

Effect of Side Groove Geometry on Crack Propagation Behavior and K_{1SSC} in DCB Test

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ABSTRACT

The double-cantilever beam (DCB) test method standardized in NACE TM0177-2016 is being increasingly applied as a quality assurance test to specify the performance of carbon and low-alloy steels for the sour service. The DCB test can contribute to the quantitative evaluation of the fracture toughness in a specific environment by assessing the crack arrest of a pre-cracked specimen. The test method has been discussed from the viewpoint of specimen geometries, such as side-groove root configurations, which are considered to change the stress concentration and thereby prevent the edge crack occurrence.

In this paper, the DCB test was conducted with the current standard V-type and a proposed U-type side-groove configuration in order to compare crack propagation behaviors, by using in-situ ultrasonic observations and K_{1SSC} values with 110 ksi sour grade material in a simulated sour environment. Crack propagation began a few hours after initiation of the test in NACE Solution A saturated with 1 bar H_2S gas. The crack propagation rate and the final crack length were similar between the DCB specimens with the V-type and U-type side grooves. The obtained K_{1SSC} values were almost the same, regardless of the side-groove configuration. In addition, the frequency of edge cracks for DCB specimens with the

U-type side groove was lower than that of those with the V-type side groove. Therefore, it is appropriate to use the proposed U-type side-groove configuration for the DCB test.

Key words: Double Cantilever Beam, Sulfide stress cracking, FEA, K_{1SSC} , NACE TM0177-2016 Method D, Compliance, Crack start position.

INTRODUCTION

The resistance of low-alloy steel oil country tubular goods (OCTG) to sulfide stress cracking (SSC) is an important issue regarding material selection. The NACE TM0177-2016¹ standard describes several test methods to be used to assess the susceptibility of steels during initiation and propagation of SSC. To determine the fracture toughness in a sour environment, described as K_{1SSC} , the NACE TM0177-2016 Method D (double-cantilever beam (DCB)) test method¹, which was first proposed by Heady², is increasingly applied as a quality control test for OCTG. The K_1 relation for the present DCB specimen in NACE TM0177-2016 was experimentally observed to follow a modified version, as given in Equation (1).

$$K_{1SSC} = \frac{Pa(2\sqrt{3}+2.38h/a)(B/B_n)^{1/\sqrt{3}}}{Bh^{1.5}} \quad (1)$$

K_{1SSC} = critical stress intensity factor for sulfide stress cracking

P= measured final lift-off load

a= measured final crack length

h= half specimen height

B= specimen thickness

B_n = web thickness

In this test, it is important to precisely determine the critical environmental fracture toughness in a sour environment, recently published as the concept of the limiting accessible K_{1SSC} (called K_{1LIMIT}) proposed by Ernst³ and Szklarz⁴⁻⁶. Therefore, the critical flaw size that will not initiate SSC in a specific environment can be identified by using the DCB test results for oil and gas well design.

As previously proposed³⁻⁶, the K_{1LIMIT} values can be determined by the relation between $K_{1applied}$ (initial loading through the wedge insertion or initial stress intensity factor) and K_{1SSC} . To establish a high-reliability relation, the test parameters providing significant variability in test results should be considered. Although the DCB test has been standardized in NACE TM0177-2016 Method D, it is acknowledged that test variables such as specimen geometry, initial stress intensity factor and crack starter geometry can affect the test results. There are numerous publications that discuss the factors influencing K_{1SSC} ⁷⁻¹⁶. These achievements have modified the test protocols to obtain highly reliable test results.

Edge fracture on DCB specimens is a major concern, and was reported by Sponseller¹⁰ from the viewpoint of chemical segregation and by Nakamura¹⁷⁻¹⁹ from the viewpoint of fracture mechanics. In previous papers, the effect of different side-groove configurations on the DCB specimen, such as several V-notched types and a U-notched type, on edge fracture in the DCB test was investigated from the viewpoint of the stress condition at the crack tip using finite element analysis (FEA). The side-groove configuration can play a significant role in crack initiation and propagation. With side-groove root R 0.25 (NACE standard side-groove configuration), cracking at the side-groove bottom was found to propagate faster than at the center of thickness, even in an air environment. The compliance formula in NACE TM0177-2016 can be applied for new DCB specimens with a U-type side-groove¹⁹.

In this paper, the DCB test was conducted with the current standard V-type and a proposed U-type side-groove configuration in order to compare crack propagation behaviors, by using in-situ ultrasonic observation and K_{1SSC} values with 110 ksi sour grade material in a simulated sour environment under

the standard conditions of NACE TM0177-2016 Method D. Another DCB test was performed to compare the frequency of edge cracks between the DCB specimens with the two types of side groove configuration.

