

A Novel Model to Assess Sulfide Stress Cracking (SSC) Susceptibility of Carbon Steels

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ABSTRACT

NACE TM0177 method D¹ has long been the standard method for estimating SSC susceptibility of carbon steels by directly measuring K_{ISCC} . However, the lengthy experimental duration made the generated results unreliable especially in the low H_2S concentration environments. Therefore, a novel approach based on J-integrals obtained from the notched tensile slow strain rate test (NTRRST) is established to provide a universal solution for SSC susceptibility evaluation. In the current research, the K_{ISCC} values of two different materials in air, C110 and P110, were evaluated using the new approach and compared to available data from the literature using NACE TM0177 method D¹. The effect of the notch ratio was investigated using finite element analysis (FEA) to verify the J integrals calculated using the proposed calculation method. The simulated tensile behavior was compared to the experiments performed in air and used to assess the optimal notch size. The experiments performed under H_2S containing environments were used to develop a calculation method for K_{ISCC} based on analytical solutions for the fracture energy on notched tensile specimens. Good agreement was observed between the NACE D tests and the NTSSRT results at conditions where a sour environment existed according to the NACE MR0175/ISO 15156 definition². In addition, NTSSRT experiments of those materials under different H_2S concentrations and pH were compared. The results provide further analysis of the successful evaluation of K_{ISCC} .

Key words: SCC susceptibility, K_{ISCC} , Abaqus, Carbon steels, J integrals.

INTRODUCTION

The presence of H_2S in the production of oil and gas is known to cause sulfide stress cracking (SSC) and associated failures of oil country tubular goods (OCTG)^{3, 4}. To prevent such damages, it is critical to evaluate the SSC susceptibility of those steels before installation.

Currently, the commonly utilized method to quantify the SSC susceptibility is NACE TM0177 method D, the double cantilever beam (DCB) method. It has been adequately used as a valid method for discriminating the SSC resistance of various carbon steels^{3, 4}. However, it has a fundamental limitation due to the fact that the concept of the DCB method is based on linear elastic fracture mechanism, which

might not be necessarily the universal mechanism in SCC mechanisms. In addition, the longevity of the testing period (14 days) made the results difficult to reproduce and the large size and the complicated configuration of the samples made this test expensive. As a result, a more comprehensive, abbreviated and affordable methodology is critically needed to determine the SCC resistance of tubular materials.

J integral method is an alternative method in measuring fracture toughness. As early as 1968, Rice *et al.*,⁵ proposed a path-independent integral calculation model to characterize nonlinear material behavior around a crack. In recent years, Case *et al.*,⁶ developed a J integral solution based on Rice's J integral model. The new solution used the recorded load and extension information in the notched tensile slow strain rate test (NTSSRT). The most important advantage of the J integral method is that it considers a crack inside a non-elastic body, instead of only considering linear elastic fracture mechanism as in the NACE TM0177 method D. Moreover, the duration of a tensile test (usually less than 8 hours) is much shorter compared to the DCB test. As a result, the solution chemistry does not changed as much as in the NACE D method, which improves the reproducibility significantly. In addition, the sample geometry of a notched tensile sample is also less complicated than the DCB test, which makes this method more affordable than NACE D method. Apparently, J integral method is a desirable alternative option for evaluating fracture toughness in the sour environment.

Although the J integral method has significant advantages over the NACE D method, it still has many issues to overcome. First, the values calculated in this solution need verification. To make sure this solution is valid, the numbers obtained through this model should be examined by other methods, including material simulation software or other existing testing methods. Second, the scope of J integral calculation method requires more investigation in terms of application. For example, details such as the selection of the adequate notch size, the extraction of appropriate K_{IC} or K_{ISCC} from the tensile experiment, require further investigation for the application of the novel method.

In the present study, the solution of Rice's J integral model based on the NTSSRT is introduced and the generated J integrals in various environments are compared with finite element method (FEA) simulated J integrals through Abaqus. The effect of notch ratio and the H₂S concentration on the behavior of materials C110 and P110 was investigated. Later, the extent of the application of the current model was discussed in detail and evaluated based on various available data.

SIMULATION SETTINGS AND EXPERIMENTAL PROCEDURE

Simulation settings and matrix

One purpose of the research is to find a suitable notch geometry of a tensile specimen to use in the novel J-integral model. However, to find the correct criterion of the notch ratio, it is necessary to make sure the generated results are reliable. In order to verify the generated results from the model, the effect of notch ratio was investigated and the obtained J-integrals were compared with FEA simulated results.

