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The effect of hydrogen content and welding conditions on the hydrogen induced cracking of the API X70 steel weld

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ABSTRACT

The self-restraint testing was used to investigate the influence of hydrogen content, preheating, and post-heating on the sensitivity of welding of API X70 pipeline steel to hydrogen induced cracking (HIC). The variation of hydrogen content was applied using a low hydrogen electrode E8018-G and a high hydrogen (cellulosic) electrode E8010-P1. Diffusible hydrogen of these electrodes was measured by mercury displacement method. The average diffusible hydrogen content of cellulosic electrode E8010-P1 and low hydrogen electrode E8018-G were 43.6 and 1.1 ml/100 g of weld metal, respectively. The results of visual inspection, penetrant test, and macroscopic examination showed that welding with cellulosic electrode leads to cracking unless both preheating and post-heating are applied. However, in the case of low hydrogen electrode, cracking occurs only if no preheating or post-heating is applied. The microstructure of the welded specimens in different conditions by optical and scanning electron microscopy (SEM) showed that the dominant phase in the weld zone of all specimens is bainite. The microhardness profile displayed that hardness limitation (350 HV) cannot predict the sensitivity to cold cracking; therefore, other parameters such as hydrogen content should also be considered.

Introduction

Hydrogen embrittlement in steels (and other metallic alloys) has historically been a major technological challenge in the oil and gas industry [1–3]. With the recent focus on hydrogen economy and its applicability across several other industrial sectors, hydrogen embrittlement has recently gained greater attention and become an active area of research [2,4]. It is generally accepted that atomic hydrogen can diffuse through steel and migrate to regions of high stress concentration, such as an advancing crack tip, to cause failure [5–7].

The manufacturing of steel pipelines for the transfer of oil, gas, and most recently, hydrogen is done in accordance with API 5L standard [8,9]. The need for high mechanical resistance, and good fracture toughness at low temperatures and also good weldability, requires the use of high strength low alloy steels (HSLA) that are obtained by thermomechanical processing [10].

The welds in ferritic steels have always been accompanied by hydrogen induced cracking (HIC); however, the improvement of steel making processes has led to high strength base steels containing low alloy levels that are less susceptible to HIC. In contrast, the as-cast nature of the weld metal does not

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provide the same opportunity to control the transformation processes; therefore, the microstructures as precise as HSLA steels cannot be achieved [11].

Previous studies have shown that the necessary conditions for the formation of cold cracks in weld joints involve the presence of diffusible hydrogen, tensile residual stress, susceptible microstructure, and a temperature below 200 °C [12]. The possibility of having a susceptible microstructure in the heat affected zone (HAZ) or weld metal depends on the chemical composition of the base metal and weld metal, the heat input, and preheating (which reduces the cooling rate) [13,14]. Low hydrogen welding consumables, proper baking of the consumables to remove their moisture content, and appropriate preheating and/or post-heating conditions, which would provide hydrogen with more time to diffuse out at high temperature, are chosen to reduce hydrogen level [4,14].

Recently, a number of studies have been performed on the HIC in the X70 steel weld [15–19]. Dickinson and Ries [20], Magudeeswaran et al. [21], Chakraborty et al. [14], Pandey et al. [22], and Saini et al. [4] studied the hydrogen cracking susceptibility by implant test. Dickinson and Ries [20] tested various high strength steels under different welding conditions and provided a model for predicting the influence of various parameters, such as preheating, hydrogen content, and heat input on the HIC. They expressed the results as a function of carbon equivalent, martensite start temperature, hardness of the HAZ, and hardenability. Magudeeswaran et al. [21] compared the effect of welding by ferritic steel consumables and austenitic stainless steel consumables on the HIC of AISI 4340 (a quenched and tempered) steel. They concluded that welds made by austenitic stainless steel consumables offered a greater resistance to HIC. Chakraborty et al. [14] assessed the susceptibility of DMR-249A (a HSLA) steel welds made by the E8018-C1 electrode to HIC under different conditions of electrode baking. They observed that neither the steel nor the weld was susceptible to HIC even with a high diffusible hydrogen content of 9 ml/100 g of weld metal. This insensitivity was attributed to the presence of a mostly ferrite structure and the absence of susceptible microstructure constituents such as bainite and martensite in both weld metal and HAZ. Pandey et al. [22] evaluated the effect of different levels of diffusible hydrogen content in the deposited metal in the HIC susceptibility of cast and forged P91 steel welds. They concluded that P91 steel welded by the electrode having high hydrogen level was more susceptible to HIC. Saini et al. [4] also investigated the HIC susceptibility of P92 steel welds by varying the electrode conditions. They concluded that the P92 steel plate welded by the contaminated electrode with a high level of diffusible hydrogen had more susceptibility to HIC.

