Bending the Repair: Expanding Repair Techniques for Circumferential Stress Corrosion

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Abstract

Circumferential stress corrosion cracking (C-SCC) is being identified on a more frequent basis. More often than not, these indications require repair upon discovery. Repair techniques are limited due to the progression of the crack colonies in the circumferential direction. Industry standards limit the applicability of some repairs as the crack direction lies perpendicular to the applied hoop stress and forms due to an axial or bending stress present on the pipeline. Traditional repair techniques, such as a Type B sleeve, Mechanical Clamp, or grinding may have limitations in some scenarios. Therefore, additional testing of repair techniques is warranted.

C-SCC forms when the pipeline experiences an axial or bending load. In many ways, the environment to form and grow SCC is removed once excavated in repaired or recoated. Therefore, these indications would grow due to normal operations of the pipeline – which may include axial bending cycles. Understanding how the repair technique behaves in a bending regime is critically important to accessing other repair options. This study examines a Type A Compression Sleeve and a Composite Repair for their applicability in repairing C-SCC.

C-SCC colonies removed from service were selected for various repair techniques and one colony selected for an unreinforced control sample. C-SCC indications were strain gaged to monitor growth during the test and samples were installed in a pure bending apparatus. The unreinforced sample was cycled (bending load) to failure and the repaired samples were subsequently cycled to the same amount and then subjected to a burst test. Results show that the use of other repair techniques provide sufficient reinforcement under typical bending loads expected. This allows additional repair techniques when C-SCC is encountered in the field.

Program Description

The goal of this program was to perform testing to validate additional repair methods for C-SCC rather than the traditionally utilized repair methods: Type B sleeve, mechanical clamp, or grinding. Limitations of these repairs are discussed below:

- *Type B sleeve:* fully welded sleeves may be difficult to find landing zones on older steels where inclusions/laminations are more common. Encountering C-SCC on a bend would also result in a more time consuming armadillo sleeve.
- *Mechanical clamp:* clamps come with long lead times and may be considered temporary resulting in further action at a later date.
- *Grinding:* generally limited to 40% of nominal wall thickness unless pressure is substantially reduced, which consequently limits the use of this technique for deeper C-SCC.

Therefore, the use of additional repair techniques would be warranted in some situations. This study considers the use of a Type A Compression Sleeve (Petrosleeve) and a carbon fiber composite repair

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(CSNRI Atlas), comparing the results to an unreinforced sample. The test matrix consisted of four pipe samples with colonies of C-SCC removed from an active pipeline system:

- One unreinforced sample.
- Two samples were repaired in the field using a Type A Compression Sleeve (Petrosleeve). These samples were repaired after removal from the pipeline, therefore, no pressure was in the pipe during the install.
- One sample was repaired with a carbon fiber composite repair (CSNRI Atlas). The sample selected for this repair contained a noticeable bend, which would have greatly limited other repair techniques.

The pipe material utilized in this program was nominal 10-inch OD x 0.188-inch WT, API 5L, Grade X52 material manufactured by Kaiser Steel in 1963. The line transports natural gas at a maximum allowable operating pressure of 896 psig. The indications selected for testing are summarized in Table 1. Photographs of the features are shown in Figure 1 through Figure 4.

All testing was performed in bending rather than axial tension. The indications tested within this program were found on the extrados of a field bend, therefore, the pipe sample was under a local bending load otherwise cracks should have been identified at other locations around the circumference. Once the C-SCC indications are exposed and repaired (with any technique), the repaired colony would only be exposed to the stress component of SCC as the environment would have been removed. The repaired section of the pipeline would continue to be exposed to the same local bending load assuming the line is not further remediated of the stress present. Based on this assertion, all samples were deemed most appropriate to test in a bending environment.

Table 1. Summary of Test Conditions and Indications

Sample #	Test Condition	NDE		
		Length (in)	Width (in)	Depth (in)
1	Type A Compression Sleeve (Petrosleeve)	0.30	2.20	0.197 (91% AWT of 0.217 inch)
2	Type A Compression Sleeve (Petrosleeve)	2.00	1.90	0.148 (75% AWT of 0.198 inch)
3	Composite Repair (CSNRI Atlas)	0.40	3.00	0.140 (69% AWT of 0.203 inch)
4	Unreinforced	0.80	5.50	0.085 (39% AWT of 0.217 inch)

Full-Scale Bending Test Program

All testing took place at Acuren's Full-Scale Test Facility in Magnolia, TX at ambient temperature. All four samples were cycled in axial strain controlled four-point bending. The strain targets were selected to achieve an equivalent axial stress state corresponding to 72%, 100%, or 125% of the specified minimum yield stress (SMYS). The controlling strain and feature of interest were positioned

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on the outermost fiber to receive maximum tensile strain during bending. Applied load and bending moment were calculated from the hydraulic cylinder pressure used to bend the sample. The procedure for the cyclic bending and bending to failure was as follows:

1. Installed sample into four-point bend frame, See Figure 5 for bend setup dimensions.
2. Pressurized sample to the 896 ± 10 psig (MAOP).
3. Cycled the sample in four-point bending from ~230 με to the target strain and runout in Table 2
   - The sample experienced ~230 με with no bending load applied due to the internal pressure of 896 psig.
4. If sample survived 8,000 cycles, the bending moment was increased until sample failure while maintaining internal pressure at 896 ± 10 psig.
   - Sample failure was indicated by inability to maintain pressure or gross plastic deformation (increase in strain with no increase in applied load).

Table 2. Bend Cycle Test Matrix

Cycle Count	Test Pressure (psig)	Base Pipe Axial Strain Target (με)	Equivalent Stress (%SMYS)
0-5,000	896	990	72
5,001-5,750	896	1,480	100
5,751-8,000	896	1,950	125

A representative test set-up is shown in Figure 6. Samples were kept at their maximum operating pressure of 896 psig for the duration of testing. Strain cycle targets were calculated such that the feature's combined axial stress state is equivalent to 72%, 100% and 125% SMYS for the 5,000, 5,750, and 8,000 cycle runout, respectively. Figure 7 is a representative plot of the sample pressure, minimum base pipe and maximum base pipe strains during the testing and each axial strain target.

