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Systematic investigation of the role of stress-induced pits and grooves in SSC four-point bend testing of line pipe steel

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ABSTRACT

The four-point bend test as per NACE TM0316-2016 is used in the oil and gas industry as a common test to evaluate the resistance of line pipe steels to sulfide stress cracking. The appearance of stress-induced pits or grooves on the test specimens can sometimes be noted when testing is performed under high load, at low pH or in CO₂ containing test environments. When evaluating SSC specimens, it is important to distinguish between stress-induced corrosion pits and SSC crack structures and their relevance for the SSC test result.

Within this study a systematic investigation of the level of applied stress, the test gas composition and the surface finish of test specimens and their influence on the onset and growth of cracking of four-point bend SSC specimens was performed. In this context the role of shape and maximum depth of stress-induced corrosion pits and stress grooves are discussed in detail.

Key words: SSC, Four-Point Bend Test

INTRODUCTION

Sulfide Stress Cracking (SSC) is a severe and dangerous failure mode for carbon steel pipes used for the transport of sour oil and gas media. In the presence of Hydrogen Sulfide (H_2S) and water, Hydrogen atoms originating from the anodic dissolution of the material may diffuse into the steel. SSC cracks initiate as a result of hydrogen embrittlement, material parameters (e.g. hardness) and residual or applied stress.

In the past, resistance testing of line pipe steel to SSC was typically performed as a four-point bend test described in EFC publication no. 16¹ at the test conditions given in NACE TM0177 for method A.² The test consists of the application of a defined bending stress to a flat specimen machined from the pipe wall. The tests are not intended to reproduce service conditions, but to provide reproducible test environments to determine the susceptibility at very severe conditions. In 2016 the test was standardized in NACE TM0316.³

All specimens are evaluated in the tensile stressed region between the inner and outer rollers for any evidence of cracking. This includes visual evaluation, non-destructive assessment like magnetic particle inspection and metallographic sectioning at suspicious features or defined locations, if no indications are present. If no cracks initiate, the material is considered resistant to SSC for sour environments represented by the test conditions.

Under specific test conditions which sometimes include high specimen loads and Carbon Dioxide (CO_2) containing test environments, the growth of pits and/or microgrooving structures can be found on the specimen surface which was in tension. Examples are shown in Figure 1. In addition, NACE TM0316 states in a note that consideration must be given whether these corrosion pits could continue to propagate and transform to cracks at longer test duration. Therefore, a further microscopic evaluation has to be performed to determine whether SSC cracks are present.

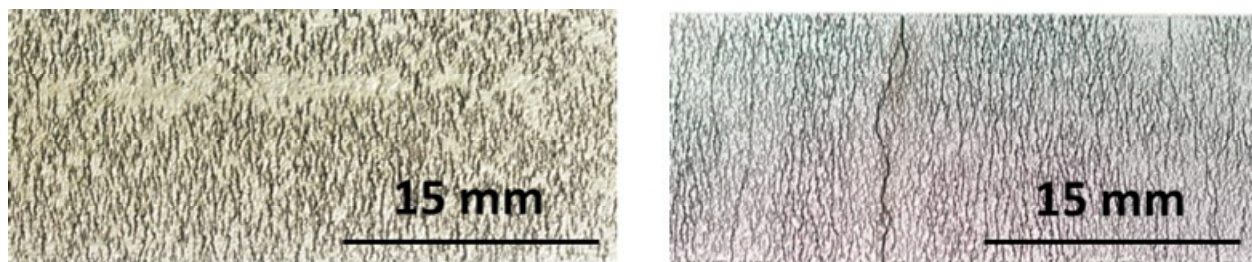


Figure 1: Example of visual appearance of SSC specimen after test termination

Pitting corrosion is not uncommon for carbon steel and is related to a mechanism different from SSC without the exclusive presence of H_2S or stress. ASTM G46⁴ describes the shape of various pits grown on unstressed specimens, however, it is currently not known to what extent the applied stress might support pit-into-crack transformation. A scheme to distinguish between pits and cracks has been presented by Pargeter in 2000 giving some first advice in a flowchart.⁵

Clear guidance to distinguish between SSC cracks and stress-induced pits or grooves, which should not be misinterpreted as SSC, was missing until now. Recently, a first publication suggesting micrographic acceptance criteria for SSC test evaluation has been published.⁶ A systematic investigation of the influencing factors for the formation of stress-induced pits and grooves, including the level of applied stress, the test gas composition and the surface finish of test specimens was therefore undertaken utilizing four-point bend SSC specimens machined from different line pipe steels.

