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GENERATION AND MONITORING OF SYNTHETIC CRACK-LIKE FEATURES IN PIPELINE MATERIALS USING CYCLIC PRESSURE LOADING

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ABSTRACT

Crack management has become a major focus for many gas and liquid transmission pipeline operators. Failures associated with crack-like features have been a concern for both pipe operators and regulatory agencies. As a result, pipeline operators are excavating large numbers of features for not only in-line inspection (ILI) validation purposes, but also to make repairs. Additionally, ILI technologies have advanced significantly in recent years and are identifying an increasing number of features with greater levels of accuracy. With increased data generation, operators are faced with an unprecedented amount of information that requires response prioritization.

Because of high levels of conservatism associated with today's assessment methods, pipeline operators are spending a significant amount of capital excavating crack-like features. There is a need for improved assessment methods that integrates testing simulated / synthetic crack-like features. This paper will provide details on a study funded to systematically generate crack-like features in pipeline materials with the application of cyclic internal pressure loading. Synthetic crack-like features were generated in 12.75-inch x 0.250-inch, Grade X42 pipe material using electronic discharge machining (EDM) to form notches. Notch depths were 10% of the nominal wall thickness and ranged from 1-inch to 3-inches in length. The pipe samples were then pressure cycled to achieve microcracking at the base of each notch.

Initial stages of the program involved sectioning features to quantify crack growth levels. Once a systematic process for growing cracks from EDM starter notches had been validated, testing involved cyclic pressure fatigue to failure and burst testing. The advantage with the crack generation methodology used in this study was the ability to generate sharp, crack-like features without altering the microstructure of the pipe material in the vicinity of the feature. Programs such as the one presented in this paper are useful for both generating features in pipeline materials and quantifying behavior of pipeline materials subjected to cyclic pressure and burst loading.

Keywords: Crack, EDM, Pipeline, Fatigue, Fracture Mechanics, Notches.

1. INTRODUCTION

Pipeline crack management has become a major focus for many gas and liquid transmission pipeline operators. As described by API RP 1176 (Reference 1), determination of the most appropriate method for assessing cracks in pipelines involves multiple factors. The most methods used by the industry nowadays are the In-line Inspection (ILI) and/or hydrotesting. Either methods can be used as the sole assessment approach, or they can be used in combination. API RP 1176 lists many considerations when each method should be applied. This work focuses on the generation of cracks in pipes that will be further examined by ILI tools. Pull-tests with ILI tools will be the next phase of this work but is not included in this paper.

ILI technologies have advanced significantly in recent years and are identifying an increasing number of features with greater levels of accuracy. Many different technologies are available in the market for crack-detection (i.e., ultrasonic and magnetic). The selection of the inspection technology/tool depends mainly on the type of threats that are expected to be found in the pipeline. This emphasizes how important it is for the operator to understand not only the pipelines' "DNA" (References 2, 3, and 4), but also its susceptibility for different types of threats. Operators should also understand the limitations and capabilities of each ILI tool.

Operators spent a significant amount of capital excavating potential crack and crack-like threats. To support excavation efforts, ILI tools need to be accurate in identifying, detecting, and sizing crack features. With accurate ILI tools, operators can save time and effort by not excavating potential false calls. To help improve the assessment methods by ILI, the work presented in this paper integrates testing simulated / synthetic crack features that will later be inspected by ILI tools. Crack sizes generated by this work will also be compared with cracks identified by future pull-tests.

In this study, synthetic crack features were generated in the pipe body (PB) of a 12.75-inch OD x 0.25-inch WT (wall thickness), Grade X42 HF-ERW (high frequency-electric resistance welded) pipe material. Again, the goal of the present study was to develop a practical method of generating consistent crack features in modern pipes. In the future, these crack features could be used to calibrate ILI tools and evaluate the accuracy of fracture mechanics predictions. Crack features were introduced by pressure cycling pipe samples with electrical discharge machining (EDM) notches. The notches will be the "starters" for crack initiation. Only PB features were generated in this study, as seam weld cracks were outside the scope of this study. Testing involved cycling samples to failure, cycling samples to a pre-determined target strain, examination of cracks, and preserving some samples to be further examined by pull-testing the ILI tools.

2. MATERIALS AND METHODS

Several steps were involved in generating synthetic crack features in pipelines. The methods are presented in the discussion that follows.

First, EDM notches were machined into the pipe. EDM notches may be placed either in the inner diameter (ID) and/or in the outer diameter (OD) of the pipe, depending on the needs of the testing program. For the purposes of this study, EDM notches were created in the OD of the pipe to simulate the type of features commonly found in the field. EDM notches serve as crack "starters" and are used to generate microcracking at the base of the notch during pressure cycling. EDM notches can also be fabricated in the seam weld, but this option was not investigated under the scope of this work.

Once the EDM notches were fabricated, end caps and pressure ports were welded to the pipe to create a closed pipe sample. Uniaxial strain gages and clip gages were installed across the EDM notches to monitor notch opening displacement (hoop direction) during pressure cycling. Biaxial strain gages were also used in the PB to calculate strain values (hoop and longitudinal directions) away from the notches. The biaxial strain gages were aligned circumferentially with the notches and in some cases 90 degrees relative to the notches. The use of multiple strain gages around the circumference of the pipe can be helpful to identify pipe ovality. Strain magnitudes are measured in microstrain ($\mu\varepsilon$; where $\mu\varepsilon$ equals 1×10^{-6}) and they are used to correlate relative notch open displacement versus crack growth.