Following the completion of the 8,000 bending cycles, samples were bent to failure by applied bending load until loss of internal pressure or gross plastic deformation (increase in deformation with no increase in strain). Gross plastic deformation is seen as the applied bending moment plateaus illustrating base pipe yield.

All reinforced samples failed via gross plastic deformation passing the calculated plastic hinge moment for the pipe sample 109 kip*ft. Sample 4 (Unreinforced) failed within the C-SCC colony and was unable to maintain pressure, shown in Figure 8. Figure 9 through Figure 12 show the samples post bend testing.

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Metallurgical Examination

The features present within the four full-scale testing samples were further examined either by documenting the fracture surface or examining the repaired indication by sectioning, chilling in liquid nitrogen, and breaking open to reveal the fracture surface. Examination of each full-scale testing sample is discussed in the subsections below. The results are summarized in Table 3 and photographs are shown in Figure 13 through **Figure 22**. Minor growth was observed on two of the repaired samples; no growth was observed on one of the repaired samples. More significant growth was observed on the unreinforced sample. The growth appeared consistent with fatigue in a bending environment applied during full-scale testing.

Table 3. Summary of Indications

Sample	Test/Repair Condition	Metallurgical	
		C-SCC Depth (in)	Growth (in)
1	Type A Compression Sleeve (Petrosleeve)	0.198 (91.2% AWT)	0.0040 (1.8% AWT)
2	Type A Compression Sleeve (Petrosleeve)	0.158 (79.8% AWT)	None
3	Composite Repair (CSNRI Atlas)	0.134 (66.0% AWT)	0.0027 (1.3% AWT)
4	Unreinforced	0.096 (44.2% AWT)	0.0456 (21.0% AWT)

Closing Comments

The purpose of this test program was to validate additional repair options for repairing C-SCC identified in the field. As discussed, C-SCC can be challenging to repair due to the presence of bends, therefore, additional repair options are warranted. All testing occurred in a bending environment and all samples were subjected to 8,000 cycles of varying stress level – at stresses likely greater than experienced in the field. Three repaired samples were compared to an unreinforced sample. Notable observations from the test program include:

- Minor growth was observed on two of the repaired samples; no growth was observed on one of the repaired samples. More significant growth was observed on the unreinforced sample. It should be noted that the repaired features were longer (circumferentially) than the unreinforced feature and therefore should be more susceptible to fatigue growth. Minor growth observed on the two repaired samples was minimal compared to the unreinforced sample.
- One sample repaired with a Type A Compression Sleeve (Sample 2) did not experience growth, while the other Type A Compression Sleeve sample (Sample 3) experienced minor growth. This may set a maximum allowable repaired feature depth assuming all other install parameters were consistent. It should be noted that the Type A Compression Sleeve for Sample 1 was shorter than the other Type A Compression Sleeve utilized (Sample 2). This

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change in length likely also contributed to the local stiffness at the location of the C-SCC feature.

- All repaired samples failed outside the repair when bent to failure. Failure was deemed as gross plastic deformation. The unreinforced sample failed within the C-SCC feature.
- Failure outside the repair and minimal growth after being subjected to a loading regime likely greater than experienced within typical pipeline systems indicate the feasibility of repairing C-SCC with either a Type A Compression Sleeve or properly designed Composite Repair. The geometry of the pipe sample (presence of a bend) may dictate which repair method is feasible.

Table 4 summarizes the features present and the metallurgical results.

Table 4. Summary of Indications

Sample	Test/Repair Condition	NDE			Metallurgical	
		Length (in)	Width (in)	Depth (in)	C-SCC Depth (in)	Growth (in)
1	Type A Compression Sleeve (Petrosleeve)	0.30	2.20	0.197 (91% AWT of 0.217 inch)	0.198 (91.2% AWT)	0.0040 (1.8% AWT)
2	Type A Compression Sleeve (Petrosleeve)	2.00	1.90	0.148 (75% AWT of 0.198 inch)	0.158 (79.8% AWT)	None
3	Composite Repair (CSNRI Atlas)	0.40	3.00	0.140 (69% AWT of 0.203 inch)	0.134 (66.0% AWT)	0.0027 (1.3% AWT)
4	Unreinforced	0.80	5.50	0.085 (39% AWT of 0.217 inch)	0.096 (44.2% AWT)	0.0456 (21.0% AWT)

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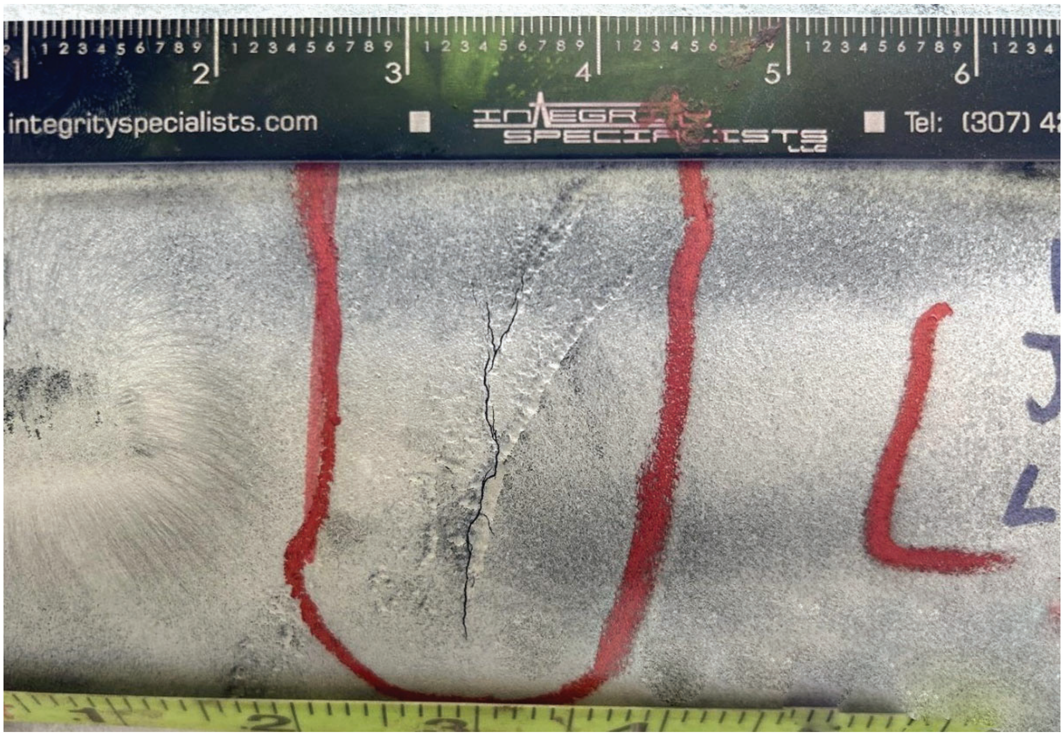

