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Hydrogen induced stress cracking in supermartensitic stainless steels – Stress threshold for coarse grained HAZ

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ABSTRACT

The objective of the present work was to investigate the influence of the microstructure on the hydrogen cracking susceptibility of two typical pipeline supermartensitic stainless steels. The work has concentrated on the coarse-grained heat affected zone because this is the typical crack initiation point. The hydrogen cracking susceptibility was tested by notched tensile test samples containing a simulated coarse grained heat affected zone. The samples were tested under constant load immersed in 3.5% NaCl and subjected to a negative potential corresponding to that induced by the cathodic corrosion protection system. The load was increased by a small amount every second day in order to establish the threshold stress for hydrogen cracking during service in seawater with hydrogen being introduced on the steel surface by the cathodic protection system. A significant influence of the second heat cycle was observed. This effect was attributed to both a variation in yield strength and the influence of precipitates on hydrogen solubility and diffusion.

1. Introduction

A number of fractures in Supermartensitic Stainless Steel (SMSS) pipelines in the North Sea have been described in references [1–4]. Almost without exception these cases have been attributed to hydrogen embrittlement, and in some of the early cases, the hydrogen source was the welding process. However, the majority of the reported cases have been attributed to hydrogen cracking where the source of hydrogen was the cathodic protection system.

The cathodic protection system used for these pipelines consists of aluminium sacrificial anodes that polarise the steel surface to −1050–1100 mV SCE. This potential is reached near the electrical connection point between the sacrificial anode and the steel, and the potential will rise with increasing distance from the anode connection point. Below about −800 mV SCE, atomic hydrogen is formed on the steel surface:

$$H_2O + e^- = OH^- + H$$

Some of the hydrogen atoms formed are absorbed by the steel material and increase the content of hydrogen dissolved in the steel. If a sufficient amount of diffusible hydrogen is present in a susceptible microstructure and subjected to tensile stresses, hydrogen embrittlement and cracking will be the result. The principles of hydrogen cracking are explained further in references [5–8].

Since the initiation points for the observed cracking have been the weld toe, the present experiments have all been carried out on a simulated Coarse Grained Heat Affected Zone (CGHAZ) microstructure. The CGHAZ simulation was carried out using a Smitweld simulator.

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The weld toe has a stress raising effect due to the geometry of the weld cap and any weld defect that may be situated in this area. In addition, the CGHAZ zone may be more susceptible to hydrogen embrittlement than the base metal because of its high strength and hardness as a result of its content of untempered martensite or different types and distribution of precipitates.

The objectives of the experiments described herein were to:

- Establish a threshold stress for hydrogen cracking during service in the CGHAZ of two different pipeline steels. The steels selected were typical pipeline steels used in the North Sea.
- Investigate the influence of different heat cycles on the hydrogen embrittlement of the CGHAZ.

The test pieces had a one millimetre notch machined in the simulated zone in order to include the stress raiser effect of the weld cap and a typical weld defect such as a weld undercut. Two test samples with no notch were also tested.

2. Experimental procedures

2.1. Materials

Two typical pipeline materials were used for the tests, designated steels A and B. Their chemical composition is shown in Table 1.

The tensile test samples were cut from the pipe wall in the direction of the pipe axis, normally referred to as the longitudinal direction.

2.2. Weld HAZ simulation

Before weld simulation, the test materials were machined into 13 mm × 13 mm square section specimens 160 mm long. The weld simulation test samples were cut from the pipe wall in the direction of the pipe axis, normally referred to as the longitudinal direction.

The weld simulation was performed using a Smitweld weld simulator. The Smitweld simulator heats a narrow zone 3–5 mm wide in the centre of the test sample by resistance heating. The sample is clamped in water cooled copper clamps that also supply the electric current to the sample. The heating and cooling rates are controlled by regulating the current through the sample. The temperature of the sample is measured by a thermocouple welded to the centre of the sample. Thermocouples of the Platinum–Rhodium type, normally designated S-type, were used. A Calibrator instrument of type AOIP–18621 was used in order to calibrate the Smitweld temperature measurements prior to simulation.

The final machining to the tensile test shape shown in Fig. 1 took place after weld simulation. The specimen was polished and etched in order to position the notch correctly in the weld simulated material.

In order to confirm the phase transformations that occurred during the temperature cycle, dilatometer measurements were recorded during the weld simulation. The dilatometer readings confirmed clearly the transformation to δ-ferrite during the first heating cycle.

Fig. 2 shows a typical Smitweld heating cycle. The second temperature peak represents a second heat cycle in the HAZ by for example a subsequent weld pass.

2.3. Simulated CGHAZ heat cycles

The CGHAZ of SMSS is formed where the peak temperature during the welding cycle has been above A_{c5} (1350–1380 °C). At these temperatures, grain growth is rapid, and large ferrite grains are formed. Upon cooling, the structure transforms to austenite and subsequently to martensite below M_s.

Table 2 shows the heat cycles used in the weld simulation experiments. All samples were heated to 1400 °C, designated T_{p1}, and contained microstructures found in the CGHAZ. The two first sets of samples were tested in this ''as-welded'' condition, while all the remaining samples were subjected to a second heat cycle. In practice, the second heat cycle may be caused by a subsequent weld pass or a post weld heat treatment cycle.

Post weld heat treatment at 620–650 °C for 5 min has become standard industry practice in order to repair chromium depletion along grain boundaries and minimise the susceptibility to intergranular corrosion. All samples were allowed to cool down to temperatures below 40 °C between the heat cycles in order to ensure complete martensite transformation.

Table 1
Chemical composition of test materials.

Steel	C	Si	Mn	P	S	Cr	Ni	Al	Mo	Nb	V	Ti	Co	B
A	0.006	0.12	0.44	0.013	0.002	12.0	6.4	0.03	2.5	<0.01	0.04	0.11	0.04	<0.001
B	0.010	0.11	0.66	0.017	0.002	12.0	5.6	0.03	2.2	<0.01	0.02	<0.01	0.09	<0.001