After fabrication and the test set-up was completed, the pipe samples were pressure cycled until failure (thru-wall cracking) or until a pre-determined target strain had been reached. Crack initiation was indicated by an increase in the relative opening displacement of the notches. After pressure-cycling of the samples, crack formation was examined by mounting a transverse specimen, or by breaking the feature open for a longitudinal view.

For this study, five (5) pipe samples were fabricated as shown in Table 1. All Samples were 6-ft long and fabricated using 12.75-inch OD x 0.25-inch WT, Grade X42 HF-ERW pipe material. Each sample had a set of EDM notches installed as shown in **Error! Reference source not found.** (Notch Geometry). All notches were 0.025-inch deep (10% of the pipe's nominal wall thickness) and 0.01-inch wide (as narrow as possible, limited by the EDM electrodes). Pipe samples were pressure cycled from 99 to 1,186 psig (6-72% SMYS). The stopping criteria were to either cycle the samples to failure (thru-wall cracks) or until the target strain level had been reached.

Initially, three different EDM notch geometries were evaluated, designated as type "A", "B", and "C". Notch "A" is 1.5-inch long, Notch "B" is comprised of two tightly spaced 1-inch long notches, and Notch "C" is 3-inches long. To investigate these three notch geometries, Sample 1 (sacrificial sample) was fabricated containing two of each type. Figure 1 shows the locations of the notches in Sample 1 with respect to the longitudinal seam, while Figure 2 **Error! Reference source not found.**details the notch geometries. During pressure cycling the notch openings were monitored by uniaxial strain gages installed across them. Clip gages were also used on a few notches for comparison purposes.

The sacrificial sample (Sample 1) was pressure cycled until failure (thru-wall crack). Following the failure, all notches were examined for crack formation. Notches "A" and "C" were examined using a method that involves mounting one half of the feature to view the transverse profile and breaking open the other half to view the longitudinal profile, as shown in Figure 3. For Notches "B", only the longitudinal profiles were examined (meridional view).

All cracks initiated at the bottom of the notches and grew in the radial direction. For the most part crack growth was not observed in the longitudinal direction beyond the notch length. As mentioned previously, Notch "B" was comprised of two tightly spaced notches (0.25-inches apart, Figure 2**Error! Reference source not found.**). As close as they were, even in that arrangement the cracks did not interact during pressure cycling. Final crack depths varied between notches, but all crack lengths were equal to the notch length.

Figure 4 shows cracks initiated from Notches "A2", "B0", and "C1". The notch geometry for Samples 2-5 was chosen based on the crack growth results from the sacrificial sample. As discussed later in the results section, Sample 1 failed at feature type "C" (fastest crack growth rate); therefore, for optimizing testing schedule and to guarantee a crack length within ILI tool detectable tolerance, feature type "C" (3-inch long notch) was the selected candidate to be used in the other samples (Samples 2-5). Figure 5 shows the geometry of the notches and schematics for Samples 2-5.

In addition to the pressure-cycling testing, various post-cycling activities were also completed that included burst testing, crack examination, and grinding of the EDM notches. All post-testing activities for each pipe sample are listed in Table 2 (Post Cycling Activity). Samples 4 and 5 were not examined for cracks (broken open) as they will be used in the next phase of this work that involves inspection using ILI tools in a pull-thru test.

3. RESULTS AND DISCUSSION

For Sample 1 (sacrificial sample), failure was reported at 63,987 cycles. However, after examining the data (including the recorded video), it was noticed that the axial strain gage on Notch C2 disbonded before the reported total number of cycles due to a small leak (thru-wall crack). The pressure-cycling continued for additional 3,987 cycles until the cycling pump could not keep up with the selected pressure-cycling regime. Data past 60,000 cycles was not considered in determining the target strain for the next samples.

As mentioned before, Samples 2-5 were identical in that each sample was fabricated with two 3-inch notches. They were initially pressure cycled at the same time. The set of Samples 3 and 5 and the set of Samples 2 and 4 were tested in series with the sets being parallel to each other. Figure 6 shows the arrangement for Samples 2-5. For this arrangement, failure was reported at 68,627 cycles (Sample 2 notch B). Like Sample 1 testing, a leak was observed before the pressure-cycling pump stopped. The leak caused an electric short in the strain gages at Samples 2 (Notches “A” and “B”), 3 (Notch “A”), and 5 (Notch “A”). The last useable data point was at 65,000 cycles.

Under fatigue cycling, crack growth can rapidly increase during the last cycles before failure. Few additional cycles, when compared to the total number of cycles to failure, can grow a half-wall crack into a thru-wall. The increase in the hoop strain curves across the notches are comparable to fatigue crack growth predictions when using Paris’ Law (Reference 5), a simple power law.

After failure occurred, Sample 2 was removed for post-cycling examination. A thru-wall crack (Notch “C2”) was exposed (Figure 7a), and the crack on Notch “C1” was measured (0.083-inches, Figure 7b). Note that the crack measurement was taken from the bottom of the notch to the crack tip. In other words, the initial “starter” notch depth of 0.025-inches was not included in the crack size measurements.

Calculated hoop strains across the notches varied among the samples and notches. Consequently, in order to better compare the increase in strain for different samples and potentially relate them to crack growth, hoop strains values were normalized. Figure 8 shows the normalized peak strains for Sample 1 (3-inch features only) and Sample 2. In both samples, cracks grew thru-wall from the bottom of the notches. Based on the material properties, geometry (i.e., pipe and notches), and loading conditions for this study, Samples 1 and 2 developed a thru-wall crack when the hoop strain increased by ~80-90% from its initial value measured during the first few pressure cycles.