Figure 1. Photograph of the Sample 1 indication selected for repair using a Type A Compression Sleeve.

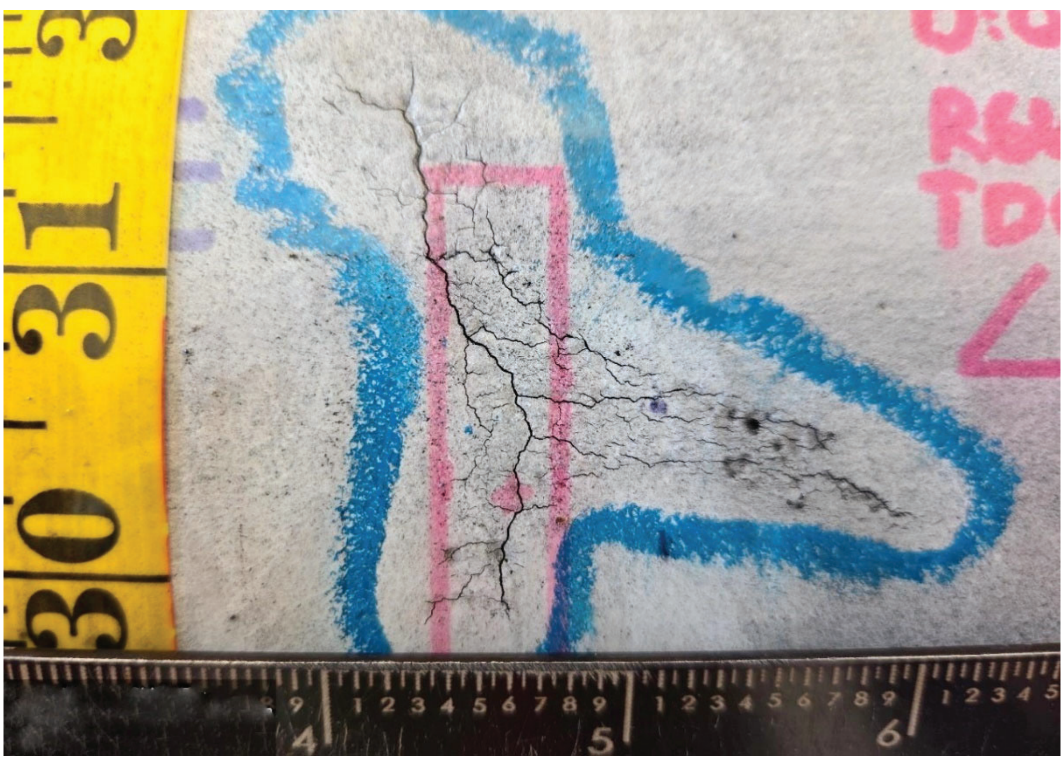

Figure 2. Photograph of the Sample 2 indication selected for repair using a Type A Compression Sleeve.

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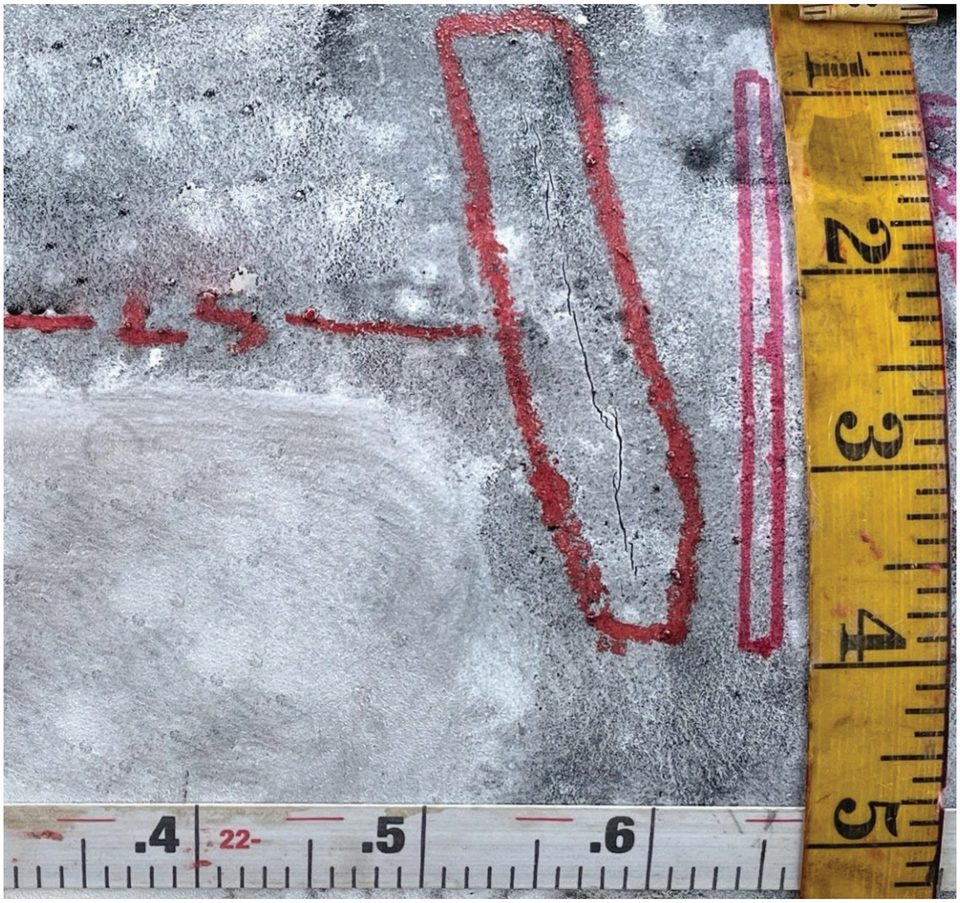

Figure 3. Photograph of the Sample 3 indication selected for repair using composite.

