A Numerical Study of Hydrogen Diffusion in a Part-size Sleeve-on-Pipe Mock-up Exposed to Two Different Levels of Post Weld Heat Treatment

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Deeper waters impose considerable challenges for eventual remote pipeline repair and remote hot-tapping. The purposes of this study were (1) to replicate the thermal history of a laboratory-produced part-size sleeve-on-pipe mock-up, which was designed to replicate the geometry and highest restraint levels of a remote pipeline repair scenario that was exposed to pre- and post-heating; and (2) to examine the decay of hydrogen in and adjacent to a test weld, which closed the gap between the sleeve and the pipe. Measured temperatures and \( \Delta T_{H/5} \) weld metal cooling rates were reproduced satisfactorily by the computer model.

Two test cases were selected for modeling. One created a crack-free weld, while the other did not. The main difference was the pre- and post-weld heating temperature. Two approaches for the modeling of hydrogen diffusion were applied, one based on an apparent diffusion coefficient and another based on the calculation of trapping. With respect to the incidence of cracking and the level of hydrogen obtained after the post-weld heating period, both approaches for the modeling of hydrogen diffusion support the experimental findings.

INTRODUCTION

Deeper waters impose considerable challenges for eventual remote pipeline repair and remote hot-tapping as diver-assisted operations are not normally permitted below 180-m sea depth in Norwegian waters (Woodward, 2006). This means that fully automated, remotely controlled welding equipment must be developed, and this concept has high priority for the Norwegian petroleum industry. Dry hyperbaric welding techniques are being developed for these applications.

Hydrogen embrittlement is a serious detrimental problem when welding offshore steel structures, as failure may have serious consequences for the environment. For offshore pipelines, the main hydrogen sources are cathodic protection and hydrogen in the weld metal. Traditionally, it is the heat-affected zone (HAZ) adjacent to the weld that constitutes the critical area. Part of the hydrogen that is dissolved in the weld metal escapes through the external surfaces, while the rest diffuses slowly to the surrounding steel structure and into the typical brittle HAZ. Due to trapping and the fact that hydrogen diffusion is strongly influenced by this phenomenon, a computational model of this process is typically complex.

Trapped atomic hydrogen occurs at sites such as dislocations, grain boundaries, and phase interfaces. The mobility of these atoms is associated with an energy barrier. A much lower energy barrier is associated with the mobility of dissolved hydrogen in the iron lattice. For ferritic steels at room temperature, the apparent or the effective diffusion coefficient, which includes the effect of trapping, can be several orders of magnitude lower than the real (lattice) diffusion coefficient. The diffusion coefficient increases with the temperature, and for this reason, post weld heat treatment (PWHT) is an efficient and well-known method to reduce the hydrogen content in the weld metal and in the HAZ.

In the hyperbaric welding chamber at Cranfield, tests have been carried out for adding a single test weld to close the gap between a sleeve and a pipe. Due to the size, the test geometry was reduced to a part-size sleeve-on-pipe mock-up. The main focus was on PWHT and to establish a procedure on how to avoid hydrogen-assisted cracking (HAC). The results confirm that PWHT has a significant effect on avoiding cracks. Two test cases were selected for modeling. One created a crack-free weld, while the other did not. The main difference between them is the PWHT temperature. Concentrations lower than 1–2 mL H/100 g Fe, which in this study is approximated to 1–2 wt ppm, are suggested to minimize the risk of cracking due to hydrogen (Wongpaya et al., 2007).

In this study, the computer model WeldSimS (Fjær et al., 2007, 2012) has been applied to replicate the thermal history in the sleeve-on-pipe mock-up and to examine the decay of hydrogen in and adjacent to the weld. The focus is on the hydrogen level obtained at the end of the PWHT time period, and to examine if the model results confirm the critical hydrogen level below which there will be a small risk of cracking. Two approaches for the modeling of hydrogen diffusion are tested. The first applies an apparent diffusion coefficient that accounts for the effect of trapping. This coefficient is always lower than the lattice diffusion coefficient. The main objection to this approach is the large spread of data reported in the literature. The second approach uses the lattice diffusion coefficient and calculates trapping directly. The challenge for this approach is to find relevant trap parameters, such as trap density and activation energies, that are valid for the specific material being modeled.

COMPUTATIONAL DOMAIN

The computational domain of the part-size sleeve-on-pipe mock-up is shown in Fig. 1. It contains four main parts: an X65 30° pipe sector, an X65 30° sleeve sector, weld segments, and Argon. The weld segments are divided into two sub-domains, the anchor welds (front and side) and the 100-mm-long front test weld. The