In order to avoid thru-wall cracks, while at the same time providing sizable crack size for future non-destructive examinations involving pull-test with ILI tools, a target strain range to stop the test for the remaining samples was set to 1,250 microstrain. This strain corresponds to an average increase of approximately 50-60% from the initial strain. At 65,000 cycles, the increase peak strain in Samples 3-5 varied from 10-40%. Figure 9 shows the normalized peak strains for Samples 2-5. Based on these initial results, it was expected that Sample 3 would reach the target strain first, followed by Sample 5 and then Sample 4.

Strain gages were replaced on Samples 3-5, and pressure cycling was resumed. The remaining three samples were again tested at the same time with all three samples being cycled in parallel. From this point on, testing was closely observed to avoid thru-wall cracks. The intent of the last three samples were to perform a burst test/crack examination in one of the samples and prepare the other two for future ILI. Sample 3 (Notch “C1”) reached the target strain at 71,158 cycles. The test was stopped, and post activities were performed that included burst testing and crack examinations. Notches “C1” and “C2” developed crack depths of 0.095 and 0.07-inches, respectively. Figure 10 provide strain range as a function of cycle number, while Figure 11 provides crack depth as a function of strain range for Samples 3-5.

Testing was then resumed for Samples 4 and 5. Since a strain gage in Sample 5 disbonded before reaching the target strain, the test was stopped at 76,720 cycles to avoid an unintended failure in this sample. Sample 5 was preserved after the test in that no post cycling activity was performed to allow for future inspection by ILI tools. Sample 4 reached the target strain at approximately 79,266 cycles. Sample 4 will also be inspected by ILI tools, but the initial “starter” notches were removed by grinding.

4. CONCLUSION

Pipe body crack features were generated in 12.75-inch OD x 0.25-inch WT, Grade X42 HF-ERW pipe material using EDM “starter” notches. Notch opening displacements were monitored throughout testing. A total of five (5) samples were fabricated for the test program and the pressure cycle range for all test samples was 99 to 1,186 psig (6-72% SMYS). Multiple EDM notch geometries were considered and evaluated.

Cracks were successfully generated from the bottom of the EDM notches. Pipe body biaxial strain gages on Samples 2-5 reported somewhat different hoop strain values during initial cycling, even though the pipe samples were identical and subjected to the same loading conditions. Some difference in hoop strain values might be expected once cracks are initiated, but PB hoop strains were constantly higher in Sample 2 followed by Samples 5-3 (similar values) and lower in Sample 4. This sequence (S2, S5-S3, and S4), was the order of which the samples had failed/reached the target strain. Only one strain gage was used to monitor PB hoop strain and the applied pressure was recorded by one pressure transducer. In the future, the use of multiple PB strain gages around the circumference and additional pressure transducers may be helpful to identify pipe ovality and potential differences in pressures among the samples.

Samples 2-5 contained two EDM notches per sample. While this allows two cracks to be generated simultaneously, it is impractical to bring the notches to the same final strain range. In fact, the final strain range observed across the EDM notches appears to correlate reasonably well with the crack depth. Based on the preceding observation, having a greater control over the crack depth to reach a specific target is an unlikely task considering current measurement technologies, so having one EDM notch per sample is recommended. In this manner, individual notches could be cycled until a target strain range is achieved.

Several comments are made in relation to overall observations from this study. First, a testing methodology for generating crack features has been evaluated and found to be useful for growing cracks from EDM starter notches. Secondly, there is a correlation between hoop strain measurements at the notch opening and crack growth. Additional work is needed in this field to integrate the use of advanced Non-Destructive Evaluation (NDE) for monitoring crack growth during cycling, as well as considering the use of the DC potential drop (DCPD) method as a means for monitoring crack growth. Furthermore, future efforts might consider the integration of Computed Tomography (CT) to bolster improvement in this technology field.

Finally, based on the authors' observations there continues to be a knowledge gap in actual failure pressures and those predicted using fracture mechanics methods. For comparison purposes, a burst pressure was calculated using the MAT-8 program (Reference 6). Using a pipe diameter of 12.75-inches, a wall thickness of 0.24-inches (i.e., based on actual measurements), a crack depth and length of 0.095-inches and 3.0-inches (respectively), and a toughness of 183 ksi-$\sqrt{\text{in}}$, the estimated burst pressure was 1,690 psig. Material testing was performed to verify fracture toughness and yield and tensile strengths. The actual burst pressure for Notch S3-A was 2,050 psig, which is 21% greater than the calculated value. Until improvements are made in predictive analysis methods, the pipeline industry is going to be forced to make overly conservative assumptions that will lead to potentially excessive dig programs.

This paper has provided details on a study program designed to generate/examine external crack features in pipeline material under internal pressure-cycling. The eventual goal of this work is to develop a process to systematically generate sizable cracks within ILI tool tolerances and improve ILI tools and data analysis. The methodology used in this work can be improved and expanded for generating cracks in the longitudinal welds, multiple pipe ODs, different pipe material/grades, internal cracks, and cracks at specific sizes. Future efforts will integrate material property data, including fracture toughness, to predict and correlate crack propagation based on measured strain data

As a follow-on to this study, a subsequent phase of work will be conducted involving pull-testing of ILI tools in pipes having synthetic cracks. Data analysts will evaluate signal characteristics for known crack features, allowing them to achieve better alignment with in-field ILI runs having similar characteristics. Also, the ability to do an ILI pull-test in a pipe with known cracks details will encourage refinements in ILI tool designs and specifications.

