FRACTURE MECHANICS IN THE ENVIRONMENT (IN-SITU)

THE DETRIMENTAL EFFECT OF CP, CO_2, AND H_2S OR OTHER ENVIRONMENTAL PARAMETERS ON FRACTURE TOUGHNESS

CONTENTS

BACKGROUND

One of the many challenges currently facing the oil & gas industry is the exposure of pipelines to increasingly complex environmental conditions that degrade the fracture toughness properties of their materials. A lack of standardized test techniques and consequently limited specific materials-related data and knowledge available affects the reliability of Engineering Critical Assessments (ECA) and Fitness for Service (FFS) evaluations.

The qualitative "workmanship" approach to weld flaw acceptance has been increasingly replaced by well-established alternative criteria based on quantitative fracture mechanics procedures, such as those outlined in BS 7910[1] and API 1104[2]. The accuracy of these procedures is reliant on key input data, which adequately characterizes physical properties of the pipe material and the welds used during pipe manufacture and pipeline construction.

There are many qualitative tests in use to evaluate the susceptibility of materials to cracking in sour environments. However, there is a growing need in the oil & gas industry to generate accurate quantitative data for use in Engineering Critical Assessments (ECA), used to derive weld flaw acceptance criteria during construction. This data is further used for ongoing FFS evaluations, and it has to be generated using project-specific material and environmental conditions.

Although often seen as an additional burden, the time, effort, and expenditure required to perform the necessary testing is essential, as it underpins any structural analysis. Without it, any analysis can be at best overly conservative, or at worst, unsafe.

There are, of course, standardized test methods for fracture toughness testing. However, it is increasingly apparent that the test methods to establish the behavior of metallic materials and welds used in extreme environments need to be adapted and standardized.

FRACTURE TOUGHNESS TESTING

It is valuable to review a few high-level definitions and an overview of key physical parameters, which will be discussed later in this article.

As is well known, most materials can be defined and characterized by their properties of strength and toughness. Strength is a measure of how well a material can resist being deformed from its original shape. In contrast, toughness is the ability of a material (with a notch or crack/defect) to absorb energy and plastically deform without fracturing.

A crack or flaw extension by a fracture toughness mechanism has two basic failure criteria: brittle cleavage fracture (unstable cleavage fracture) or ductile tearing (stable tearing resulting in plastic collapse). Depending on the behavior of the material, this fracture toughness can be expressed in terms of:

Elastic (Brittle) → K_{IC}, CTOD, J_{IC}, CTOD-R Curves, J-R Curves ← Plastic (Ductile)

When performing a test or a series of tests, the fracture toughness can be expressed as a single point value (K, crack tip opening displacement (CTOD / δ) or J as seen in Figure 1) or a resistance curve (CTOD-R or JR as seen in Figure 2).

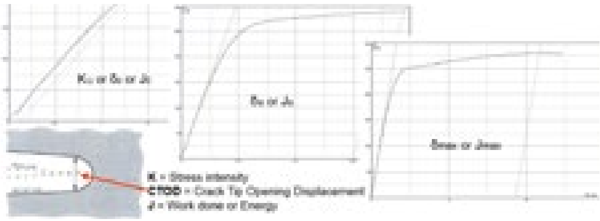

Figure 1: Single point toughness value

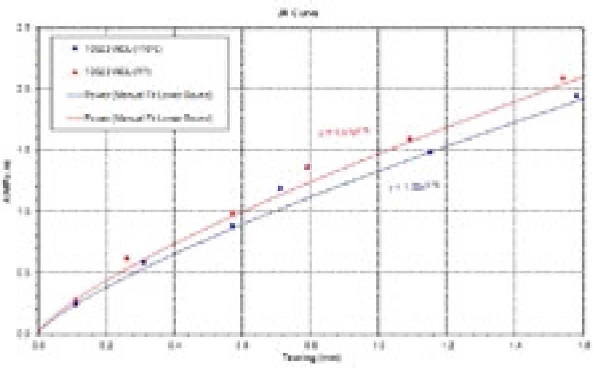

Figure 2: Resistance curve toughness value

SAMPLE GEOMETRY

The most common specimen configurations used in the oil & gas industry are Single-Edge Notched Bend (SENB); Compact Tension (CT); and Single-Edge Notched Tension (SENT). However, there are many other well-defined configurations, and the selection of the specimen geometry is usually dictated by the configuration of the component under test.