Law et al. [23] used four point bending method to develop a test that isolated and quantitatively assessed the effects of diffusible hydrogen on HIC in the weld metal. They believed that this method was suitable for two reasons; first, it placed the weld bead at the position of maximum stress, so that the test would not be prematurely concluded due to the parent metal or HAZ cracking, and second, it exposed the maximum volume of weld metal to the imposed maximum stress.

A standard and close to actual conditions method in the gas pipeline weld is the self-restraint test [24] which has not been previously reported for the X70 steel weld. By self-restraint test using a low hydrogen electrode and a high hydrogen (cellulosic) electrode, the present study investigates the effect of preheating and post-heating on the probability of HIC in the X70 steel weld.

Experimental

Determination of hydrogen content in weld metal

Displacement of mercury standard method based on ISO 3690 [25] was used to measure diffusible hydrogen in weld metal. For this purpose, a set-up was prepared according to the standard to measure diffusible hydrogen, which is shown in Fig. 1. Moreover, the welding fixture was made based on this standard (Fig. 2). The fixture was supposed to rapidly transfer heat to the copper blocks so that the specimen is cooled immediately after welding to trap all the hydrogen.

The test piece assembly must be made of plain carbon non-rimming steel with a carbon content of less than 0.18 wt% and a sulfur content of less than 0.02 wt%. Test pieces were prepared with dimensions of $30 \times 15 \times 10\ mm^3$. The test assembly was degassed at 650 °C for 1 h to remove any bulk hydrogen and was cooled in the furnace. Each test piece assembly was finished with one operation on a surface grinder so as to ensure a uniform width to obtain proper clamping.

The test piece, which was previously welded, cleaned and immersed in liquid nitrogen, was removed from the liquid nitrogen, rinsed with acetone at temperatures close to 0 °C, dried in a jet of air and transferred to the wide limb of the Y-tube. Then, by evacuating the air, the probable residual of acetone or air was removed from the Y-tube. Using a magnet, the test piece was maneuvered into the position under the capillary tube. After sufficient time, diffusible hydrogen evolved from the test piece and collected in the capillary tube. The length of the hydrogen gas column and the differential level of mercury between the two limbs of the Y-tube were measured. The ambient temperature and atmospheric pressure were measured and recorded, too. Using these values and

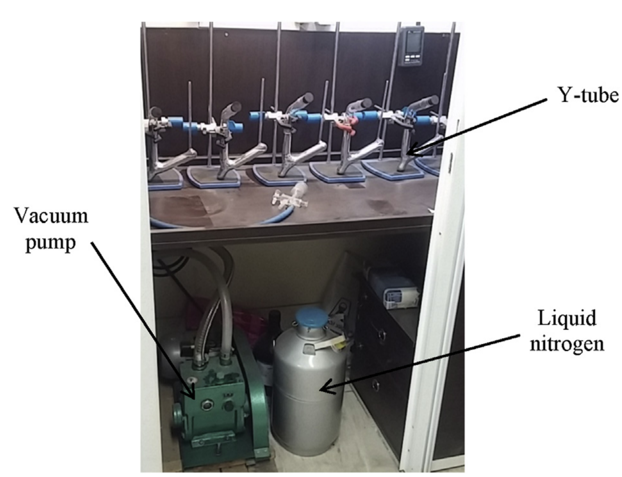

Fig. 1 – The set-up prepared for measuring diffusible hydrogen based on ISO 3690 standard.