

The Development of Eta Function for the Calculation of J-Integral Based on Notch Tensile Testing in Sulfide Stress Cracking (SSC) Susceptibility Evaluation

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ABSTRACT

A new methodology to evaluate the SSC susceptibility of high strength low alloy carbon steels (HSLA) based on a round notched tensile slow strain rate (NTSSRT) method was introduced and discussed by the authors in CORROSION 2021¹. This novel method provides an economic and more efficient way of evaluating SSC susceptibility of high strength carbon steels compared to the traditional DCB test² or other fracture mechanics test methods.

The approach unitizes round notch tensile specimen under slow strain rate tested in situ in sour environment. The post-processing of the tensile test results is done with the use of fracture mechanics based approach where the notch is postulated to behave as a sharp crack. The critical stress intensity factor is calculated using an FEA calibrated correlation function (the eta function) and designated as the K_{ISSC} for the materials.

In the present study, the calibrated eta-values were derived by use of finite element modeling to calculate the plastic component of the fracture toughness as measured in terms of the Rice's J-integral for the NTSSRT geometry. The eta values were obtained by use of FEA simulations for an Oil Country Tubular Goods (OCTG) C110 carbon steel. The effect of the notch depth and sample size (gauge diameter) on the eta factors were investigated. A new eta function was developed to capture a range of the notch sizes and test sample gauge radiuses (diameters). The new eta factors were applied to the test results obtained using the NTSSRT sample of C110 material. It was found that the new eta function can capture the fracture toughness of C110 material over a range of H_2S concentrations when compared to the standard DCB based test method.

Key words: eta function, SSC susceptibility, K_{ISSC} , FEA, J integrals.

INTRODUCTION

Carbon steels and low alloy steels have been used extensively in the oil and gas industry for many decades. The success of their applications in the energy sector is a balanced result of the materials affordability and operation needs in the fields. Producing H_2S containing fluids remains a challenge for well integrity as no compromise is acceptable. In recent years, there have been various investigations in the methods of measured material fracture resistance to reduce the conservatism or at least to define new ways that better fit with the field experience in producing H_2S containing fluids. This is because the presence of H_2S is a contributing factor that may lead to cracking in susceptible materials and therefore shorten their service duration and also compromise well integrity. Therefore, evaluation of the performance of steels in sour environment is critical prior to the applications of those steels to prevent asset loss and environmental damages.

So far, one of the most extensively used methods to evaluate capacity of steel for resistance to fracture in H_2S environments (i.e. sour fracture toughness) is NACE TM0177 method D, the so-called double cantilever beam (DCB) method², due to several reasons, among which are the relative simplicity for use in laboratory settings and due to its ability to provide (at least_ indicative quantified results instead of just a pass/fail test result. However, there are several limitations in such a test. Firstly it is applicable when the test sample meets the validity requirements on sample size which in practice limits this method to high strength alloys and also to moderate and severe sour environments such that the principles of linear elastic fracture mechanics prevail. However, for carbon and low alloy steels that serve in low-sour environment or are fabricated from lower strength OCTG grades, the linear elastic fracture mechanism is not necessarily satisfied. In the authors' prior work, a novel evaluation method that utilizes NTSSRT results had been introduced¹. The methodology is a path-independent J-integral based method that is postulated can apply across a range of J-dominant crack tip (notch tip) fracture mechanisms. From a practical perspective performing a tensile test requires much less effort and saves on

materials and also testing time. The method can provide an accurate prediction of material fracture capacity in sour K_{ISSC} by comparing with the available data in the literature.

However, the post-process of the obtained results can be tedious and prolonged. The complicated procedure of post processing included in this new method is largely due to a lack of valid eta function. In fact, this method had been examined by other researchers but also aborted due to challenges in finding the suitable eta functions^{3,4}. Clearly, the biggest obstacle in standardizing this novel method is the development of a universal eta function.