EXPERIMENTAL PROCEDURE

Investigated Materials

Three line-pipe materials were investigated within this project.

- Pipe A was a 711 mm (28 inch) diameter SAWL pipe with 30 mm wall thickness designated for sour service. The grade was equivalent to API 5L X65. The actual yield strength (AYS) was 528 MPa.
- Pipe B was a 1222 mm (48 inch) diameter SAWL pipe with 22 mm wall thickness. The grade was equivalent to API 5L X80. The AYS was 579 MPa.
- Pipe C was a 1070 mm (42 inch) diameter SAWL pipe with 14 mm wall thickness. The grade was equivalent to API 5L X100. The AYS was 685 MPa.

The chemical composition of the materials was determined using optical emission spectrometry (OES) and is shown in Table 1.

Table 1
Chemical analysis for investigated pipes A - C

Chemical Analysis [Weight %]								
	C	Si	Mn	P	S	Ni	Nb + V + Ti	Others
Pipe A	0.04	0.32	1.41	0.008	< 0.001	0.27	0.06	Cu
Pipe B	0.06	0.30	1.51	0.011	< 0.001	0.43	0.07	Cu, Cr
Pipe C	0.07	0.31	1.84	0.011	0.001	0.36	0.06	Mo, Cu

Test Procedure

Prismatic four-point bend specimens with a length of 140 mm and a width of 15 mm were machined longitudinal to the pipe axis from base material at a distance of 1 mm below the pipe inside. The specimen thickness was 5 mm. Unless otherwise stated the surface finish was within the requirements of NACE TM0316-2016 with a R_a value $\leq 0.25 \mu\text{m}$. The test duration for the SSC tests was 720 h. The test temperature was 24 °C. For each test condition triplicate specimen sets were tested. Unless otherwise stated the specimens were stressed to a stress level representing 90 % of the actual yield strengths. NACE TM0177 test solution A was used for all experiments. The test gas was either pure H_2S , pure CO_2 or pre-mixed bottled test gas consisting of 0,3 % H_2S in CO_2 , 20 % H_2S in CO_2 and 20 % H_2S in N_2 . Evaluation was performed visually at 1x and 10x magnification, by wet magnetic particle inspection (MPI) and by metallographic evaluation of longitudinal sections.

RESULTS AND DISCUSSION

Overview

The influence of individual test parameters on the occurrence and growth of stress-induced pits or grooves for the four-point bend test was investigated systematically by variation of one parameter at a time and keeping all other relevant parameters constant.

Influence of the test gas composition

Two corrosive gases that could initiate pitting are generally used in SSC tests. Whereas H_2S always must be present for any test condition, CO_2 is used as additional or balance gas in tests under fitness-for-purpose test conditions. Thus, understanding the role and interplay of both test gases is very important. Four-point bend tests were performed using five different test gases:

- I 100 % CO_2 : Only Carbon Dioxide corrosion is taking place. No SSC-test.
- II 0,3 % H_2S / 99,7 % CO_2 : Presence of traces of H_2S in CO_2
- III 20 % H_2S / 80 % CO_2 : Typical fit-for-purpose test condition
- IV 20 % H_2S / 80 % N_2 : Typical fit-for-purpose test condition where CO_2 has been replaced by an inert gas
- V 100 % H_2S : Standard and most severe test condition without CO_2

Under otherwise identical test conditions (90 % AYS, 720 h test duration) the influence of the corrosive gases was compared on specimens from the three different pipeline steels.

Results for Pipe A

Visual evaluation of SSC specimens tested at a load of 90 % AYS in the test atmospheres I – V showed no visible grooving for pure CO_2 (I) and pure H_2S (V) and slightly visible microgrooving over the complete test area between the inner rollers of the test jig for the other test gases with the highest tendency at 20 % H_2S and 80 % CO_2 (III). Magnetic particle inspection did not give any indications. A comparison can be made on the results of the metallographic evaluation, which are shown in Figure 2. No pitting has been induced under a 100 % CO_2 test gas atmosphere (I). At 100 % H_2S shallow pits with a maximum depth of 30 μm have developed. For any of the utilized test gas mixtures of H_2S and CO_2 (and also N_2), similar shaped pits, mostly branching with a characteristic angle, can be noted. This observation correlates well with the literature finding that corrosion pits can grow branching at an oblique angle under severe stress.⁷ In a recently published paper those observed features are characterized as stress-assisted corrosion pits (SAC).⁶ The maximum observed pit/groove depths were 155 μm for (II), 250 μm for (III) and 150 μm for (IV).