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Development of methods for evaluating hydrogen compatibility and suitability

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ABSTRACT

The embrittlement of metals exposed to hydrogen environments is well documented. With the deployment of hydrogen fuel cell vehicles in the consumer sector, there is a need to improve the engineering basis for the selection of materials of construction for equipment that stores and distributes high-pressure gaseous hydrogen. This brief overview summarizes publicly available guidance for evaluating materials compatibility with high-pressure gaseous hydrogen. Additionally, a new standard for measuring engineering data in gaseous hydrogen and evaluating materials suitability for service in gaseous hydrogen is introduced: the CHMC1 standard provides a general framework for qualifying materials for hydrogen service. The CHCM1 standard is unique in its broad scope and performance-based strategy for quantitatively assessing materials in their service environment and for the intended structural requirements.

Introduction

Hydrogen embrittlement is an important phenomenon that can strongly impact the performance of systems for the storage and delivery of gaseous hydrogen [1], including fuel cell vehicles and their refueling systems. As markets for other fuel cell systems grow (such as hydrogen-powered forklifts and stationary backup power modules), there is a need for robust strategies to accommodate hydrogen embrittlement in a variety of hydrogen systems. Materials selection and qualification for gaseous hydrogen service must recognize that susceptibility to hydrogen embrittlement depends on numerous variables such as hydrogen gas pressure, temperature and applied stress. Furthermore, materials qualification should not necessarily be restricted to demonstrating immunity to hydrogen embrittlement. In the broadest sense, the objective of materials qualification is to quantify susceptibility to hydrogen embrittlement using accepted design-relevant metrics (e.g., fracture toughness and fatigue strength), and then to employ these metrics in engineering designs to define limits on allowable operating conditions (e.g., gas pressure, temperature, stress).

Qualification of materials for hydrogen service can be thought of as a two-step process: (1) *hydrogen compatibility*, measurement of materials properties or performance in the relevant environment(s); followed by (2) *hydrogen suitability*, analysis to determine appropriateness of the materials properties in a given design and for intended service conditions. These two steps can also be thought of as materials evaluation (compatibility) and component evaluation (suitability). While compatibility testing can sometimes be sufficient to address hydrogen embrittlement, hydrogen compatibility alone is generally overly restrictive for qualifying materials for

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hydrogen service. Transportable gas cylinders, for example, are safe and reliable in hydrogen environments, even though the Cr–Mo steel from which they are constructed is susceptible to hydrogen embrittlement. Although materials compatibility alone would suggest that these materials should not be used with gaseous hydrogen, suitability of Cr–Mo steel for the specific application of transportable hydrogen pressure vessels can be established by engineering analysis. Conversely, hydrogen compatibility testing or experience should not be assumed to be transferrable or applied haphazardly; the fact that Cr–Mo steel is appropriate for transporting gaseous hydrogen in gas cylinders does not necessarily make it appropriate for other hydrogen applications.

A number of codes and standards exist for qualifying materials for hydrogen service, especially for hydrogen pressure vessels. There remains, however, a need for standardized methods for qualifying materials for other components, in particular for components such as valves, pressure relief devices, regulators and metering devices. The CHMC1 standard from CSA Group attempts to fill this gap in materials qualification methods. The bulk of this overview is a description of this relatively new standard; the authors are part of the Technical Advisory Group (TAG) that developed the CHMC1 standard.

Prior to a discussion of the CHMC1 standard, we briefly sketch the landscape of documents that address materials selection and qualification for hydrogen service. Due to the limited resources for evaluation of hydrogen embrittlement, the nascent hydrogen-energy industry relies to some degree on reference documents that include general guidance on materials selection for hydrogen service. We begin with a list of the more common, publicly available reference documents that include discussion of materials selection. Several codes and standards that receive international attention in the context of materials qualification for hydrogen service are also briefly mentioned.

We do not attempt to summarize all of the existing documents related to materials testing and qualification for hydrogen service. Rather, we provide the reader with a list of the more commonly referenced documents in the context of hydrogen compatibility and materials qualification. Moreover, we purposefully avoid the complicated issues of hierarchy, applicability, authority, and jurisdiction of regulations, codes and standards (RCS) and do not attempt to place the listed documents in the broader context of RCS. While the documents listed here are North American centric, these documents reflect our best understanding of the current state-of-the-art for evaluating materials for service in high-pressure gaseous hydrogen.

Existing documents

Reference documents

The numerous sources of general information related to materials selection for hydrogen systems reflect the challenges with testing in hydrogen environments and lack of consensus on methodologies for qualification of materials for hydrogen service. In general, reference documents for hydrogen systems include guidance on more than materials selection and the advice on materials selection is often based on limited materials compatibility testing, perhaps even just a few tests. Those documents listed here have different aims, but they share the common feature of providing guidance and recommendations on materials for service with hydrogen, or in some cases providing engineering data measured in gaseous hydrogen.

- *Guide to Safety of Hydrogen and Hydrogen Systems*: although initially available from NASA [2], this report has become an ANSI-approved document (American National Standards Institute) issued by the American Institute of Aeronautics and Astronautics (AIAA), as document number G-095. The materials selection guidance in this reference is based on the many seminal works from the 1960s and 1970s on characterizing the performance of materials in high-pressure gaseous hydrogen (e.g., refs. [3–5]).
- *Basic considerations for the safety of hydrogen systems (ISO TR 15916)*: similar in scope to AIAA G-095, this document acknowledges the importance of materials selection and highlights the need to carefully consider the suitability of materials for their intended service conditions.
- *Hydrogen Transportation Pipelines*: this reference document was prepared by international experts and describes best practices for transmission of gaseous hydrogen and hydrogen mixtures by pipeline. The document makes specific recommendations to limit the effects of hydrogen embrittlement on pipeline materials, such as appropriate classes of materials for hydrogen service, compositional limits and strength limits. This document is available from the European Industrial Gases Association (EIGA) [6], as well as from the Compressed Gas Association (CGA) as document number G-5.6.
- *Hydrogen Cylinders and Transport Vessels*: this document [7] is similar in scope to the EIGA/CGA document for pipelines except the scope is transportable pressure vessels.
- *Hydrogen Standardization Interim Report for Tanks, Piping and Pipelines*: this document [8] from the American Society of Mechanical Engineers (ASME) summarizes engineering experience on hydrogen systems and provides some limited recommendations on materials selection for hydrogen service.
- *Design Guidelines for Hydrogen Piping and Pipelines*: this document [9] synthesizes the information from the ASME's interim standardization report [8] to provide design guidelines and the basis for the ASME B31.12 code for hydrogen piping and pipelines.
- *Technical Reference for Hydrogen Compatibility of Materials*: this document is an online reference [10] that provides a summary of materials data measured in gaseous hydrogen. Data are organized by specific material, such that individual materials sections can be periodically updated. This reference has also been released in its entirety as a formal report in 2008 [11] and with updated sections in 2012 [12].

Codes and standards

While the above documents are useful resources on hydrogen embrittlement, these reference documents do not provide