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Table 1: Test Matrix

Sample Number	Notch Geometry	Cycling Description	Post Cycling Activity
Sample 1	Eight (8) EDM notches ranging from 1-inch to 3-inches long	Sacrificial, Cycle to Failure	Crack examination
Sample 2	Two (2) EDM notches, 3-inches long	Cycle to failure	Crack examination
Sample 3	Two (2) EDM notches, 3-inches long	Pre-cycle to 1,250 με(1)	Burst test & crack examination
Sample 4	Two (2) EDM notches, 3-inches long	Pre-cycle to 1,250 με(1)	Grind away EDM notches, ship sample to ROSEN
Sample 5	Two (2) EDM notches, 3-inches long	Pre-cycle to 1,250 με(1)	Ship sample to ROSEN

NOTES: (1) Strain (hoop) measured across the EDM notch. Based on the material properties and selected geometries (pipe and notches), this value was determined to be of enough magnitude to generate sizable cracks.

Table 2: Summary of Results

Notch	Length (in)	# of Cycles	Final Strain Range (με)	Final Notch Gage Range (in)	Crack Depth (in)	Burst Pressure (psig)
S1-A1	1.7	60,000	994	-	0.017	-
S1-A2	1.7	60,000	1,054	0.0016	0.030	-
S1-B0	1	60,000	-	0.0016	0.034	-
S1-B1	1	60,000	933	-	0.024	-
S1-B2	1	60,000	914	-	0.026	-
S1-B3	1	60,000	962	-	0.028	-
S1-C1	3	60,000	890	-	0.027	-
S1-C2	3	60,000	> 1,372*	-	Thru-wall**	-
S2-C1	3	65,000	1,126	-	0.083	-
S2-C2	3	65,000	1,415	-	Thru-wall**	-
S3-C1	3	71,158	1,278	-	0.095	2,050
S3-C2	3	71,158	913	-	0.070	
S4-C1	3	79,266	905	-	TBD***	-
S4-C2	3	79,266	1,266	-	TBD***	-
S5-C1	3	71,158	>1,156*	-	TBD***	-
S5-C2	3	71,158	1,120	-	TBD***	-

**Last recorded data point prior to gage disbondment.*
***Crack measurement shows 0.203-inches at the center of the feature. The thru-wall portion of the crack was not in the center of the feature as expected. The thru-wall portion was not visible because it was contained on the side of the feature that was compression mounted to obtain the transverse view.*
**** Sizing will be determined by ILI tools (pull-test).*