The fracture toughness in a NTSSRT test is calculated by combining the elastic and plastic parts of the fracture toughness which are commonly measured by the J-integrals such as outlined Equation 1.

$$J = J_{el} + J_{pl} \quad 1$$

Where, J_{el} and J_{pl} are the elastic and plastic component of the J values, respectively. J_{el} can be interpreted as given in Equation 2.

$$J_{el} = \frac{K^2}{E/(1 - \nu^2)} \quad 2$$

Here, K is the Stress Intensity Factor (SIF) for the tensile sample, E and ν are the elastic module and Poisson's ratio.

The plastic part of the J-integral is calculated from the expression given in Equations 3 and it comprises a calibration function (so called eta function), the plastic work performed in the load-gauge displacement plot and the net-section area of the sample.

$$J_{pl} = \frac{\eta_J A_{pl}}{B_N b_0} \quad 3$$

η_J is the eta values, A_{pl} is the plastic area under the load vs. load line displacement. B_N and b_0 are the net specimen thickness and the initial uncracked ligament in a SE(T) specimen.

As introduced before, for the tensile sample, a valid eta function has not been established before. However, there have been many efforts in developing eta function in other tests. In a SE(T) type test, J_{pl} is derived by Sumpter and Turner⁵ based on Rice's work that integrates the J values to the area under the load versus load-line displacement, as shown in Equation 3.

In the cases for the tensile samples, the definition of A_{pl} is still valid and can be obtained from the test force vs. extension curves. The plastic area A_{pl} is redefined to use of the net-section of the sample ($r-a$). Therefore, Equation 3 can be adopted as Equation 4 for a tensile sample.

$$J_{pl} = \frac{\eta_J A_{pl}}{\pi * (r - a)^2} \quad 4$$

Clearly, once both the J_{el} and J_{pl} can be obtained from the FEA simulation then an eta value can be calculated on the NTSSRT results. Conversely for a known eta value the NTSSRT tests result can be processed following the above approach.

$$K = \sqrt{\frac{J * E}{(1 - \nu^2)}} \quad 5$$

In the current research, the eta values were calculated using the finite element package Abaqus*, Both the J_{pl} and J_{el} components were determined for a given geometry & material combination. In our earlier effort, the total J has been simulated. In order to obtain J_{pl} , we need to simulate J_{el} by simulation of material with only elastic behavior. Once the J_{el} values can be obtained and the J_{pl} can be calculated by subtracting by total J . Furthermore, the effect of the notch ratio and sample size is investigated as the simulation matrix listed in Table 1. Other simulation details can be found in our previous publication¹. Notice here, only C110 was studied but we are working on other steels at the time to investigate whether this method is universal for other carbon steels.

In the current research, an eta function for the NTSSRT test geometry for the C110 carbon steel has been developed by the FEA simulated J values. The effect of the notch ratio and sample size on the eta values were examined. In addition, a proposed testing procedure based on this method has been established. The stress intensity factors generated from the NTSSRT based approach and from the traditional DCB tests are compared and discussed.

EXPERIMENTAL STUDY

Experimental procedures and matrix

In order to validity the new solution NTSSRT tests of C110 were performed at environments containing different H_2S partial pressure as shown in Table 1, The procedural details can be found in our last paper¹. The experimental matrix can be found in Table 2.

Table 1.
Simulation matrix.

Materials	L/inch	$\theta/^\circ$	R/inch	r/inch	a/inch	a/r
C110	2	30	0.1875	0.0625	0.025	0.2
					0.0375	0.3
					0.05	0.4
					0.0625	0.5
					0.075	0.6
					0.0875	0.7
			0.1875	0.125	0.025	0.2
					0.0375	0.3
					0.05	0.4
					0.0625	0.5
					0.075	0.6
					0.0875	0.7
			0.375	0.25	0.025	0.2
					0.0375	0.3
					0.05	0.4
					0.0625	0.5
					0.075	0.6
					0.0875	0.7

* Trade mark.

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