Sour-Well Serviceability of Higher-Strength Coiled Tubing

A joint-industry project (JIP) was initiated approximately 2 years ago to extend the research conducted into the serviceability of coiled tubing (CT) for under-balanced sour-well drilling and work-over operations to higher-strength [90- to 110-ksi specified-minimum-yield-stress (SMYS)] grades. A significantly different and unique laboratory testing protocol is used in the present JIP research. The methodology calls for full-body tubing specimens that have been immersed in a sour solution of varying severity followed by testing in a bend-fatigue machine (BFM) to determine the low-cycle fatigue performance of high-strength CT materials degraded by exposure to a sour environment.

Introduction

Over many years, sour-well interventions have been performed with CT with relatively few failures. This success likely is the result of a variety of factors including time of exposure to sour conditions, adequate corrosion-protection programs, inherent resistance to hydrogen sulfide (H_2S) damage by different CT materials, continuing research into the response of CT materials to sour conditions, and generally good CT-management procedures to minimize the risk of failure. A better understanding of the response of CT materials while exposed to sour downhole conditions has been the focus of research for several years. The testing used both coupon and full-body CT test specimens. The testing protocal included standard and custom-designed fixtures comprising slow-strain-rate testing (SSRT), axial low-cycle corrosion fatigue (LCCF), double-cantilever beam (DCB), Natl. Assn. of Corrosion Engineers (NACE) hydrogen-induced cracking (HIC) and proof-ring tests, acoustic-emission (AE) measurements of crack-incubation times, constant-load tests (CLTs) on full-body specimens for sulfide stress cracking (SSC), BFM tests on CT sour-fatigue specimens, and a custom-designed hydrogen-diffusion vacuum cell for full-body CT specimens. Extensive metallographic examinations were performed to investigate failure mechanisms, fracture characteristics, and relationships to CT material properties and environmental severity.

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The initial JIP considered only CT-strength grades of 70 and 80 ksi and concluded with a recommendation that sour-service CT strings be limited to a maximum strength of 80-ksi yield. This was based on SSRT strain-to-fracture limitations for CT of higher strength using conventional A606/607 modified materials. Bend-fatigue lives of CT materials were estimated on the basis of LCCF measurements by assuming that the ratio of axial- to bend-fatigue life in sweet environments applied equally to sour conditions. The 80-grade sour CT limit served the JIP companies well but imposed an undesirable limitation on sour-well interventions for which higher-strength CT strings were required.

The purpose of the full-length paper is to share the major interim findings of the second JIP, involving tests conducted over the last $1^1/2$ years on higher-strength CT90, CT100, and CT110 grades. The majority of these data involves actual low-cycle fatigue tests on 7-ft-long CT specimens that were submerged in a sour solution for 4 days before fatigue loading to failure.

Low-Cycle Bend-Fatigue Testing

The low-cycle bend-fatigue performance of CT specimens previously exposed to a sour environment is being measured by first immersing, typically for 4 days, 7-ft-long $1^3/4$-in.-diameter specimens in one of several stainless-steel chambers **(Fig. 1).** The ends of these specimens are either left open or plugged for double- and single-sided exposure to a NACE standard "A" solution through which H_2S gas is percolated continuously. The H_2S concentration for different tests ranged from 1 to 100% at atmospheric pressure. Following immersion, the sour-bend-fatigue specimens were packed in dry ice and transferred in an insulated box to the BFM. After removal one at a time from the ice box and allowing sufficient time to reach room temperature, each specimen was subjected to bend-fatigue loading to failure in the BFM. Testing parameters were 48- and 72-in. bend forms and internal pressures adjusted to maintain a constant hoop stress of 19,500 psi based on 3,000 psi and 0.134-in. wall thickness. Test specimens included some 70- and 80-ksi grades (but mostly 90-, 100-, and 110-ksi grades) bias and girth/butt welded, prefatigued, and surface-damaged with and without anticracking corrosion inhibitors

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Fig. 1—Sour immersion cells for CT bend-fatigue specimen pre-exposure.

applied during previous immersion in sour solutions.

CLT

To determine the susceptibility of CT to SSC as a result of elastic tensile and pressure working loads in sour wells, laboratory tests are being performed that subject a short full-body CT specimen to constant internal pressure and axial stresses while being submerged continuously in NACE Sour-Solution "A" and H_2S of varying concentration. The duration of these CLTs is 92 hours to allow sufficient time for any HIC and/or SSC to develop. Test pressures were 3,000 psi, and tensile loads were such that the von Mises equivalent stress would not exceed a maximum of 80% of the SMYS of the CT material being tested. CLT specimens that survived the 92-hour loading period would be pulled to failure to determine what effects, if any, the exposure to sour conditions had on the CT tensile properties. Specimens that failed at the maximum applied stresses would be retested at lower applied load to determine the threshold stresses below which SSC would not occur. The same apparatus used for SSRT and LCCF testing during the previous JIP was used for the CLT fixture. CLT specimens tested so far included 90-, 100- and 110-ksi grades without anticracking corrosion inhibitor protection.