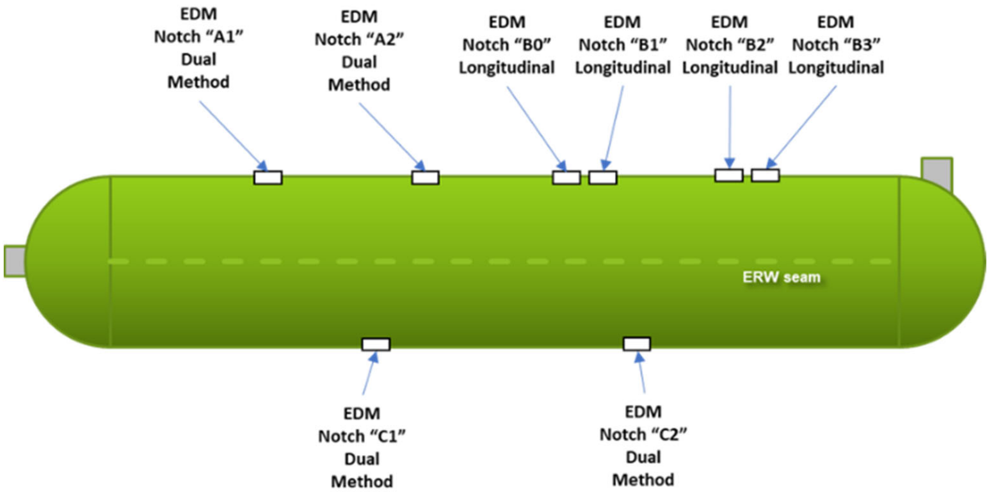


Figure 1: Sample 1 (Sacrificial Sample) Schematics

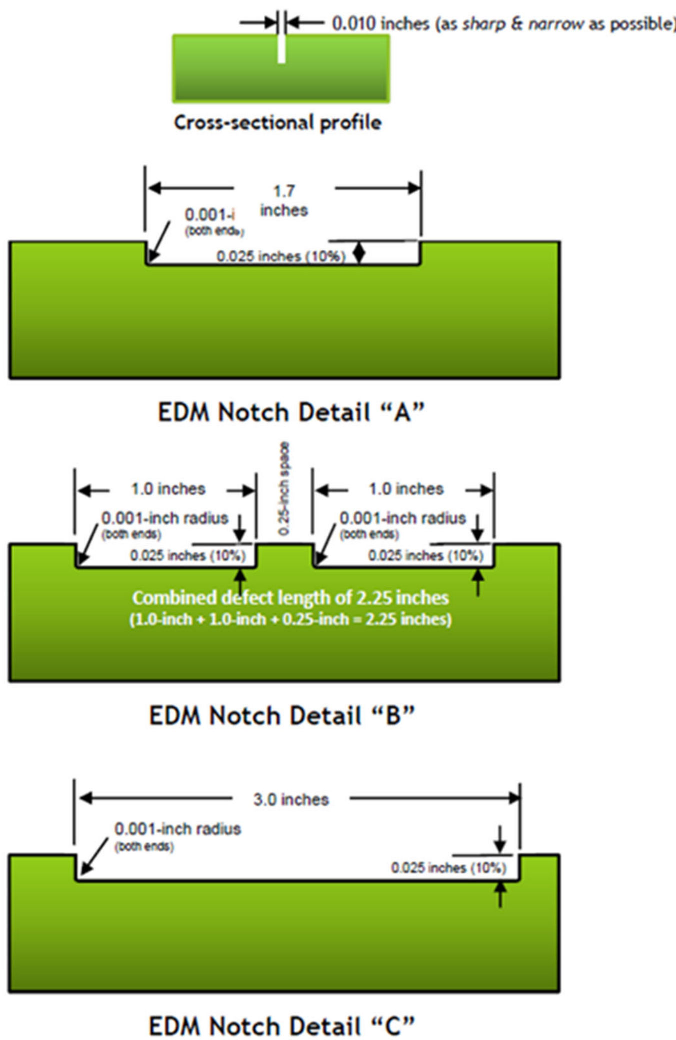


Figure 2: Geometry of Samples

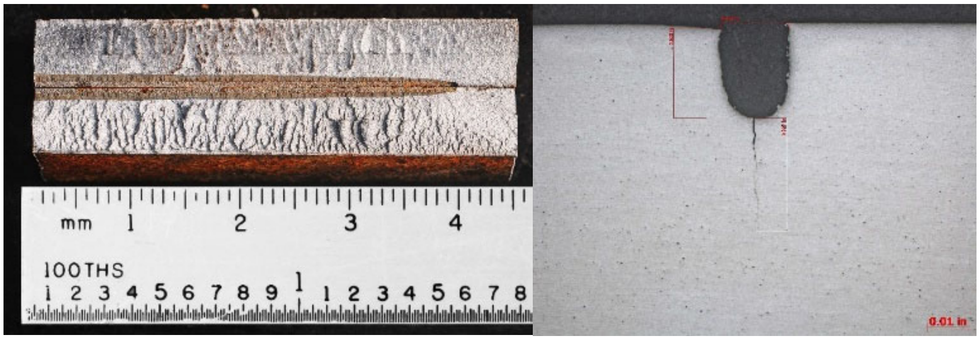


Figure 3: Crack Examination Showing Longitudinal and Transverse Views (respectively)

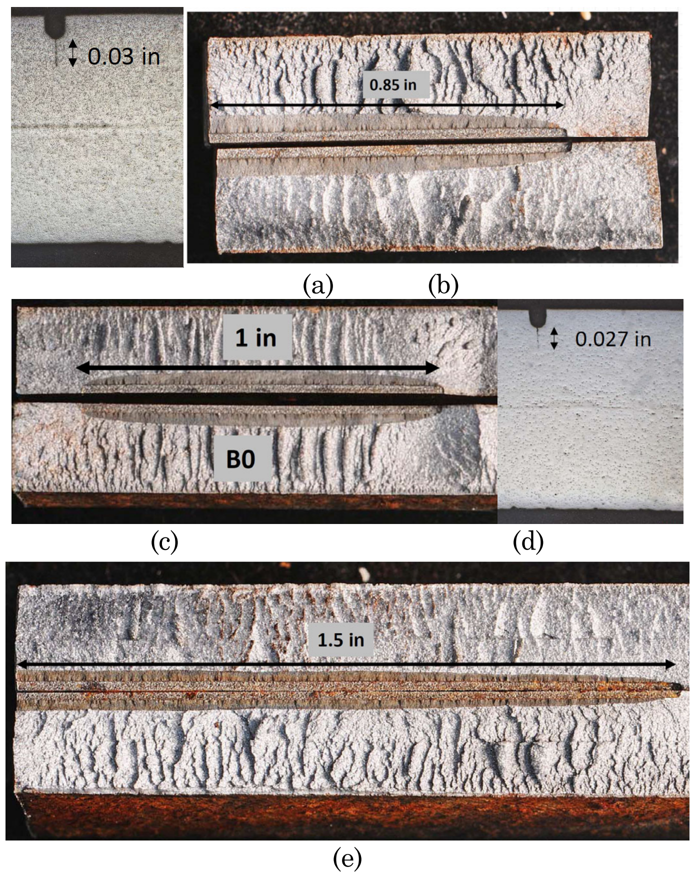


Figure 4: Cracks Generated from Notches A2 (a,b), B0 (c), C1 (d,e)