Figure 4. Photograph of the Sample 4 indication selected for unreinforced sample.

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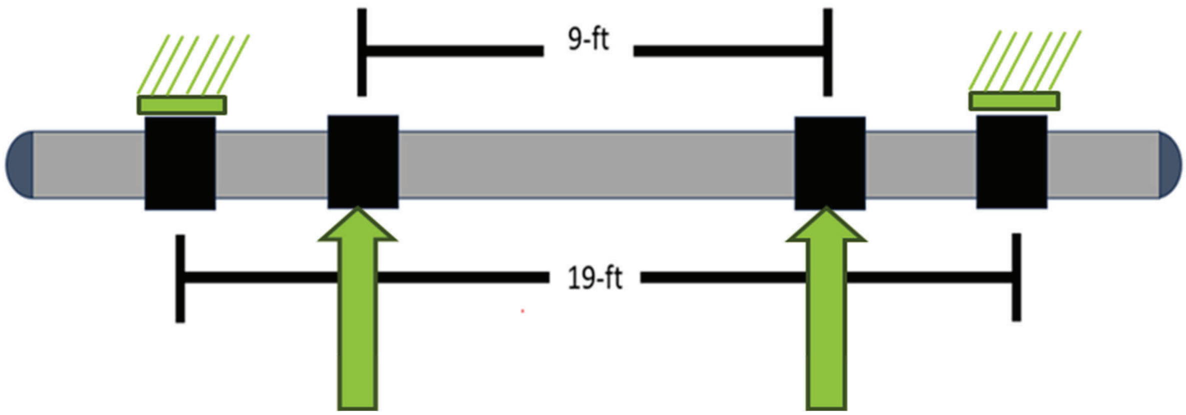

Figure 5. Four-point bending sample setup

Figure 6. Sample 1 (Type A Compression Sleeve) in test setup.

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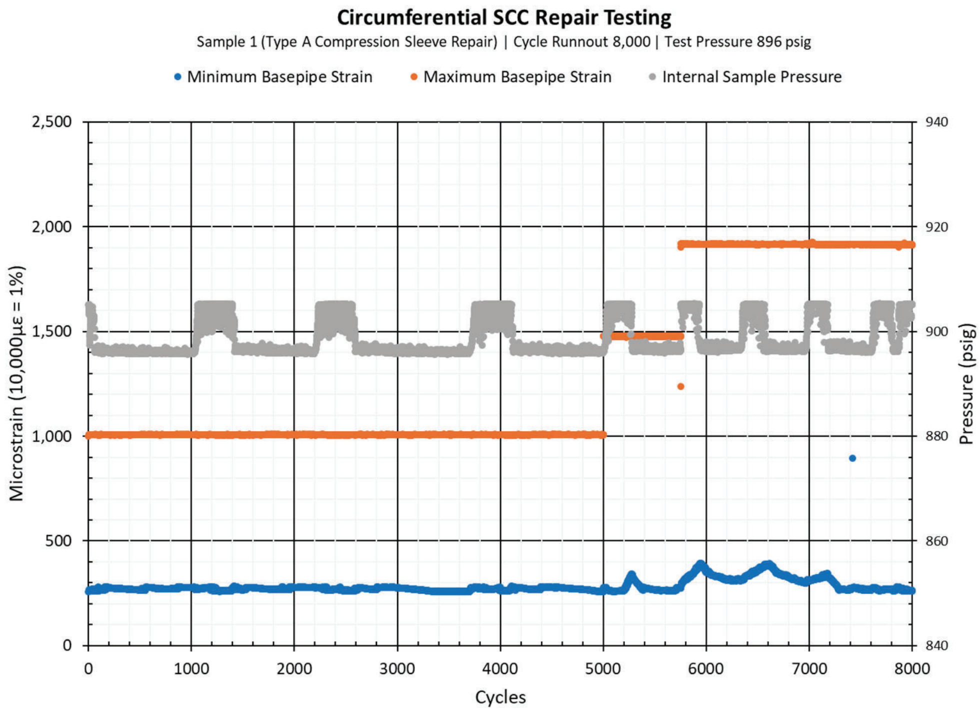

Figure 7. Sample 1 (Type A Compression Sleeve) cycle strains and internal pressure during bend cycling.