Crack-Incubation Times

Irreversible damage such as HIC and SSC in CT materials requires a finite period of time to develop after the initial time of exposure to a sour environment. Knowledge of these crack-incubation times is one important aspect of managing CT strings in sour service that had not been addressed in previous JIP research. For example, although it is advisable to use newly milled strings for sour service whenever possible, even a new string entering its first well will have significant residual stresses induced from a finite number of plastic-bend-fatigue cycles that it must undergo before entering the wellbore. Therefore, it is important to know if the intensity of such residual stresses is sufficient to induce SSC even without the addition of external working-load stresses.

To determine the incubation times required for various cracking mechanisms to initiate, a separate corrosion cell was designed and constructed out of Plexiglas. Three CT specimens approximately 3-ft long and of varying diameter were inserted vertically in the cylindrical cell filled with NACE Sour Solution "A" with 100% H_2S gas continuously percolated through the solution. The specimens were sealed against the bottom flange of the cell to limit exposure to the outside surface only. The top end of the specimens was allowed to penetrate the upper flange of the cell such that AE sensors could be attached to each without being exposed to the sour solution. The AE sensors were wired to a custom AE-monitoring system that can not only monitor the time of occurrence of cracking events but also identify the origin of the crack as either surface or midwall of the CT specimens. This is accomplished by monitoring both in-plane and out-of-plane noise sources, breaking these signals into low- (20 to 60 kHz) and high- (100 to 500 kHz) frequency (LF, HF) channels, and calculating the ratio of high to low frequencies of signals with peak amplitudes above a selected threshold value. Out-of-plane sources are indicated by a low ratio (less than 1) and in-plane sources by "infinite" ratios much greater than 1. Out-of-plane signals are generated by

LF flexural waves, HF shear waves, or weak HF extensional waves. In-plane signals are generated by weak LF flexural waves, HF shear waves, or HF extensional waves. Crack incubation times so far have been measured for CT70, CT80, and CT90 grades that had been precycled a finite number of times to develop a residual-stress pattern that would exist in a new string by the time it enters the sour well.

Resistance to HIC

Bend-fatigue tests with sour CT specimens have shown that the presence of irreversible damage caused by HIC severely limits the useful service life of CT strings. Therefore, it is important to develop a methodology that can evaluate the susceptibility of a candidate sour-service string to this type of damage before placing it in service. A standard NACE testing methodology already exists for evaluating the HIC resistance of line-pipe steels. Unlike line pipe, CT is not meant to be exposed to a sour environment indefinitely (unless used for other applications such as hanging-off strings or sour gathering lines); however, efforts are under way to use the same methodology to help qualify CT for sour service.

This method exposes the six sides of CT coupons cut from a tubing specimen to a sour solution for 96 hours. Quantitative information, such as HIC crack-length ratios, crack-thickness ratio, and crack-sensitivity ratio, is obtained from metallographic examination of the test coupons. Because only the external surface of sour bend-fatigue specimens is exposed to the NACE solution, HIC occurring in the test coupons extracted from the BFM specimens may not necessarily form in the bend-fatigue specimens. (It was noted previously that single-sided exposure may preclude HIC that would otherwise form in the same specimen with both its outer and inner surface exposed to the sour solution.) Encouraging results already have been obtained that indicate that critical values for the crack ratios could be defined so the risk of HIC developing in the sour-service string will be minimized. Sufficient test data currently are not available to define these critical ratios.

Summary and Recommendations

Approximately 250 sour BFM tests have been completed to date, and more remain to be performed before the present JIP is terminated. Substantial progress also has been accomplished with other tests designed to give a better understanding of the response of higher-strength CT materials in sour environments. From the results obtained so far, the following summary statements and recommendations can be made.

1. Without HIC damage, the bend-fatigue life of higher-strength CT is reduced to 50 to 70% of sweet life up to approximately 50% H_2S in a standard NACE “A” solution. At 100% H_2S, low-cycle bend-fatigue reduction is in the range of 40 to 50% of sweet life.
2. Sour bend-fatigue life is not significantly affected by H_2S concentration, provided the tubing is not damaged by HIC.
3. If HIC damage is incurred, the bend-fatigue life is reduced to 10 to 30% of sweet life.
4. The HIC crack-incubation period for CT containing only residual stresses appears to be on the order of $1^1/2$ to 3 days for CT70, CT80, and CT90 grades.
5. Prefatigued (i.e., used) CT strings do not reduce the sour bend-fatigue life, provided no significant damage exists in the used string.
6. Mechanically induced surface damage can cause significant reduction in sour CT bend-fatigue life.
7. Use anticracking corrosion inhibitors to preclude HIC/SSC and mitigate surface damage.
8. CT strings cannot sustain the same maximum-allowable tensile loads permitted for nonsour service if the string has incurred HIC and/or SSC.
9. Anticracking corrosion inhibitors are effective against HIC/SSC but do not provide 100% of sweet life.
10. If properly managed, higher-strength (CT90, CT100, and CT110) strings appear to be fit for purpose for sour service regardless of low strain-to-failure performance in a slow-strain-rate test.
11. Use and/or development of HIC-resistant CT90 grades and HIC/SSC-resistant CT100 and CT110 is highly recommended for sour service.
12. Avoid using butt welds in sour-service strings wherever possible. **JPT**