

Laboratory Testing to Investigate if Coated Pipelines are Safe for Transportation of Hydrogen Gas

Amal Al-Borno, Ph.D.
Charter Coating Service (2000) Ltd
No. 6, 4604 - 13 Street N.E
Calgary, Alberta T2E 6P1, Canada

Jeffrey Rogozinski, Ph.D.
Sherwin-Williams
1101 S. 3rd Street,
Minneapolis, MN 55415, USA

Jigar K. Mistry, Ph.D.
Sherwin-Williams
1101 S. 3rd Street,
Minneapolis, MN 55415, USA

Yuan Li, Ph.D.
Charter Coating Service (2000) Ltd
No. 6, 4604 - 13 Street N.E
Calgary, Alberta T2E 6P1, Canada

Moavin Islam, Ph.D.
Corrosion Forensics LLC
43782 Tolamac Drive
Ashburn, VA 20147, USA

ABSTRACT

Hydrogen is gaining momentum as the centerpiece of clean energy initiatives in many countries and may hold the key to the inevitable and needed transition from fossil fuels to renewable energy. It is estimated by various sources that the global economic impact would be about \$1T (one trillion dollars) by the year 2035. Hydrogen can be extracted from natural gas and other fossil fuels commonly known as “blue” hydrogen, or from renewable energy sources or from water by electrolysis, termed “green” hydrogen.

The known deleterious effects of H₂ on high strength pipeline steel (embrittlement, decrease in ductility, acceleration of fatigue crack growth, etc.) makes it a potential challenge for economic and safe transportation of hydrogen gas from the production source to the end user.

This study presents the test protocol designed to investigate if internal coatings can help mitigate the deleterious interaction between pipeline steel and hydrogen. Test results of six coating systems vs bare (uncoated) metal are presented and discussed based on their impact on mechanical properties of X-80 pipeline steel (yield strength, ultimate tensile strength, % elongation, and % reduction of area).

Key words: Gas Pipelines, Coatings, Hydrogen Embrittlement (HE), API X-80 steel.

INTRODUCTION

Governments and energy companies are increasingly looking at hydrogen as an alternative to fossil fuels, and it is considered that without hydrogen the world cannot aim to be a net zero carbon economy by 2050¹. Consequently, hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. Combustion of hydrogen does not produce greenhouse gases such as carbon dioxide and methane, particulates, sulfur oxides or ground level ozone². Thus, hydrogen offers ways to decarbonize a range of sectors, as well as help improve air quality and strengthen energy security.

Due to its low density, hydrogen is hard to store on a large scale or transport via road or ship, but it flows about three times faster than natural gas in pipelines, making them a good option for large-scale transport, according to the U.S. Department of Energy. That means oil-and-gas companies can use their existing pipeline infrastructure or add pipes to it, to transport the fuel.

For large volumes and long distances, transportation via pipelines to large energy consumers is the most financially attractive alternative^{3,4}. Additionally, blending hydrogen into natural gas has been proposed as a mean of delivering pure hydrogen to markets, by using separation and purification technologies downstream to extract hydrogen from the natural gas/hydrogen blend close to the point of end use⁵. Blending hydrogen would provide a boost to hydrogen supply technologies without incurring the investment costs and risks of developing new hydrogen transmission and distribution infrastructure².

The main concern in transporting hydrogen in steel in pipelines is embrittlement. The term hydrogen embrittlement (HE) encompasses a wide range of the deleterious effects that have been associated with hydrogen on materials. HE is a known failure mechanism, primarily based on experience with “sour” hydrocarbons containing high hydrogen sulfide content. Causes of embrittlement are mainly related to the pipeline material and operating conditions, including hydrogen concentration. HE is characterized by a loss of ductility due to hydrogen diffusion into surface flaws resulting in increased sensitivity to fatigue. It is a time-dependent phenomenon with failure occurring at stress levels well below the yield limit^{6,7}. Higher pressures increase the risk of embrittlement.

Although there is agreement that hydrogen does not affect elastic properties of materials, it is recognized that hydrogen affects mechanical properties of both low- and high-strength materials, and the effect can be characterized by loss in ductility, reduction in strength, reduction in fracture toughness, and enhanced crack growth. It is reported in the literature⁸ that hydrogen gas degrades the tensile ductility of carbon steels, particularly in the presence of stress concentrations. Additionally, hydrogen gas lowers fracture toughness, and certain metallurgical conditions can render the steels susceptible to crack extension under static loading. Hydrogen gas also accelerates fatigue crack growth, even at relatively low hydrogen gas partial pressures, suggesting that small fractions of hydrogen in gas blends must be considered in fatigue life assessments.

There is consensus among researchers that hydrogen effects depend on a wide range of factors among them exposure time, type of environment, temperature, pressure, stress level and state, properties of material, microstructure, hydrogen concentration, surface conditions, diffusion rates, etc., indicating that hydrogen effects are complex and remain elusive despite decades of research that this topic has been studied⁹.

In general, the higher strength steels (API X-70 and above) tend to be more susceptible to hydrogen attack compared to the lower grade steels such as API X-42 and API X-52. Research results¹⁰ indicate that X-80 pipeline steel is susceptible to hydrogen-induced embrittlement in natural gas/hydrogen mixtures and the HE susceptibility increases with the hydrogen partial pressure. Additionally, the HE susceptibility depends on the textured microstructure caused by hot rolling, especially for notched specimens. The design calculation by measured fatigue data reveals that the fatigue life of the X80 steel pipeline is dramatically degraded by the added hydrogen.