The logical fracture toughness sample geometry to extract from a pipeline butt weld is a SENB geometry sample, as recommended in API 1104[2] Annex A and illustrated below in Figure 3.

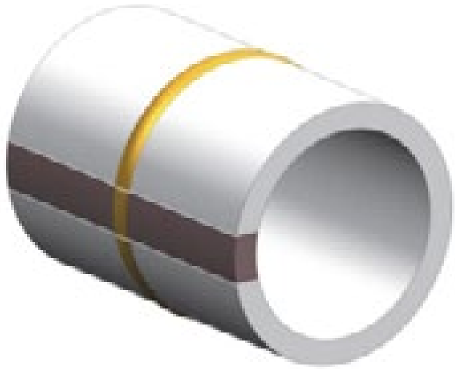

Figure 3: SENB Fracture Toughness geometry sample extraction from a pipe butt weld

One option is to modify the sample geometry and notch depth selection to represent the structural constraint more closely. For instance, the use of the SENT geometry as the relaxation of constraint allows for a more representative and less conservative fracture toughness value compared to the more highly constrained SENB and CT geometry sample configurations.

ENVIRONMENTAL TESTING METHODOLOGY

The behavior of most metallic materials in the air at room temperature (RT), elevated or sub-ambient temperatures, has been extensively investigated, and the resulting generic data or pass/fail criteria can be used in design. Although some data is available for materials based in seawater, a significant challenge faced by the industry is the lack of specific material data and knowledge on materials subjected to complex environments and, in particular, sour service conditions.

We have outlined below some specifics related to in-situ fracture toughness testing which provide critical input data to pipeline ECA and FFS analyses.

TESTING ENVIRONMENT

The critical environmental parameters associated with line pipe and girth welds used in the oil & gas industry are: pH;H_2S and/or CO_2 partial pressures; cathodic protection; temperature; salt concentration; and inhibitors. However, the combination and concentration of these parameters change on a project by project basis.

To replicate some of the environmental conditions, testing can be performed in a standardized solution such as 5%wt NaCl, ASTM D1141[3], NACE TM0177[4], or EFC 16[5].

As stated in practice guidelines: DNVGL-RP-F1086 Appendix C, it is recommended to perform the in-situ fracture toughness tests at room temperature (typically the worst case).

The specimen geometry frequently used in a test environment is SENB. The samples are notched and pre-cracked in "air", to generate a sharp crack at the starting point of the in-situ test, and can be coated (typically, 5 of the 6 sides, to simulate one sided diffusion) with or without the notch face exposed.

Post pre-cracking and coating, the sample is exposed to the test environment for a set number of days in order to reach hydrogen saturation. Four days is commonly used for this "pre-soaking" / "pre-conditioning" stage. However, the time required may need validation through separate testing, as the coating configuration, specimen size, and environment can affect the test.

TEST METHOD - RISING DISPLACEMENT *IN-SITU* FRACTURE TOUGHNESS

There are a number of international standards governing the testing of fracture toughness samples in "air". However, this feature does not address the specifics related to testing in-situ.

The aim of the in-situ rising displacement fracture toughness testing is to determine a critical toughness and, if appropriate, an initiation value for a crack extension by tearing in the specific environment.

The rising displacement test method uses a single specimen approach with DCPD to measure crack extension at loading rated (K-rates) between 0.1 and 0.005 N.mm-3/2/s (this is ~500 to 10,000 times slower than a comparable test performed in air).

