Abstract

Hydrogen is known to cause sudden and abrupt failures in materials even at a fraction of its designed strength. The phenomenon is broadly known as hydrogen embrittlement (HE) and is particularly important for line pipe grade steels which are used for the storage and transportation of oil and natural gas. The hydrocarbons in these mediums are an abundant source of H. The situation is expected to become more aggravated when H_2 gas itself needs to be transported as an alternate source of energy in near future. Therefore, the prevention of H-related failures in steels, especially line pipe grades, is of prime importance.

It is known that atomic and diffusible H migrates to the points of stress concentration (cracks for example) and aggravates the failure. Two strategies have been proposed in the recent past to mitigate the problem: (1) steels can be designed with traps in the microstructure to stop the free migration of H atoms, and/or (2) coatings can be laid over components to reduce the H ingress during service. The microalloyed precipitates, *i.e.*, carbides of Nb, Ti, and V act as strong trap sites for H and are reported to improve resistance against HE in laboratory tests. Accordingly, the H trapping ability has been reported as a measure of the resistance against HE in literature. However, the estimation of H trapping ability is a lengthy process requiring elaborate tests like H charging, curation, and trapped H estimation which need days to complete. Furthermore, the best possible microalloying element (and processing conditions) to achieve the maximum H trapping ability has not yet been reported. In addition, the coatings reported in the literature lack application over large-scale components such as line pipes due to one or more of the reasons like poor resistance to H diffusion, structural integrity, corrosion resistance, coatability, *etc.*

In the present work, the H trapping ability of precipitates of microalloying elements (NbC, TiC, and VC) in a low C steel was studied using three model steels. The steels were austenitized and subsequently, aged at varying temperature-time combinations to achieve precipitates in ferrite. The precipitation reactions were simulated beforehand using the TC-Prisma module in Thermocalc software and validated with the help of a small-angle neutron scattering (SANS) study. Subsequently, the H trapping ability in the aged alloys (after electrochemical H charging followed by residual H measurements) has been compared and correlated with the precipitate attributes such as interface character, volume fraction, number density, and size (all estimated using SANS). The relative H trapping ability has been found to be TiC > NbC > VC and the best possible aging condition to achieve maximum H trapping has been determined. Moreover, an atomic-level study has been conducted to reveal the trapping sites of H in NbC precipitates using high-resolution transmission electron microscopy (HRTEM) and 3D atom probe tomography (3D-APT).

Additionally, a computational approach has been proposed to assess the H trapping ability from electrochemical H permeation data using three model microalloyed steels and four commercially available API (American Petroleum Institute) steels as substrates. The proposed method is quicker and does not require elaborate and time-consuming tests required for the estimation of H trapping ability. Additionally, the existing mathematical models of analyzing the H permeation tests have been critically assessed with the help of the above-mentioned H permeation data of the four API steels.

Finally, three Ni-based amorphous coatings have been proposed as H barriers for the first time. The coatings can be laid using simple electroless methods and showed excellent resistance to hydrogen permeation and embrittlement. In addition, the coatings showed superior wear and corrosion resistance required for applications like line pipe.

Keywords: Hydrogen embrittlement; Hydrogen trapping in steels; Microalloyed precipitate; Hydrogen permeation, Hydrogen barrier coating.