The simulation geometry is given in Figure 1. Figure 1 (a) shows a general geometry of the simulated sample. The R is the radius at the top of the specimen, and r is the radius at the bottom of the specimen. In Figure 1(b), the detail of the notch is given. The notch depth is defined as a, the notch angle is 2 θ and half angle is θ . Here, only the quarter sample was simulated because the specimen is symmetric, the quarter sample is enough for the simulation. In addition, it reduced the simulation load. Because the specimen is cylindrical, the sample was defined as an axisymmetric deformable shell to reduce the calculation load. The properties of C110 and P110 were generated from typical strain-stress relationship. The relationships are given in Figure 2. An artificial linear increase in the true stress-strain curve was applied when maximum load/stress were achieved in the tensile test for matching with the test data after sample necking. The reason for the artificial addition is that the strain concentration in the notch can exceed the strains measured in the uniaxial tensile test. In addition, it should be pointed out that the stress and strain mentioned in this report is true stress and strain, unless specially mentioned.

Two boundary conditions are defined. The first boundary condition is to make sure there was no motion in y direction at the symmetry plane around the notch in the middle of the sample; the second one is to set an elongation at the top of the sample. By applying different elongations at the top, it was possible to circumscribe J integrals change with the elongations. In the mesh module, a global mesh seed size of 0.02 was defined. Local mesh seed size of 0.001 was defined at the bottom of the sample around the notch. This small mesh seed size makes the generated J-integrals more accurate. The simulation matrix is given in Table 1.

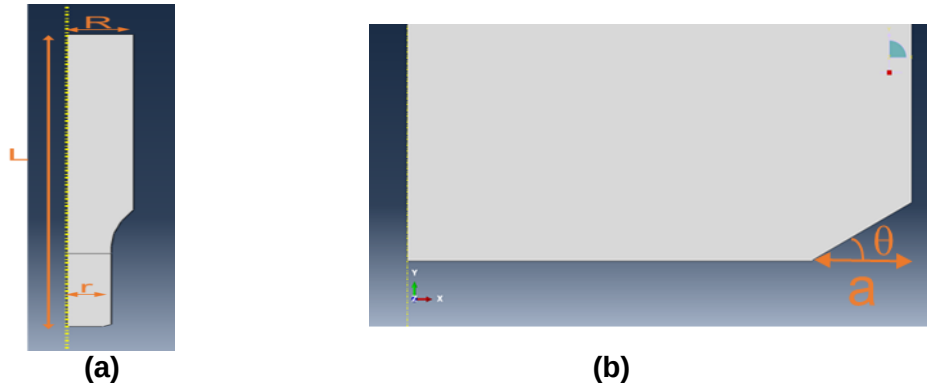


Figure 1: Simulation geometry (a) Simulation part (b) Notch geometry

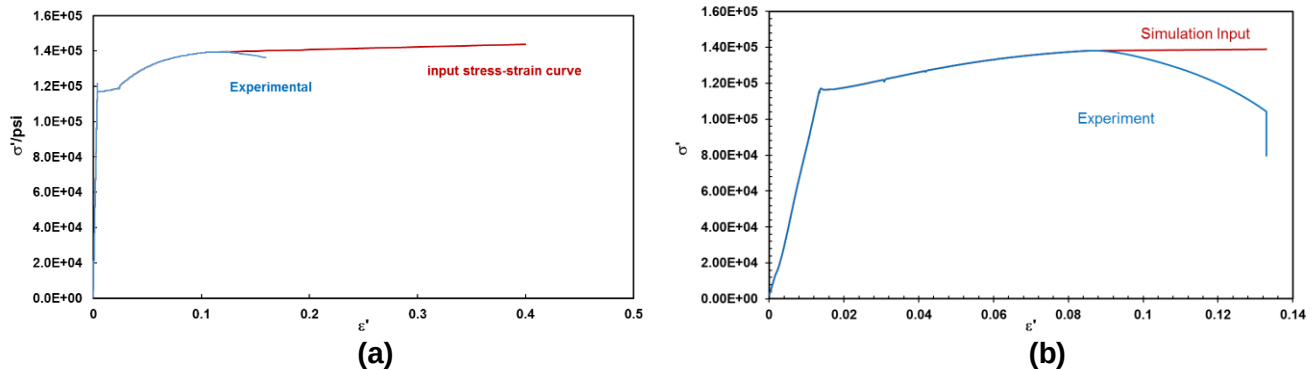


Figure 2. Material properties of C110 (a) and P110 (b) in the simulation (Blue line is generated from experiment and red line is the input material properties in Abaqus.