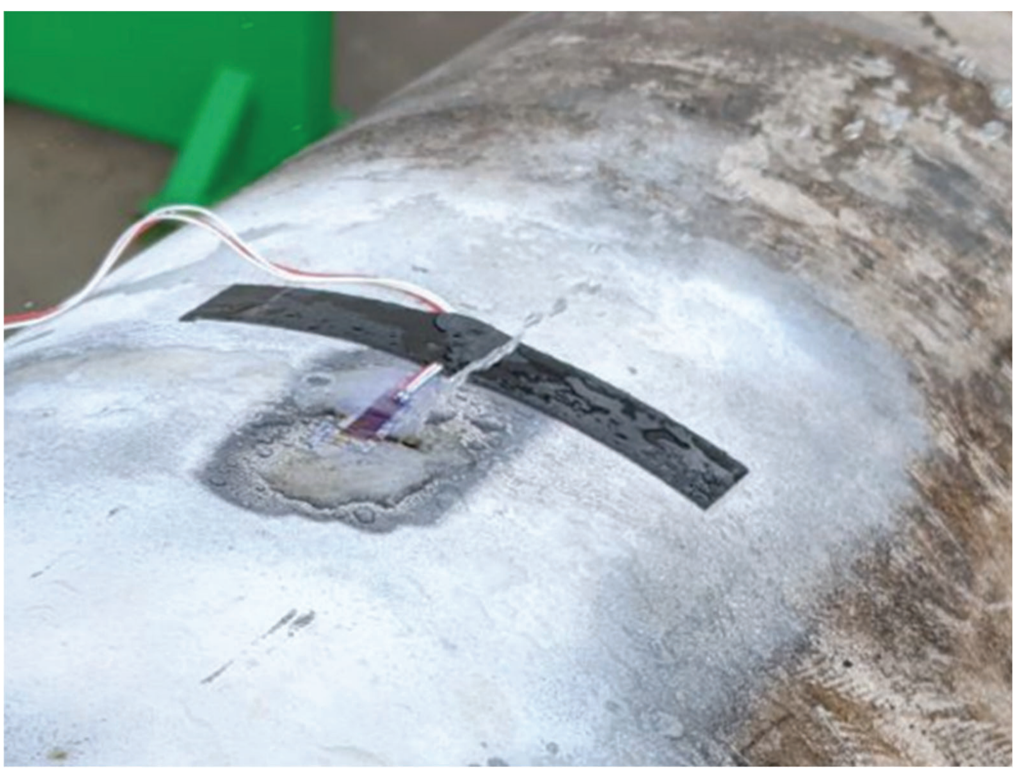

Figure 8. Sample 4 (Unreinforced) leak location.

 https://doi.org/10.52202/078572-0096

Figure 9. Sample 1 (Type A Compression Sleeve) post test.

Figure 10. Sample 2 (Type A Compression Sleeve) post test.

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Figure 11. Sample 3 (Composite Repair) post test.

Figure 12. Sample 4 (Unreinforced) plastic deformation post test.

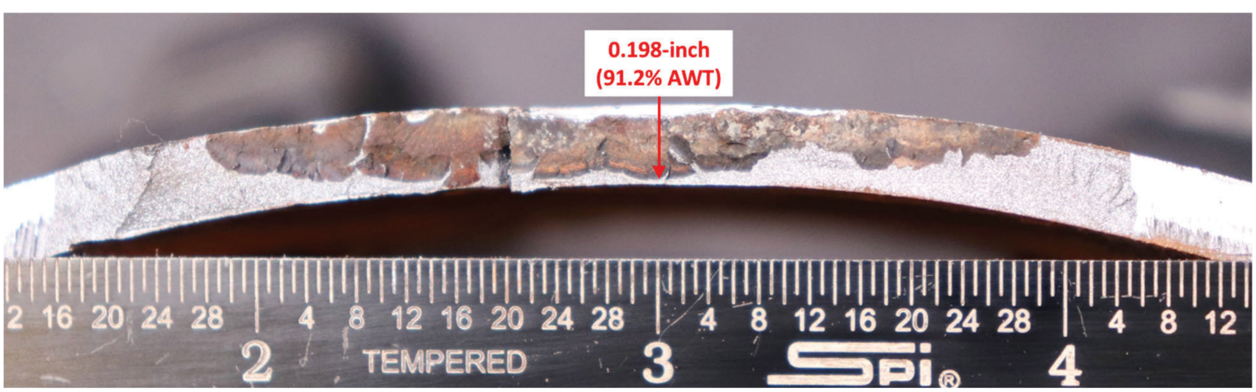

Figure 13. Photograph of the Sample 1 indication after breaking open (Type A Compression Sleeve Repair). Major numbered scale divisions are inches.

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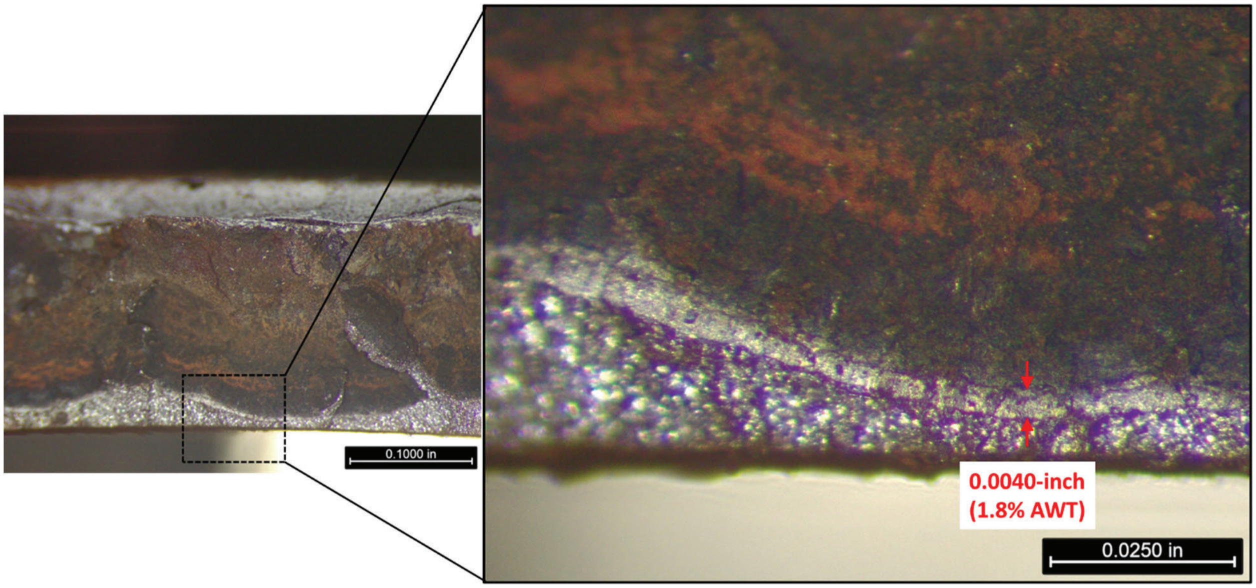

Figure 14. Photograph at the base of the Sample 1 indication (Type A Compression Sleeve Repair) showing area of growth. Original magnification: Left: 12.8x, Right: 48x.