The fracture toughness test output is expressed as J or CTOD at maximum load (Critical), 0.2mm or 0.05mm of crack extension. A J or CTOD-R curve may also be produced.

ENVIRONMENTAL TESTING - EXPERIMENT EXAMPLES

It is also critical to consider the detrimental effect of Cathodic Protection (CP), CO_2 and H_2S or other environmental parameters, on fracture toughness of carbon steel pipe material.

Fracture Toughness - effect of cathodic protection

In this example, pipe material was tested in-situ in seawater with and without active CP. A photograph of the testing setup is shown below in Figure 4.

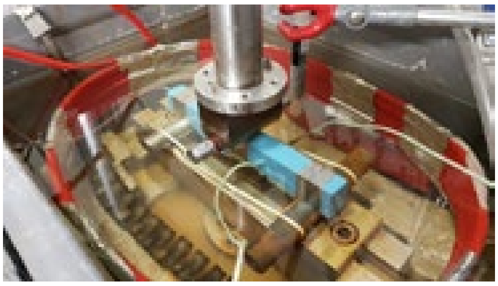

Figure 4: In-Situ Fracture Toughness Testing in Seawater with CP at Element Aberdeen laboratory

A reference sample was tested without CP to provide the baseline information for the material. Tests were performed to investigate the influence of active CP and test speed on the fracture toughness of both carbon steel parent metal and girth weld material.

As shown in the graphs in Figure 5, the application of CP resulted in a reduction of the CTOD by a factor of ~6. Also, as can be seen in the two graphs in Figure 6, a reduction in the test speed resulted in a further decrease in the CTOD by a factor of ~2.

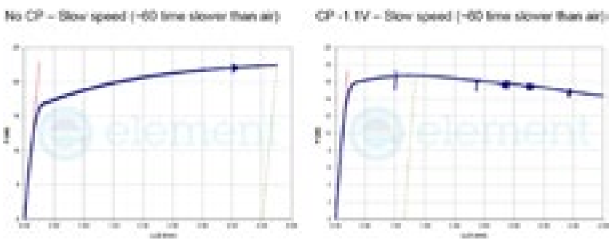

Figure 5: Effect of CP on CTOD results

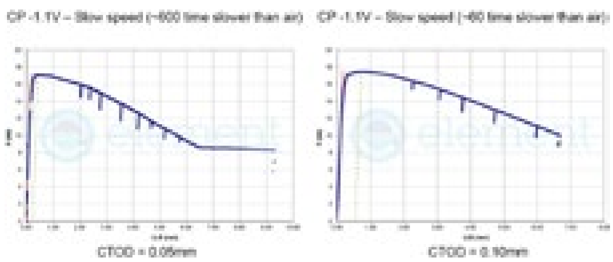

Figure 6: Effect of CP and speed on CTOD results

Fracture Toughness - effect of H_2S/CO_2

In another test, pipe material was tested in-situ in EFC165 solution with an H2S/CO2 gas mix at elevated pressure. A photograph of the setup is shown in Figure 7.

Figure 7: in-situ FT testing at elevated pressure with H2S/CO2 at Element Aberdeen laboratory

Carbon steel parent metal and girth weld material was tested in air and in-situ at elevated pressure with H2S/CO2 to generate J-R curves and an environmental knock down factor (KDF).

The results found that under these environmental conditions, the parent metal experienced a KDF of 10 and for the weld metal a KDF of 6. The experimental J-R curves are shown below in Figure 8.