EXPERIMENTAL PROCEDURE

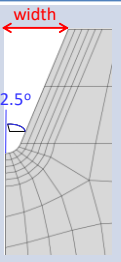
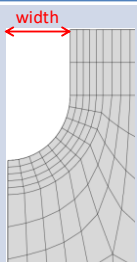
Configuration of DCB test specimen

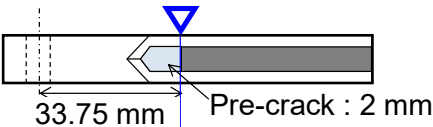
A single sample of pipe (OD 250 mm x WT 43.73 mm) was used for all tests to avoid variations due to differences in materials. The pipe was a high-strength low-alloy steel sour grade OCTG with a specified minimum yield strength of 110 ksi (760 MPa) achieved through quenching and tempering heat treatments. The mechanical properties are shown in Table 1.

To investigate the influence of the side-groove configuration on the test results, standard size DCB specimens with a V-type side groove, as described in NACE TM0177-2016¹, and specimens with a U-type side groove, as shown in Figure 1(a), were produced from the mid-wall of the material. The crack starter configurations specified in NACE TM0177-2016, shown in Figure 1(b), were of two specimen types: a chevron-notched specimen with standard side-groove with a fatigue pre-crack, and a chevron-notched specimen with a U-type side-groove root of R 0.95 with a fatigue pre-crack. The side-groove width was same as the standard size.

Table 1 Details of tested Material for investigation of crack propagation behavior.

Grade	Pipe size (mm)	Yield Strength (YS)		Tensile Strength (TS)	
		MPa	ksi	MPa	ksi
110 ksi Grade	OD 250 x WT 43.73	783	113	861	125.2

Side-groove R	V R 0.25 mm	U R 0.95 mm
Configuration		
Configuration memo	Standard V side groove	width : equal to standard V side groove



(a) Side-groove configuration

(b) Crack starter configuration

Figure 1: DCB specimen configurations.

Combination of DCB test and in-situ Ultrasonic Testing (UST) device for measuring crack length

The DCB test according to NACE TM0177-2016 Method D was conducted under the two test conditions summarized in Table 2. Condition #1 was selected as the standard condition defined in NACE TM0177-2016 Solution A, with an arm displacement of 0.51 mm: the nominal arm displacement was in the middle of the allowable range for API grade C110 in NACE TM0177-2016. To investigate the influence of side-groove configuration on crack propagation behavior, the V-type side-groove and U-type side-groove specimens were set in the same vessel. In addition, in order to investigate the influence of more severe mechanical conditions on crack propagation, Condition #2 was selected by using an arm displacement of 0.89 mm for the V-type and U-type side-groove specimens. All DCB

specimens were loaded by insertion of a wedge with an appropriate thickness. The wedge was inserted by the vise method.

The test temperature in containers where the DCB specimens were placed was controlled to 24 $\pm$ 1.0°C using a water bath. In all cases, the pH of the test solution was measured initially (before and after H₂S saturation) and finally at the end of the test period. The H₂S concentration in the test solution was measured at the start and at the end of the test.

Crack propagation behavior was measured using an in-situ UST observation instrument²⁰. Figure 2 shows a schematic drawing of the in-situ UST instrument. The crack portion detection system was composed of a 10 MHz ultrasonic probe in the detection side, and the detection side chamber was separated from the DCB test side by a plastic barrier. The DCB test-side chamber was filled with a test solution (NACE-A solution, pH 2.7) and the detection side was filled with water. The C-scan depth was set to the center of the width of the DCB specimen.

Figure 3 shows a schematic drawing of longitudinal sections of DCB test specimens and examples of C-scanning maps obtained at the start of the DCB test. The test solution was de-aerated with nitrogen and purged with H₂S before the DCB test. To achieve a saturated H₂S concentration in the test solution, 1 bar H₂S gas was injected for 1 hour with a flow rate of 200 mL/min. After reaching H₂S concentration saturation, the H₂S gas flow rate was kept very low during the DCB test to maintain the H₂S concentration.

C-scan mapping was automatically performed during the DCB test. An auto-scan was undertaken at 1- to 20-hour intervals to observe the crack propagation behavior. Under these conditions, immersion was stopped after approximately 100 hours because the cracks were arrested.

After exposure, the wedge was removed from the DCB specimen by using a tensile machine at a displacement rate of 0.5 mm/min. The lift-off load value was determined from the abrupt change in the slope of the stress versus strain curve ("lift-off" curve). After measuring the lift-off load, the DCB specimen was chilled with liquid nitrogen and broken with a hammer and chisel to measure the crack length at crack arrest. Then, the $K_{I_{SSC}}$ values were calculated by Equation (1).