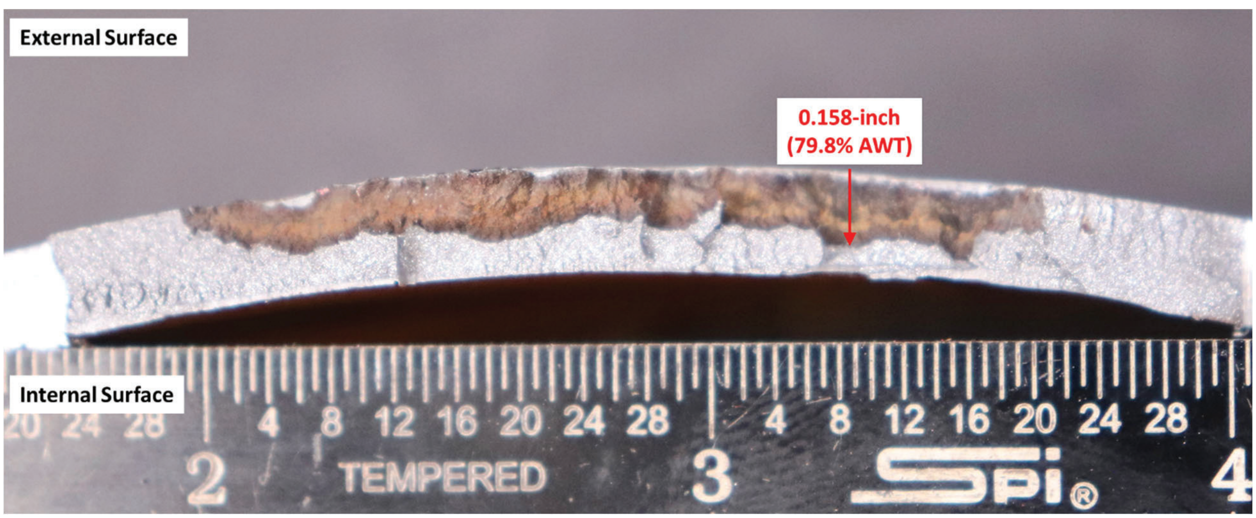

Figure 15. Photograph of the Sample 2 indication after breaking open (Type A Compression Sleeve Repair). Major numbered scale divisions are inches.

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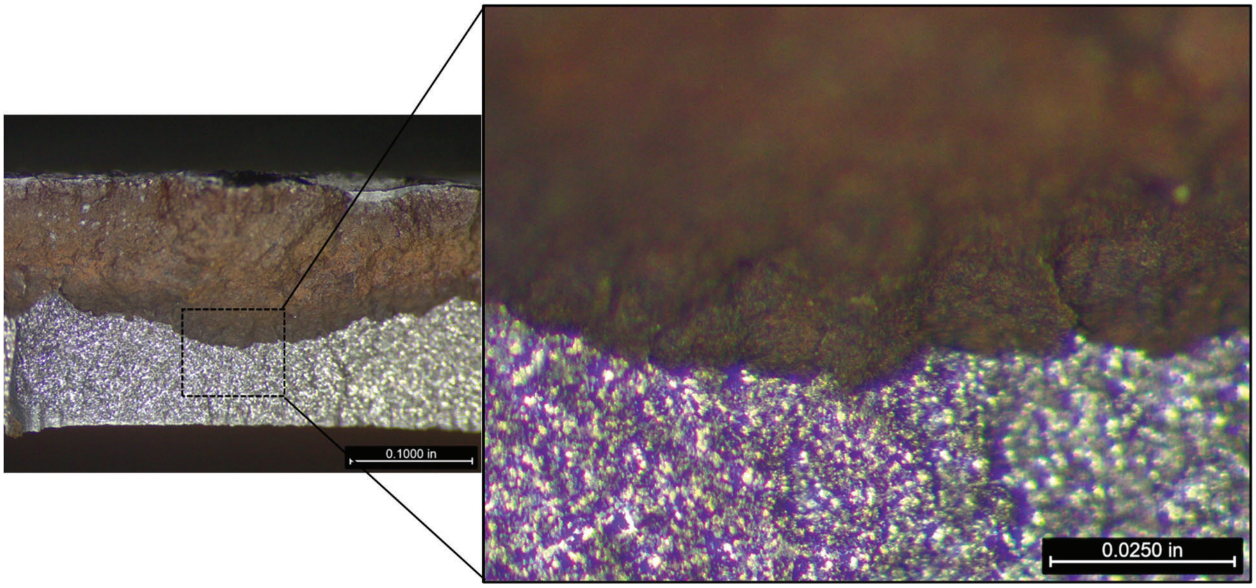

Figure 16. Photograph at the base of the Sample 2 indication (Type A Compression Sleeve Repair) showing no growth. Original magnification: Left: 12.8x, Right: 48x.

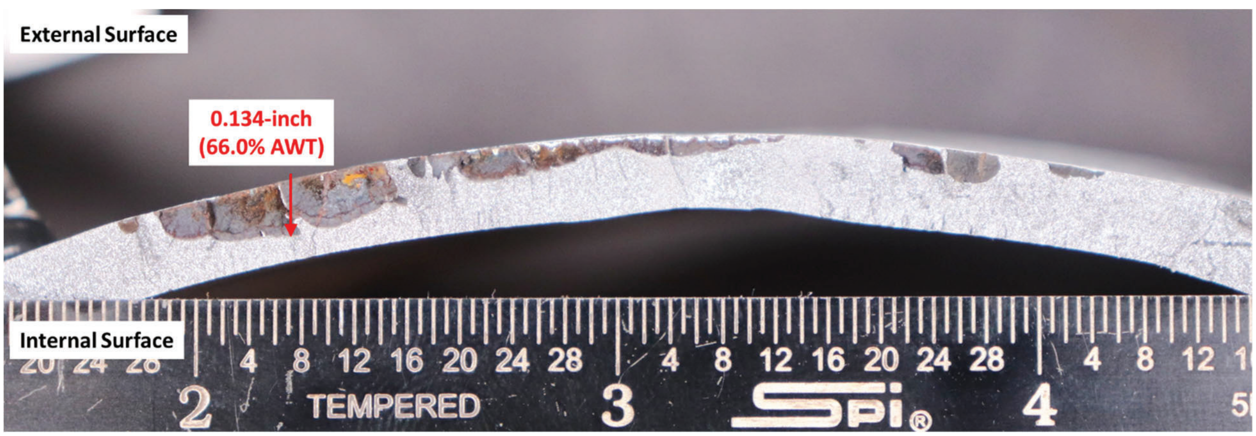

Figure 17. Photograph of the Sample 3 indication after breaking open (Composite Repair). Major numbered scale divisions are inches.