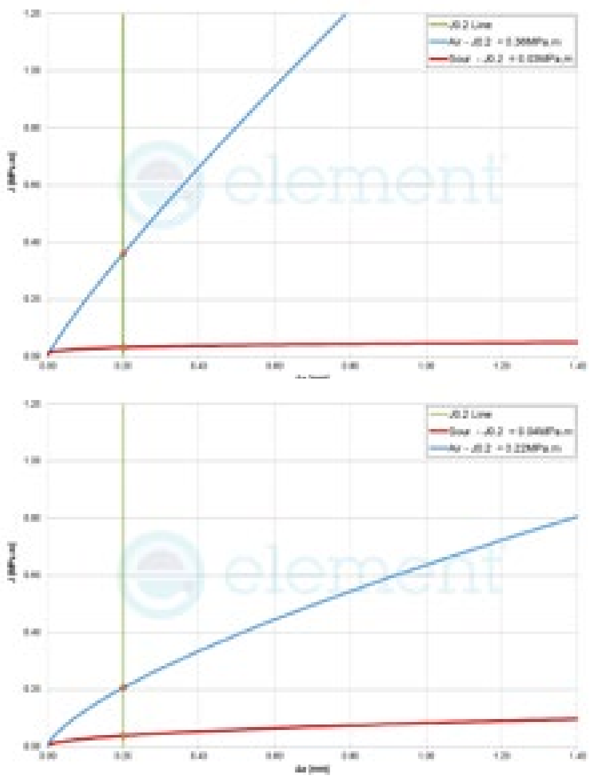

Figure 8: Parent (top) and Weld (bottom) Material J-R Curve "Air" Versus "Sour"

THE RESULTING IMPACT ON THE ECA & FFS ANALYSIS

Compared to equivalent testing in air, the results from these tests show a significant loss of fracture toughness. Although better than some of the generic knock down factors used in place of testing, a factor 10 on toughness is noteworthy. Significantly, the shape of the J-R curve has changed, resulting in the portion of the curve above the initiation value being flatter. This potentially changes the mechanism of further crack extension by tearing from an increase in driving force, to potentially a more time-dependent mechanism.

Depending on the installation and operational demands, this degradation of the material properties may be accommodated within the ECA or FFS evaluation. However, this may not be the case, resulting in either a reduction in the initial weld flaw acceptance criteria or some other change in the operation of the pipeline or, ultimately, even a significant reduction in service life.

Decreasing the weld flaw acceptance criteria can lead to more reliance on weld repairs, which, depending on the process, can be inferior to that achieved from an automatic welding process. This can lead to additional costs and delays without any tangible increase in the overall integrity of the pipeline.

From an ongoing fitness for service perspective, additional analysis can be achieved utilizing actual operational conditions and in-service inspections. However, without the initial test data generated at the pipe procurement and pipeline manufacturing stage using project environmental conditions, such analysis may be less able to demonstrate ongoing integrity.

CONCLUSION

It is widely accepted in the oil & gas industry that sour service testing still needs ongoing research. Although there is some information in the public domain, no standardized methods or data exist. This is partly due to the complexity of the environmental conditions and the variability they have on the material properties.

To accommodate the more severe environmental service conditions needed for the industry, it is no longer adequate to adopt a "workmanship" approach to weld flaw. A fitness for service approach is required, though the use of generic knockdown factors combined with a series of other conservative input parameters or additional global safety factors, can lead to an overly pessimistic and unworkable weld flaw acceptance criteria.

As an industry, we need a more pragmatic approach to testing and analysis, using more realistic, project-specific, but conservative parameters. This will ultimately achieve fitness for service, which will help the industry find the right balance between safety, reliability, and cost.

REFERENCES

1. BS 7910 (latest revision): "Guide to methods for assessing the acceptability of flaws in metallic structures".
2. API 1104 Twenty First Edition, September 2013 "Welding of pipelines and related facilities"
3. ASTM D1141 (latest revision), "Standard Practice for the Preparation of Substitute Ocean Water".
4. NACE TM0177 (latest revision), "Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H_2S Environments".
5. EFC 16 (latest revision), "Guidelines on Materials Requirements for Carbon and Low Alloy Steels for H_2S-Containing Environments in Oil and Gas Production".
6. DNVGL-RP-F108 (October 2017) Appendix C, "Sour service testing guidelines for the fatigue and fracture limit state".

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