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Guest Editorial

Five papers related to hydrogen effects on materials are collectively published in this issue of *ASME Journal of Pressure Vessel Technology* (JPVT).

Hydrogen was identified as a distinct element in 1766 by Henry Cavendish. Subsequent research led to the discovery of the fuel cell effect (Christian Friedrich Schönbein, 1839), that is, the combination of hydrogen and oxygen produced an electric current and water. This may be the first indication that hydrogen would be used as a clean energy source. The massive usage of hydrogen began with the National Aeronautics and Space Administration (NASA) which was formed in 1958. Most of the worldwide liquid hydrogen was consumed in propelling rockets into space and used as the source in fuel cells. Since 1959, hydrogen fuel cells have been used to generate the on-board electricity, heat, and water in the Apollo spacecraft as well as supporting all the subsequent space shuttle missions.

However, a large, laminated, thick-walled hydrogen storage steel vessel for the U.S. space program failed at or below the design pressure in 1965. Later, in 1968, a nickel-based alloy hydrogen tank failed in a brittle manner under the same environmental attack by gaseous hydrogen during the final stage of preparation for the Mariner 1969 Mission to Mars. These events led to a systematic government-sponsored investigation of hydrogen effects. Although pressure vessel failures due to hydrogen were sporadically reported as early as the 1920s, the first comprehensive report on hydrogen embrittlement in a wide variety of metals and alloys was issued in 1969 and was followed by another report in 1973. These two reports, along with the more recent research of hydrogen effects on the tensile, fracture, and fatigue properties of carbon steels, constitute the main portion of a paper in this issue of JPVT: “Literature Survey of Gaseous Hydrogen Effects on the Mechanical Properties of Carbon and Low Alloy Steels,” by Poh-Sang Lam, Robert L. Sindelar, Andrew J. Duncan, and Thad M. Adams. This paper, in fact, was driven by the hydrogen economy (a term coined earlier in 1970). After the 1973 OPEC oil embargo and the sharp demand for gasoline resulting from global economic growth with the accompanying environmental issues, a clear goal has been to seek less dependence on hydrocarbon fuel and replacing it with clean, environmentally sustainable, CO_2-free, renewable, and alternative energy sources like hydrogen. The emphasis on carbon and low alloy steels was to address the safe operation and material performance for the infrastructure of new and existing pipeline systems for the transfer and delivery of hydrogen or its gaseous mixtures. This may overlap certain material applications in nuclear industry such as in CANDU (CANada Deuterium Uranium—a registered trademark of Atomic Energy of Canada Ltd.) nuclear reactor piping systems. The embrittlement mechanism covered by this paper is caused by exposing metals to high pressure gaseous hydrogen, as opposed to the internal embrittlement, which is more relevant to steel manufacturing processes where hydrogen is trapped during the solidification in the ingot.

The paper authored by Mohsen Dadfarnia, Brian P. Somerday, Petros Sofronis, Ian M. Robertson, and Douglas Stalheim, entitled “Interaction of Hydrogen Transport and Material Elastoplasticity in Pipeline Steels,” focuses on the analysis of hydrogen transport in the pipeline steels (the same diffusion characteristics and analytical approach have been directly applied by these authors to other material systems such as the stainless steels). They considered that the hydrogen residing in normal interstitial lattice sites is in equilibrium with that trapped in the microstructural defects such as internal interfaces or dislocations generated by plastic deformation. Their analysis assumes a small scale yielding condition but the transient diffusion governing equation is coupled with the stress and the large deformation fields near the tip of a crack. The results help understand the hydrogen transport phenomenon in these materials and establish its relationship with the mechanical properties and the external load, especially in the area near the stress concentration site such as the tip of a flaw where high dilatational stress occurs.

Hydrogen assisted cracking (HAC) was studied for high strength 4140 and low strength AISI-SAE grade 1022 steels. This type of material degradation occurs ofttimes in pipelines and pressure vessels, especially in sour gas environments in the petroleum industry. Tests for measuring the crack growth rates and the threshold stress intensity factors were carried out to investigate the HAC mechanisms. A single analytical model was proposed to predict HAC in both 4140 and 1022 steels. The model predicts the hydrogen concentration required for crack propagation as a function of material yield strength and applied stress. Details can be found in “Investigation of Hydrogen Assisted Cracking in High and Low Strength Steels” by Samerjit Homrossukon, Sheldon Mostovoy, and Judith A. Todd.

Hydrogen chemical reaction, including hydriding, is another form of embrittlement. The base metal or its alloying constituents reacts with hydrogen to form hydrides, which may have incompatible mechanical properties leading to base meal degradation. The delayed hydride cracking (DHC) has been studied extensively for the crack initiation and growth in Zr-2.5Nb pressure tubes of CANDU nuclear reactors. Deuterium, a non-radioactive hydrogen isotope, is generated from the corrosion reaction of zirconium with the heavy water coolant. The hydrogen isotope is drawn to the high stress region near the tip of a crack or a defect (see the above-mentioned topical paper by Dadfarnia et al.). This leads to the precipitation of hydride platelets oriented along specific crystallographic planes in the zirconium alloy matrix, and a hydride region is formed over time around the flaw tip, and will crack under certain conditions. This initiation/fracture process repeats itself until the structural component fails. The overload effects on this hydride region with prescribed temperature histories were determined experimentally with the aid of acoustic emission to detect sample cracking. Jun Cui, Gordon K. Shek, and Zhirui Wang reported their findings in the paper entitled “Overload Fracture of Hydrided Region at Simulated Blunt Flaws in Zr-2.5Nb Pressure Tube Material.” In addition, the DHC initiation in Zr-2.5Nb pressure tubes was characterized with a series of thermal cycles. Experimental details and results can be found in “Delayed Hydride Cracking Initiation at Notches in Zr-2.5Nb Alloys” by Jun Cui, Gordon K. Shek, Douglas A. Scarth, and Zhirui Wang. The threshold values of the stress intensity factor at DHC initiation were determined experimentally and the fractography was carefully characterized optically and by scanning electron microscopes.

Hydrogen will continue to be encountered in many engineering applications including energy generation. The interactions between hydrogen and other materials for their respective service conditions must be understood. Needless to say, in this issue of JPVT only a very limited collection of papers is presented on hydrogen embrittlement relevant to the current state of the hydrogen economy. It is hoped that by a glimpse of this subject through these papers, readers will come to understand the difficulty and complexity inherent in material applications involving hydrogen, and to appreciate the decades of research and development that will eventually result in the successful use of hydrogen as a viable alternative energy source. More importantly, it is also hoped that, starting with these five reports, more papers dealing with hydrogen and its effects on metals can be attracted to JPVT so that a more comprehensive topical report can be compiled and presented to the pressure vessels and piping community in the near future.

I sincerely thank Professor G. E. Otto Widera for his continuing encouragement and granting me the opportunity to assemble this set of important papers on hydrogen effects. The contributions of all the authors are deeply appreciated. A special thanks goes to Professor Judith Todd and Professor Petros Sofronis, and Dr. Jun Cui who all patiently allowed me to take extra time to pull the present five papers together. Last, but not the least, allow me to thank Jessica Bulgrin, Assistant to the JPVT Editor, for administrative help and to acknowledge the support from Dr. Natraj C. Iyer, Director of Materials Science and Technology at the Savannah River National Laboratory, throughout my tenure of service to ASME and this journal.

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