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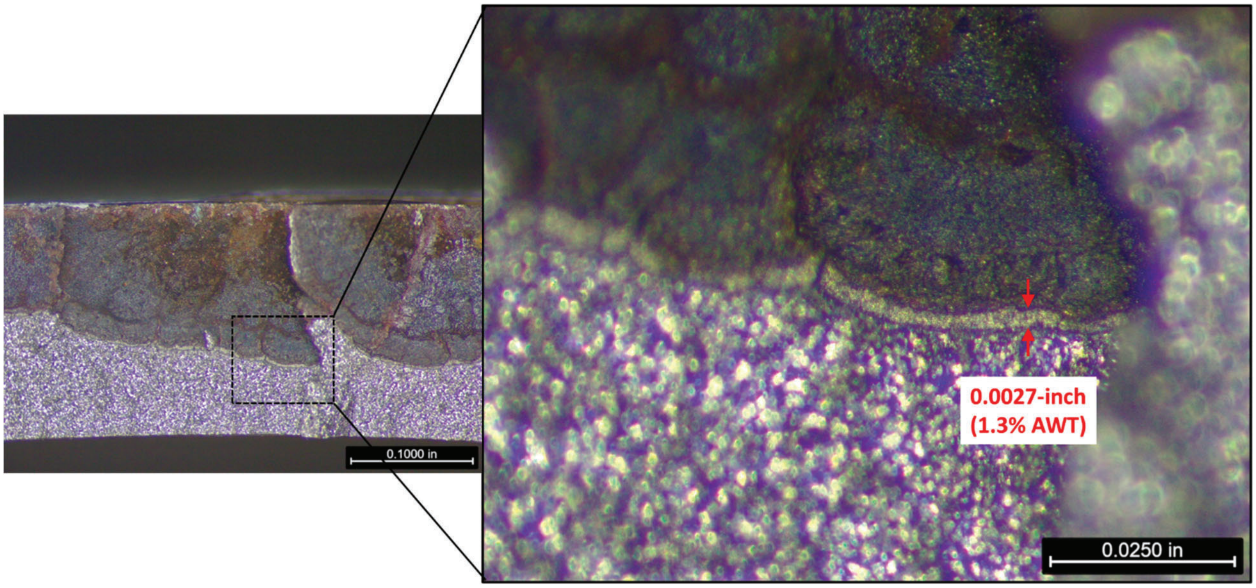

Figure 18. Photograph at the base of the Sample 3 indication (Composite Repair) showing area of growth. Original magnification: Left: 12.8x, Right: 48x.

Figure 19. Photograph of the Sample 4 indication after breaking open (Unreinforced). Major numbered scale divisions are inches.

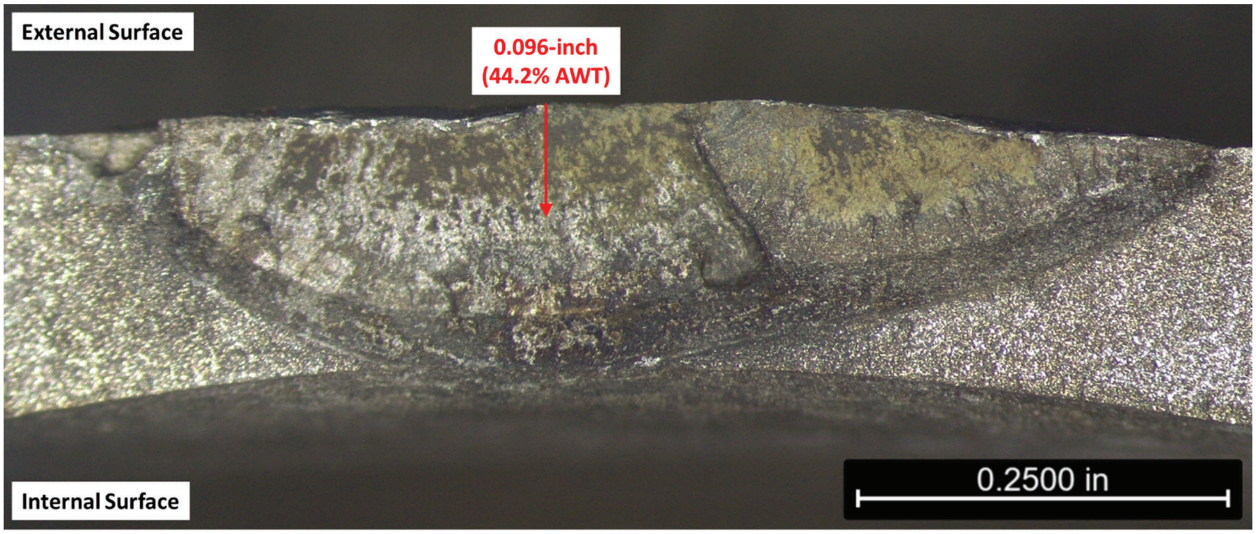

Figure 20. Photograph of the Sample 4 indication after breaking open and cleaning (Unreinforced). Original magnification is 6x.