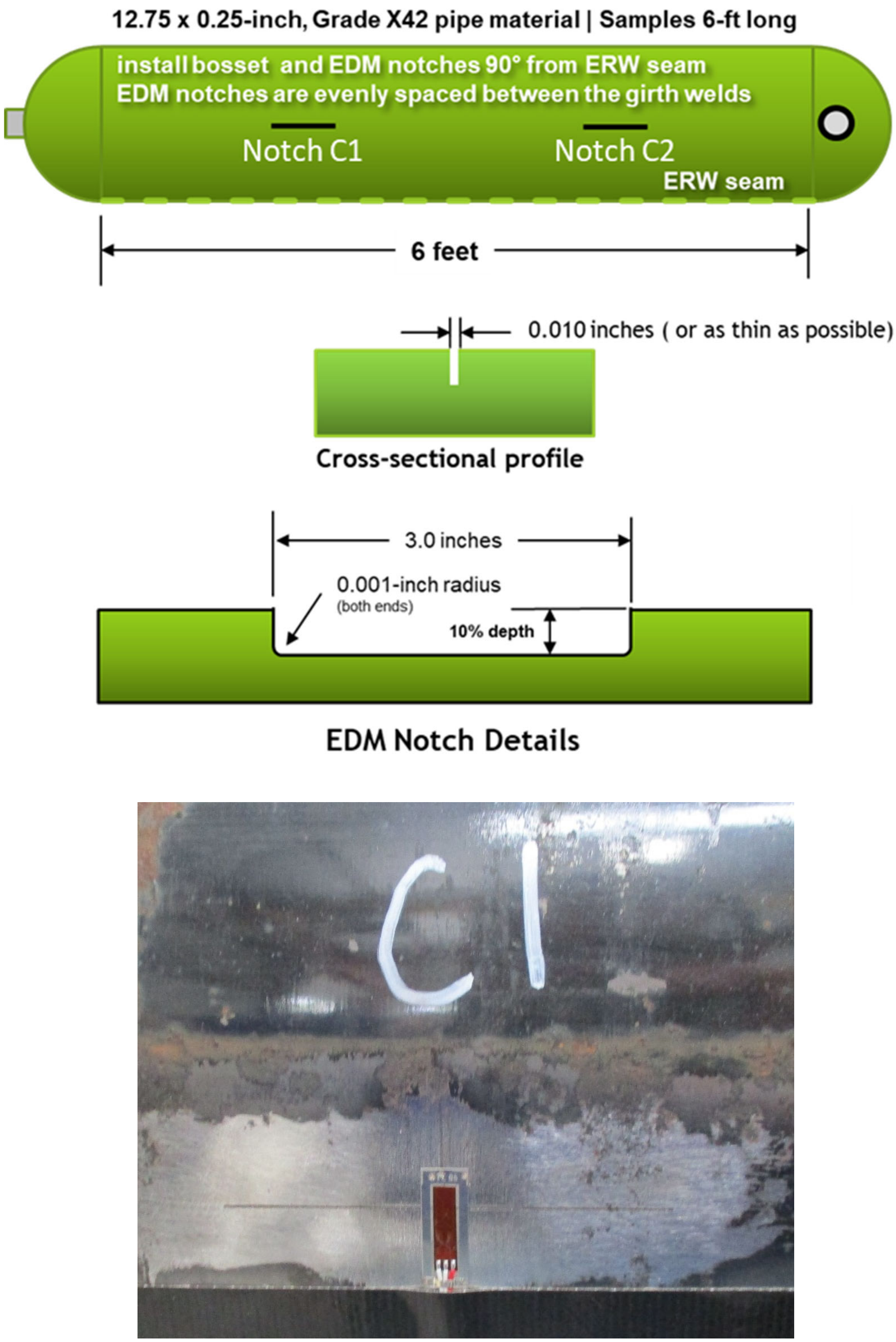


Figure 5: Notch Geometry for Samples 2 through 5 with close-up photo of strain gage

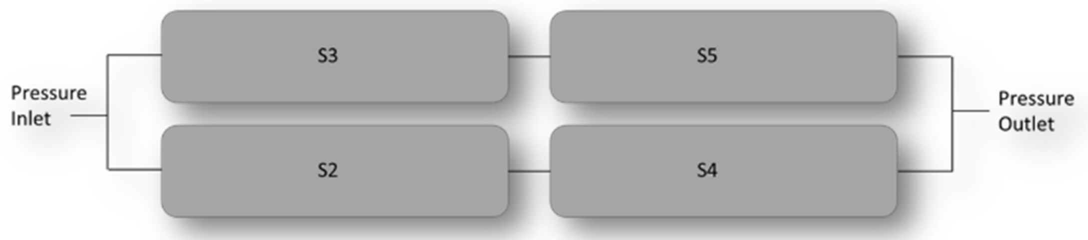
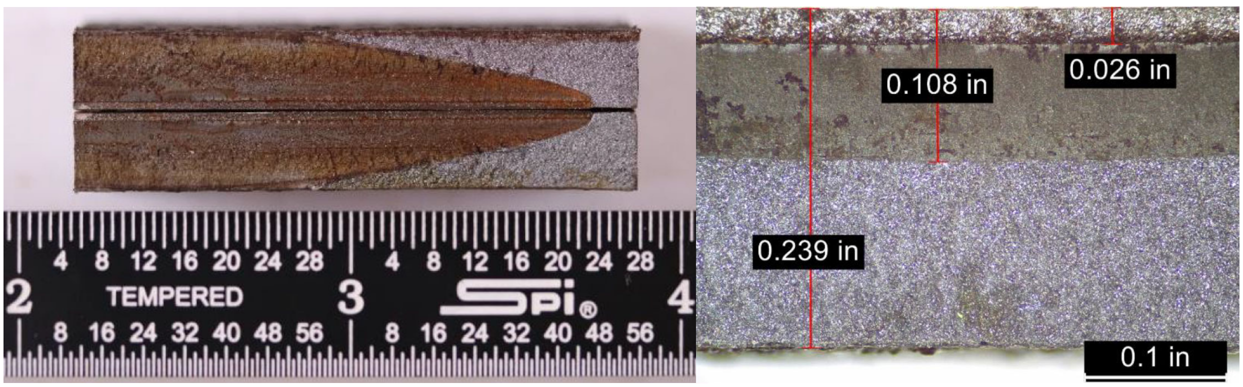


Figure 6: Initial Testing Arrangement for Samples 2 through 5



(a) (b)

