H₂ Fracture and Fatigue Behaviour of a Vintage X60 Pipeline Material and Practical Implications for Reuse in H₂ Service

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ABSTRACT

Fracture and fatigue testing was performed on the parent and weld material of a vintage offshore API 5L X60 pipeline to assess the impact of various pressures of H₂. Fracture toughness values of samples exposed to H₂ environment were lower than in air. Fatigue performance was consistent with published literature and ASME B31.12 for ∆K above 5 MPa√m. At ∆K below 5 MPa√m the fatigue crack growth is higher than predicted, possibly driven by a time dependent sustained cracking mechanism in certain microstructures. The practical relevance of these observations is presented in the context of the integrity assessment required to repurpose a pipeline for hydrogen, highlighting the importance of material performance in a H₂ environment.

KEY WORDS: Hydrogen; vintage; pipeline; fracture; fatigue; weld; integrity

INTRODUCTION

Hydrogen is becoming increasingly important as part of the energy transition and net zero initiatives. Pipelines are considered a cost-effective method for transporting larger volumes of gaseous hydrogen over longer distances, replicating the current natural gas supply chain (International Energy Agency, 2019; Wang et al., 2021). Reusing existing carbon steel natural gas transmission and/or other pipelines for hydrogen service is an attractive option. Provided existing line pipe materials and integrity management methodologies can be safely and economically adapted for transporting hydrogen, repurposed pipelines are a way to enable expansion of the hydrogen value chain at a much lower cost. A recent publication by Wang, et al. (2021) suggests that transmission by repurposing existing pipelines would be a cheaper option for distances below 5,000km.

There are about 4,500 km of hydrogen pipelines in operation today, which are mainly operated at stable pressures below 70 bar, by a few industrial gas companies (ASME, 2005; HyArc, 2017). However, existing H₂ pipeline designs in the US tend to use low-strength grades of carbon steel, smaller diameters under 20 inches and conservative design factors that result in high wall thicknesses (in-house analysis of data from www.phmsa.dot.gov, accessed June 2020). Within these limitations it is likely to be difficult to economically achieve the high throughputs anticipated for the future hydrogen value chain in the long term without expanding the operating envelope outside current design practices, as summarised by Topolski et al. (2022). Larger diameter natural gas transmission pipelines designed with larger design factors for higher pressures are attractive to consider for reuse in hydrogen – the principles discussed by Fekete, Sowards, and Amaro (2015) can also be applied to reusing exiting pipelines. However, operators need to be cautious when stepping outside the current operating window and ensure that any assumptions made will not introduce unexpected failure mechanisms.

One challenge anticipated, particularly in the early years of hydrogen transmission, is that hydrogen pipelines may operate with greater pressure variation than typically experienced in natural gas pipelines. This may be as a result of the increasing use of hydrogen produced from renewable sources, a more uncertain demand, or storing/packing hydrogen in the pipeline. However, pressure fluctuations introduce fatigue risks beyond that usually accounted for in natural gas pipeline design, as hydrogen has been shown to reduce the resistance of pipeline materials to this threat (San Marchi and Somerday, 2012). Integrity assessments therefore need to accurately reflect the impact of hydrogen on the material performance to provide confidence assessing a pipeline for repurposing for hydrogen service.

Increasing understanding and confidence will hopefully enable a reduction in the conservatism related to current hydrogen pipeline design factors in ASME B31.12-2019, which impact transport capacity and asset life. This will have a positive impact on the cost-competitiveness of projects without compromising safety. Several pipe materials have already been tested in hydrogen, with a particular emphasis on fatigue performance (Suresh and Ritchie, 1982; Chen, et al., 2009; Ronevich, et al., 2020; Chandra, Thodla, Prewitt, Matthews, & Sosa, 2021), but many works also cover the impact of hydrogen on fracture toughness (Holbrook, Cialone, Mayfield, & Scott, 1982; van Wortel, et al., 2009; Ronevich & San Marchi, 2021). The focus, particularly of more recent publications, has been on adapting natural gas pipelines for future reuse for hydrogen, with the assumption that these are majority onshore transmission networks, such as discussed in the European Hydrogen Backbone (Jens, Wang, van der Leun, Peters, & Buseman, 2021).

Outside of North America, Shell does not operate significant distances of onshore natural gas transmission pipelines. Shell pipelines tend to be designed for offshore/higher stress environments and exposed to a service that is more internally corrosive than dried natural gas. For this reason, it was decided to study the behaviour of an offshore pipe material deemed to be representative for a certain segment of Shell’s pipeline asset base that may to be considered for reuse in hydrogen. Recent publications (Briottet & Ez-Zaki, 2018; Ronevich & San Marchi, 2021) show that even small amounts of hydrogen (at pressures below 10 bar) lead to a significant reduction in fracture toughness. For this reason, the...