chloride fouling along with corrosion resistance testing in saturated ammonium chloride solutions.

CONCLUSIONS

- Provided that the temperature is kept below 200°C (392°F), relatively standard materials that are currently utilized in hydrogen compression and transportation can be utilized at pressures up to 10 ksi (69 MPa).
- 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 utilized. Higher pressure pipelines will require materials with more stable carbides to avoid degradation during service.
- For centrifugal compressors, there is an extensive service history at refineries for compressors in hydrogen environments, and API 941 has recognized that standard carbon steel can be used at these conditions. API 617 for centrifugal compressors provides limits to the maximum yield strength of a material in hydrogen service, and there is a proven service history for compressors under these operation conditions. Carbon steel is used for the pressure-containing components such as the process piping and the centrifugal compressor casing. Higher strength steels can be used for the rotating components which are kept 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 does provides limits for the amount of compression which can be achieved, perhaps resulting the need for more compression stages or a number of compressor units that will need to be utilized.
- The more significant concern for centrifugal compressors are corrosive constituents within the process gas that can generate atomic hydrogen during a corrosion reaction. Coatings can be utilized to help minimize the corrosion effects caused these corrosive constituents and prevent fouling on the internal surfaces of the compressor. Test methods for determining a material's resistance to hydrogen induced cracking such as NACE TM0284 are available, there is no industry standard that defines when these test methods should be implemented.
- Efforts are underway to find a material with a higher strength that it suitable for hydrogen compression, however, there are no officially recognized standards for the acceptance of higher strength materials. Slow strain rate tensile testing is an H_2 environment chamber or testing in a corrosion cell which generates atomic hydrogen can simulate process environments. Nickel based alloys such as Inconel 718 have displayed resistance to hydrogen induced cracking under these environments, and Aluminum alloys have shown resistance if moisture is not present.

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