Table 2 DCB test conditions for measuring crack length during the test by using in-situ UST.

Specimen size	Standard (9.53 mm)	
Notch type	Chevron notch with pre-crack ($a = 33.75$ mm)	
Side-groove root configuration	V-type side groove, U-type side groove (a pair of specimens were set in same test vessel)	
Wedge material	As-quenched material	
Wedge insertion	Vise method	
Test Solution	5.0 wt %NaCl + 0.5 wt% CH ₃ COOH	
Test gas	1 bar H ₂ S	
Volume of solution	1 liter of test solution per specimen	
Test solution pH	between 2.7 and 3.8	
H ₂ S flow rate for duration	5 ml/min per 1 l of test solution	
Test duration	100 hr	
Target arm displacement	Condition #1 0.51 mm (± 0.03)	Condition #2 0.89 mm (± 0.03)
Type of vessel	2 l capacity vessel (1 liter test solution per 1 DCB test specimen)	
Temperature control	24 C ($\pm$ 1.0)	

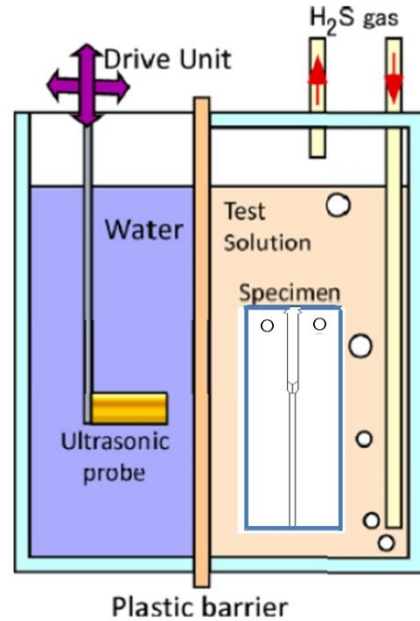


Figure 2: Schematic drawing of in-situ UST device and DCB test vessel.

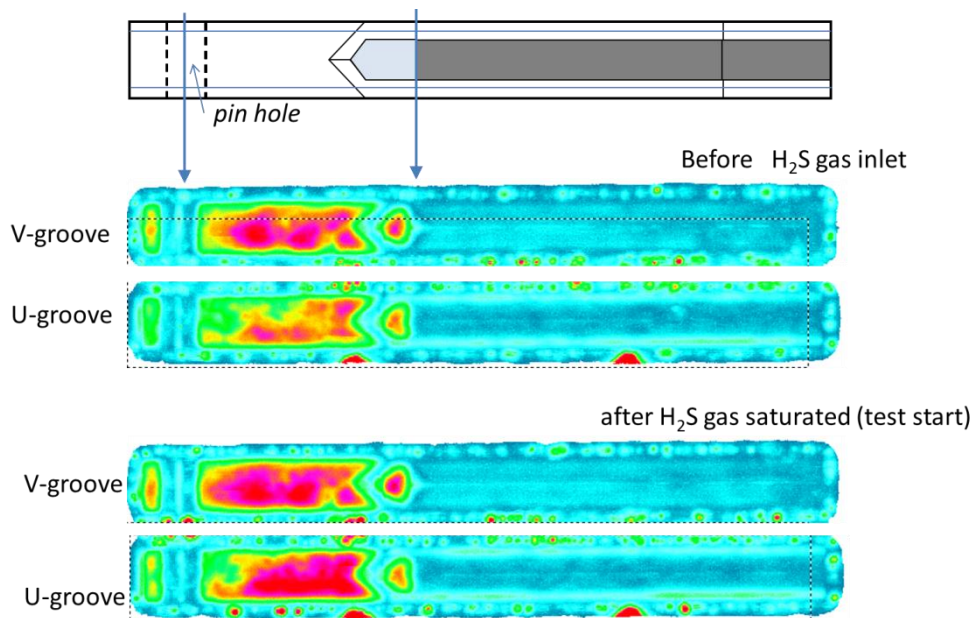


Figure 3: Schematic illustration of longitudinal section of DCB test specimen, and examples of C-scanning maps obtained at start of DCB test.

Finite Element Analysis for DCB specimens

The K values at the center of the thickness of the DCB samples were calculated using FEA¹⁹. Taking into consideration the symmetry of the DCB specimens, only a quarter of the DCB specimen was modeled. Symmetry boundary conditions were imposed on the planes (XY and XZ). The DCB opening was simulated by imposing a displacement following the Y-direction along this axis. The arm displacement was defined at the outside of the arm on the load line.