Table 1. Simulation matrix

Materials	L/inch	$\theta/^\circ$	R/inch	r/inch	a/inch	a/r
C110	2	30	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
P110	2	30	0.1875	0.125	0.0125	0.1
					0.025	0.2
					0.0375	0.3
					0.05	0.4
					0.0625	0.5

Experimental procedure and matrix

Since this novel model is based on a different cracking mechanism hydrogen enhanced localized plasticity (HELP) instead of hydrogen enhanced decohesion (HEAC), another purpose of the research is to identify how this novel model works in different sour conditions. In order to confirm the applicability of this novel model in sour environments, experiments with different concentration of H₂S were performed. The effect of H₂S activity was studied and the test matrix can be found in Table 2.

Table 2. Test matrix for studying effect of H₂S activity

Materials	Sample Length/Inch	Notch Opening Angle	Gage Diameter /inch	Notch Ratio	H ₂ S Activity	Testing Solution Chemistry	Dependent Variables
C110	4	60	0.25	40%	100ppm	NACE solution C[1], pH 4.5	K _{ISSC} estimated from different methods
					200ppm		
					300ppm		
					500ppm		
					800ppm		
					1%		
					30%		
100%					NACE A solution[1], pH 3.5		
0.01%							
0.1%							
1%							
10%							
80%							
90%							

The tested notch tensile specimen's specifications can be found in Figure 3. The size of the sample in experiments are the same as the samples listed in Table 1.

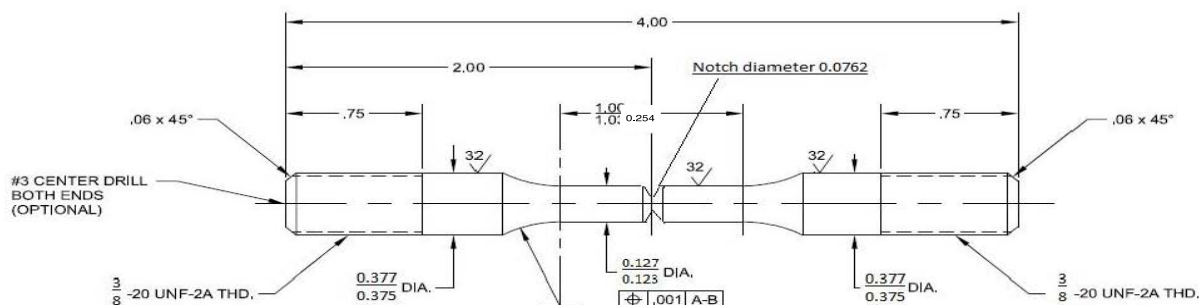


Figure 3. Dimension and tolerances of the notched tensile specimen configuration

In the experiments, the testing solution was prepared following the NACE TM0177 procedure. The solution was pre-purged with N₂ before the experiments for at least 2 hours. The concentration of H₂S and the solution pH was adjusted by controlled addition of Na₂S·9H₂O. The amount of chemicals is calculated using OLI[®] thermodynamic speciation software. The NTSSRT in corrosive environments is dependent on the initial empirical estimation of a critical extension rate at which the susceptibility to crack propagation can be observed. Based on the available literature on the effects of H₂S⁷, a strain rate of 1x10⁻⁶ s⁻¹ was selected for the tests. The testing cell can be found in Figure 4.