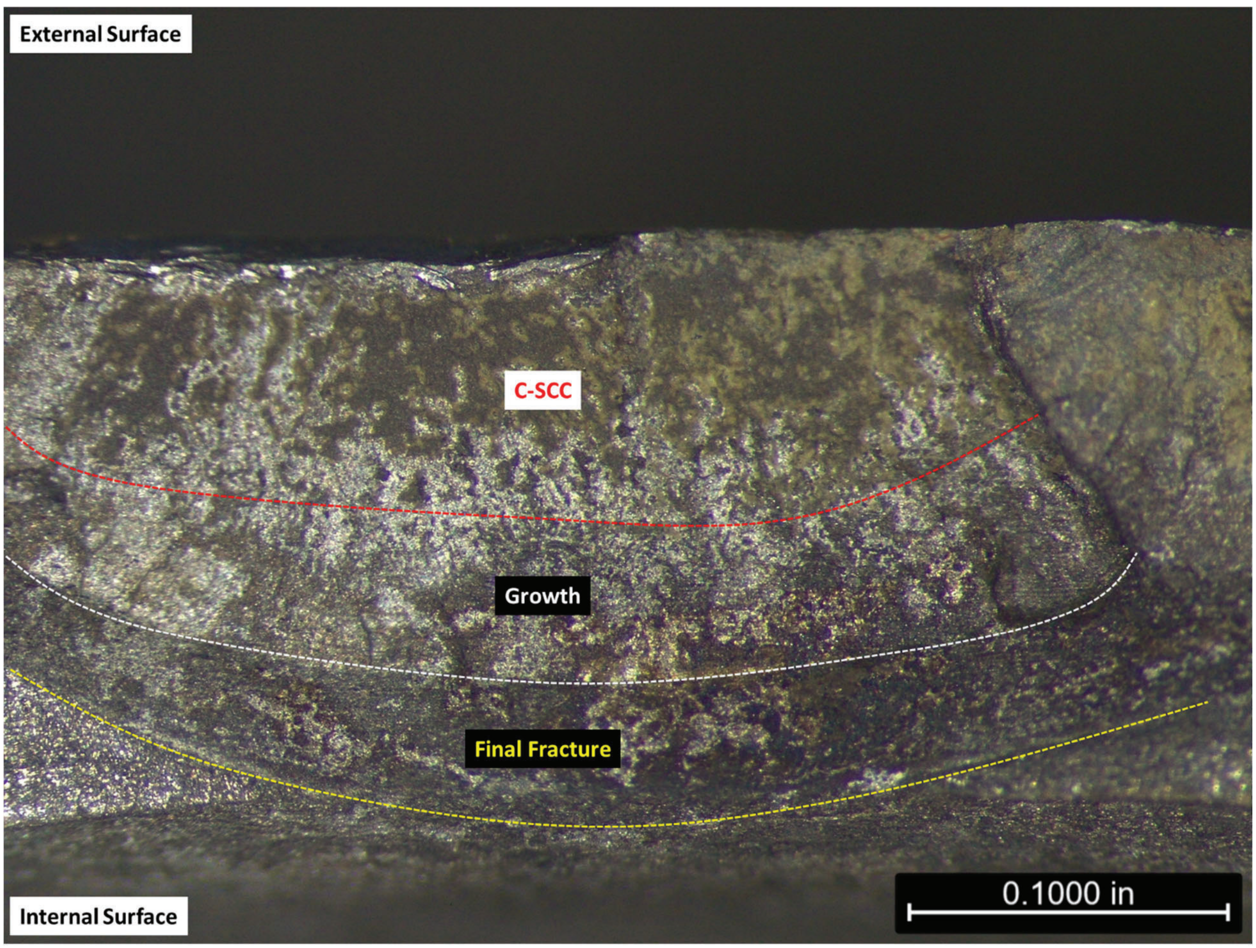

Figure 21. Photograph of boundaries present on the Sample 4 indication after breaking open and cleaning (Unreinforced). Original magnification is 12.8x.

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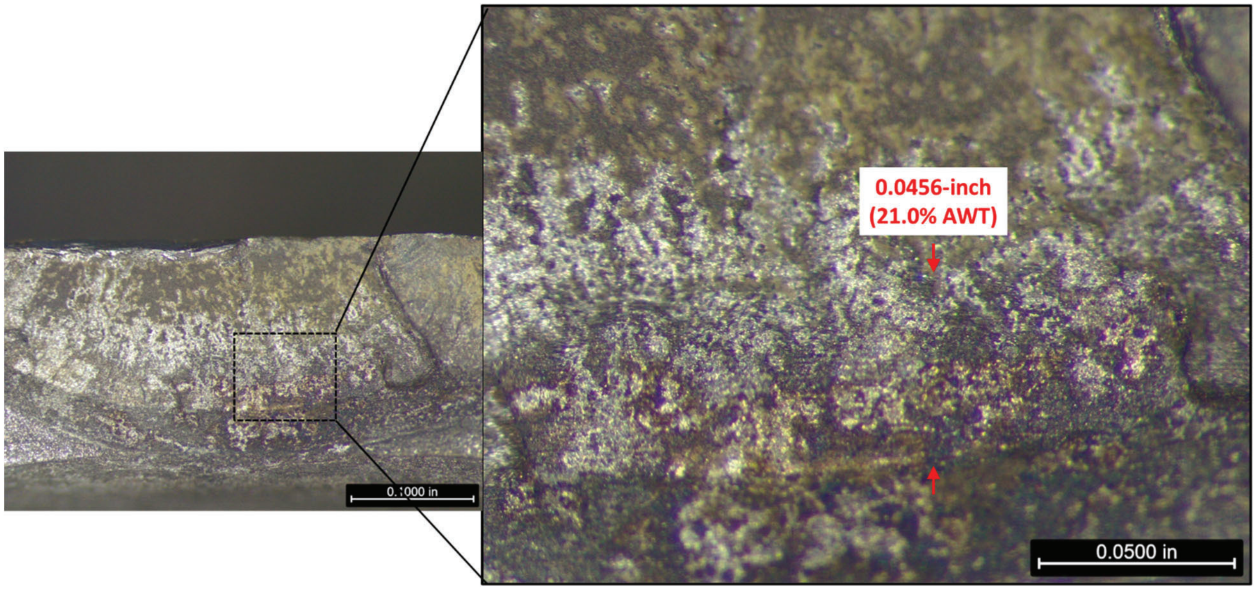

Figure 22. Photograph at the base of the Sample 4 indication (Unreinforced) showing area of growth. Original magnification: Left: 12.8x, Right: 25.6x.

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