Figure 7: Cracks on Sample 2: (a) Notch C2; (b) Notch C1

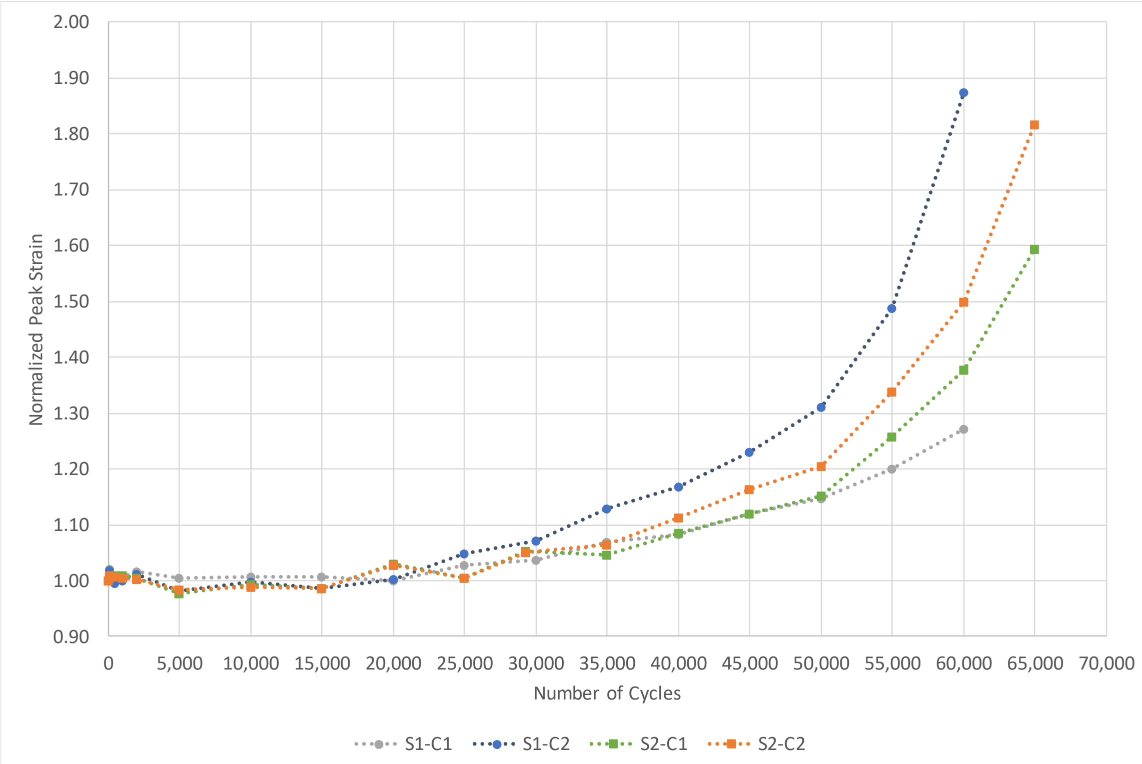


Figure 8: Normalized Peak Strains (Samples 1 and 2, 3-inch features)

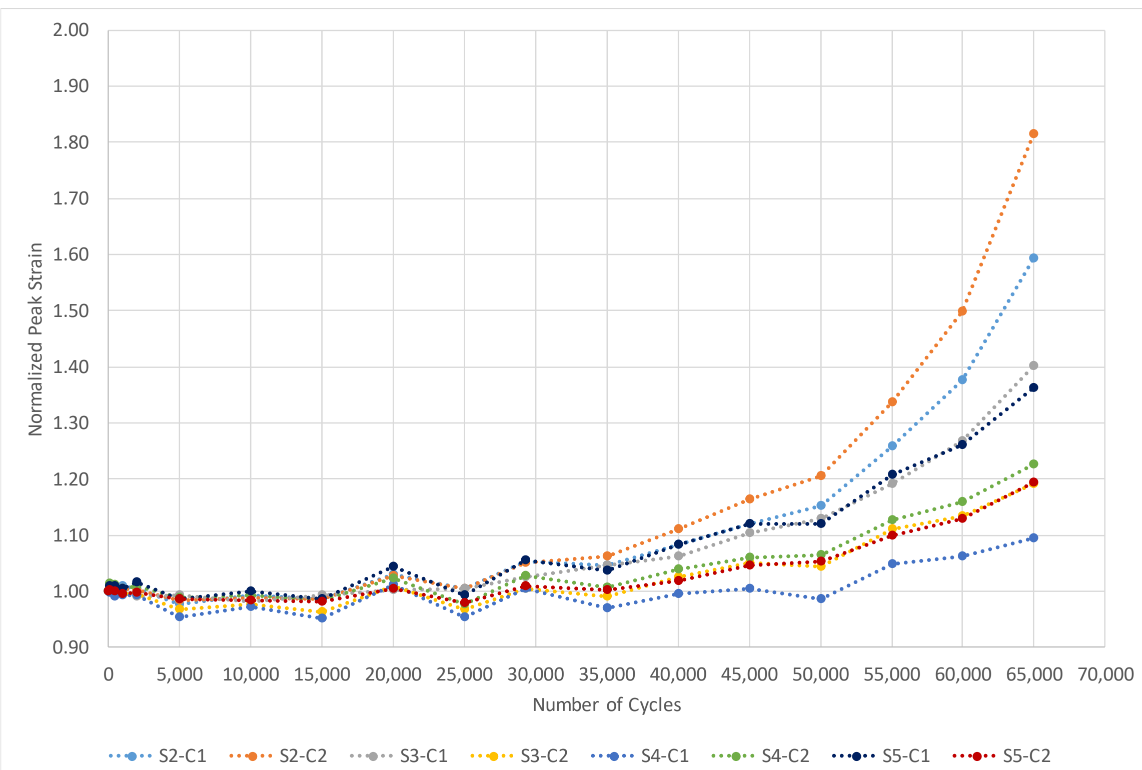


Figure 9: Normalized Peak Strains (Samples 2 through 5)