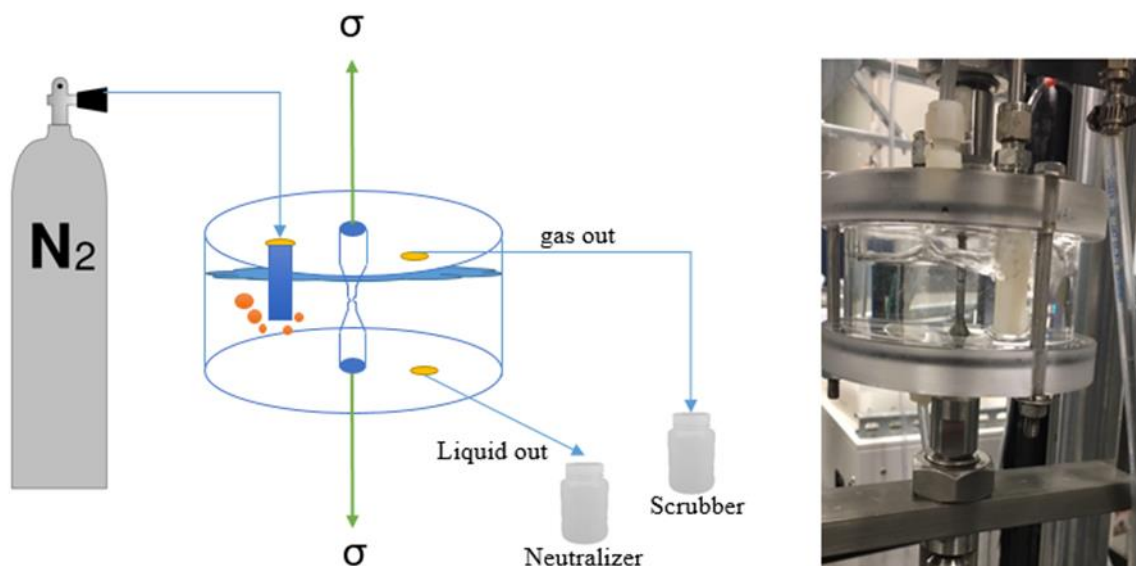


Figure 4. Test cell used in the experiments involving sour test brine

RESULTS AND DISCUSSION

Evaluation of the notch effect

The results of the NTSSRT testing on the specimens made from C110 and P110 steel are shown in Figure 5, in the form of the stress vs. strain curves at different notch sizes. As it can be appreciated from the behavior of the curves shown in Figure 5 (a), the increase in the notch depth coincides with increase in the fracture load and decrease in the overall ductility. Notably, the change in the ductility and strain hardening behavior is exhibited by the C110 steel at notch depth greater than 40%, which suggests that the occurrence of plastic collapse as the relative value of the stress vs. yield stress. The corresponding real stress vs. deformation for the P110 steel, obtained at different notch depths are shown in Figure 5 (b). As it can be observed, the trend is similar where the fracture stress increases with notch depth but coincides with the loss of ductility. In addition, the FEA simulation was performed to predict the notched tensile behavior. The result shows a good agreement between the FEA simulated tensile behavior and the experimentally determined result as only minor differences were observed between simulation and experiment (Figure 6). This suggests that FEA simulation provides good prediction of tensile behavior.

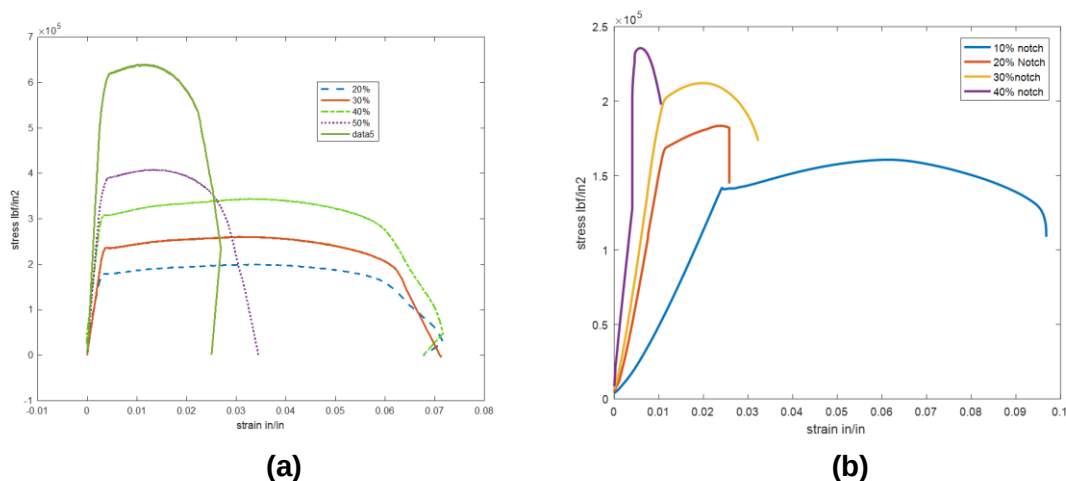


Figure 5. Effect of notch ratio on the real stress deformation relationship at different notch sizes of (a) C110, (b) P110; gage diameter=0.25", air condition at room temperature.