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Mechanism of Hydrogen Embrittlement (HE)

Numerous mechanisms have been proposed for HE, but a detailed discussion is beyond the scope of this paper. Excellent reviews of these mechanisms are available in the literature.¹¹⁻¹³ In simple terms, when a susceptible steel is exposed to a H₂ environment, the H₂ molecules dissociate into H⁺ atoms and gets adsorbed on the steel surface. The atomic hydrogen can then enter the steel matrix and can get trapped at grain boundaries, dislocations, voids, and defects in the steel (Figure 1). The H atoms recombine to form molecular H₂ gas, which build up pressure and lead to blisters and cracks depending on the existing conditions, thus effecting the mechanical properties of the steel.

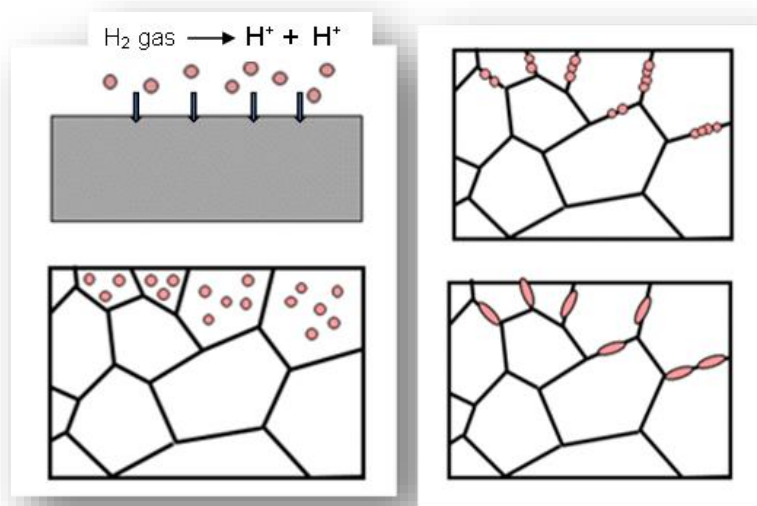


Figure 1. Hydrogen Entry into Steel

Options for Preventing or Controlling HE

A combination of steel grade and operating pressure can be suitably selected for safer operation in transporting hydrogen via pipelines. If using existing pipelines, the pressure may need to be reduced if embrittlement is found to be a potential issue. As mentioned earlier, embrittlement is more pronounced in higher strength steels. Indeed, the design of existing hydrogen pipelines is based on steel with low yield strengths and with low carbon and manganese content⁷.

Another possible option of preventing or controlling HE may be the use of specialty coatings on the internal surface of the pipeline, which does not appear to have been investigated previously. Of course, the application of such coatings on existing pipelines would be challenging and uneconomical, and hence the coating application must be done at the manufacturing stage.

Present Study

This study presents the test protocol which was designed to investigate if internal coatings can help mitigate the deleterious interaction between pipeline steel and hydrogen. Test results of six coating systems vs bare (uncoated) metal are presented and discussed based on their impact on the mechanical properties (yield strength, ultimate tensile strength, % elongation, and % reduction of area) of API X-80 pipeline steel

EXPERIMENTAL PROCEDURE

The experimental program consisted of conducting tensile tests in air on specimens of uncoated bare steel and steel coated with selected coatings to determine their mechanical properties. A second set of uncoated bare steel and coated steel specimens were exposed to 100% H₂ gas at 3000 psi (20.68 MPa) at ambient temperature in an autoclave for 30 days. Tensile tests were conducted on the autoclaved specimens and the values of the mechanical properties were compared to those obtained in air.

Coating Systems Selected

Six (6) coating systems were selected for the study as listed in Table 1 which shows the type of coating, and the dry film thickness (DFT) range in each case. All coatings were applied as per coating specifications on sand blasted tensile samples (see below for details of tensile specimens).

Table 1. Details of Selected Coating Systems

Coating System	Coating Description	DFT Range Min - Max (mils)
#1	FBE Powder with high Tg	12 – 20
#2	FBE Powder	12 – 20
#3	Polyamide Powder	10 – 20
#4	Epoxy Siloxane Hybrid - Liquid Coating	8 – 15
#5	Ceramic and Glass Flake Novolac - Phenolic Liquid Coating	70 – 100
#6	PTFE reinforced Novolac based - Liquid Coating	70 – 100

Test Protocol

To evaluate whether a coating can effectively prevent or control HE in the substrate steel, the following Test Protocol was used:

1. Test specimens were fabricated from high strength carbon steel (API X-80) which is known to be prone to HE¹⁰. The chemical composition of the steel was not determined in this study. However, the typical composition of API X-80 steel available in the literature. As given in Table 2.

Table 2. Typical Composition of API X-80 Steel

Steel Grade	Composition (%)								
	C max	Si max	Mn max	P max	S max	Al min	Mo max	Ni max	Nb max
API X80	0.08	0.26	1.75	0.011	0.0005	0.03	0.27	0.22	0.070

The test specimens were in the form of machined tensile cylindrical samples fabricated as per guidelines in ANSI/NACE TM 0177-2016^A (modified) and shown in Figure 2 below.

^A ANSI/NACE TM 0177-2016 “Standard Test Method – Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H₂S Environments,” NACE International, Houston, TX.