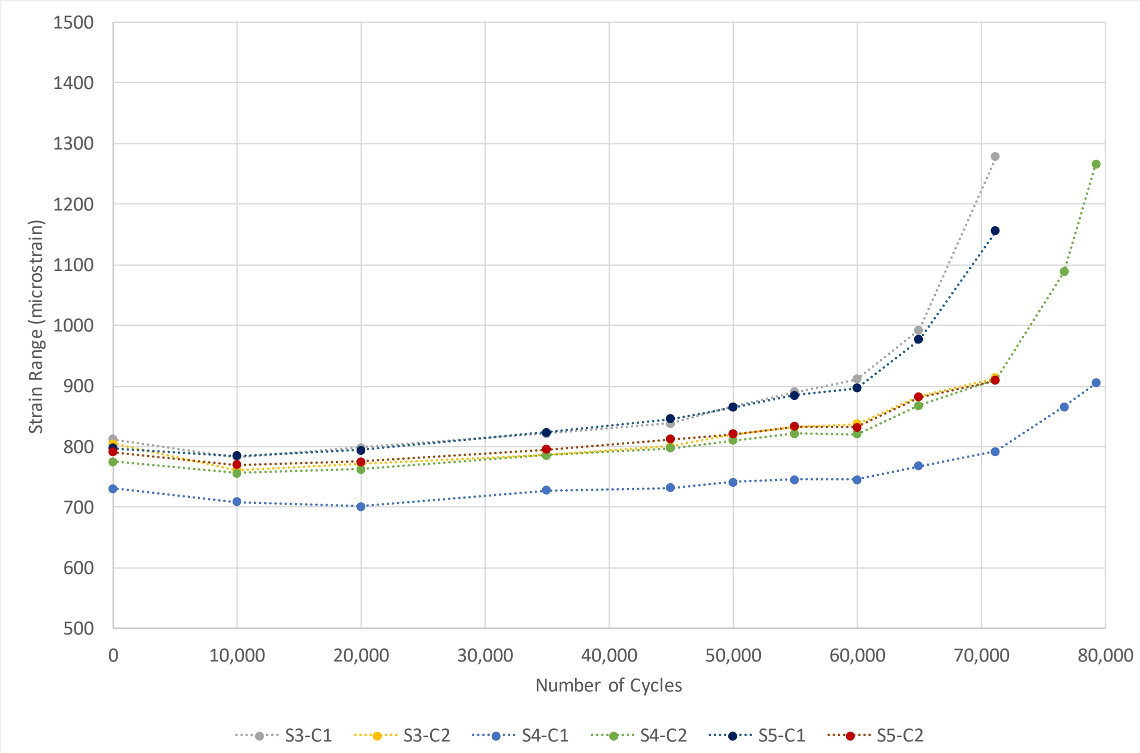


Figure 10: Strain Range as a Function of Cycle Number for Samples 3 through 5

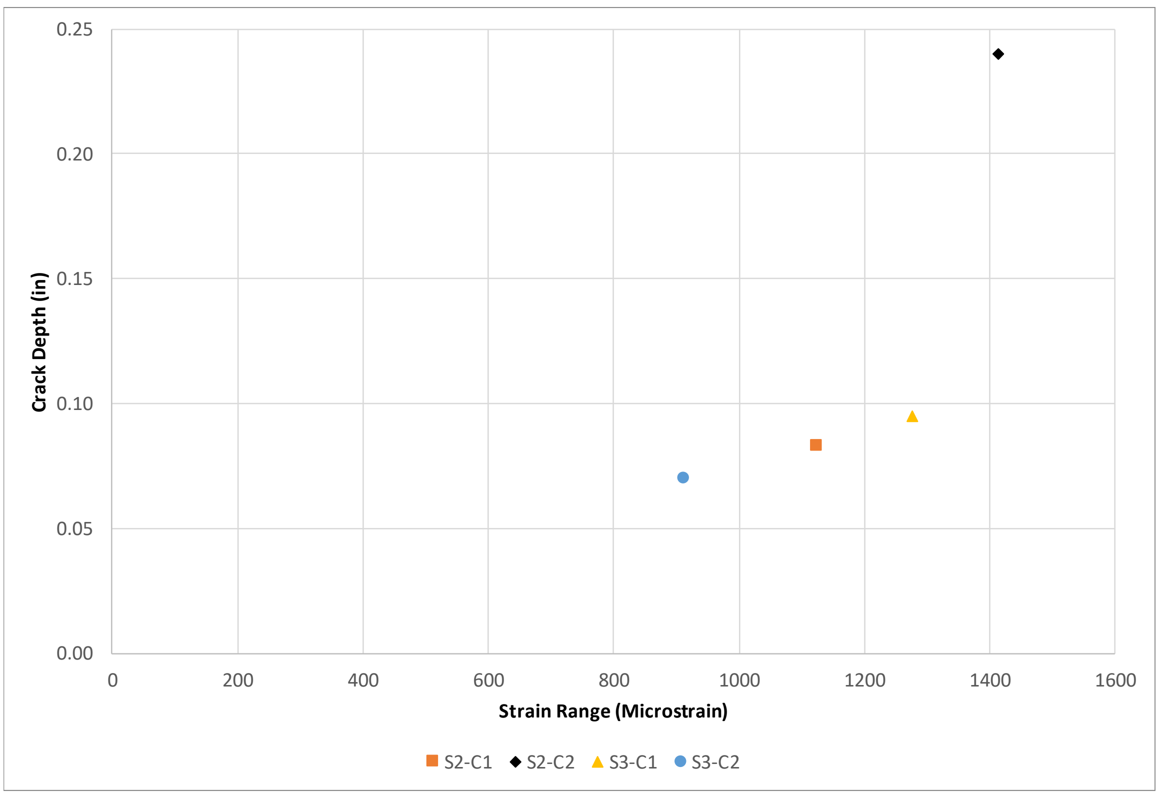


Figure 11: Crack Depth as a Function of Strain Range for Samples 3 through 5