

Study to Validate the Design of Carbon-Epoxy Technology used in the Reinforcement of Crack-Like Features

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Abstract

A full-scale test program was conducted to evaluate the performance of a carbon-epoxy composite repair system for reinforcing crack-like defects in 14-inch × 0.219-inch, Grade X46 LF-ERW (low-frequency electric resistance weld) pipe. Six pipe samples were fabricated from vintage 1960-era pipe material removed from service. Each sample featured a 3-inch-long axial crack-like defect machined in the ERW seam using electric discharge machining (EDM). Prior to testing, all samples were pre-cycled to initiate cracking at the base of the EDM notches, resulting in final crack depths of approximately 50% of the actual wall thickness.

Of the six test samples, two remained unreinforced to serve as controls, while four were reinforced using the carbon-epoxy system. A fracture mechanics-based design methodology, calibrated against the failure pressure of the unreinforced cracks, was used to determine the optimal composite thickness, calculated to be 0.220 inches.

The repair thickness successfully reinforced one sample through short-term burst testing and another through 25,000 fatigue cycles, simulating approximately 100 years of service under moderate cyclic loading. Encouraged by this performance, the remaining two fatigue samples were subjected to an extended 50,000-cycle runout. One sample completed 43,265 cycles before failure; the other completed the full runout and a subsequent burst test.

This study provides two key contributions to the pipeline industry. First, it validates a fracture mechanics-based design approach for optimizing composite reinforcement. Secondly, it demonstrates that the PermaCarbon carbon-epoxy system offers a minimum design life of 100 years under moderate cyclic conditions.

Introduction

Testing was performed to evaluate the performance of a carbon-epoxy composite repair system for reinforcing crack like defects in 14-inch x 0.219-inch, Grade X46 LF-ERW (low frequency electric resistance weld) pipe. Previous studies have shown the validity of using composite materials to reinforce planer defects in LF-ERW seams (1), but this study sought to validate a less conservate fracture mechanics based design approach, Furthermore, this program demonstrates the capabilities of the PermaCarbon carbon-epoxy system to increase the service life of aging pipeline infrastructure to a minimum of 100 years under moderate cyclic conditions.

Samples for this program were fabricated out of vintage LF-ERW pipe, harvested from a 1960s era pipeline. Notches were installed axially in the ERW bondline via electric discharge machining (EDM) at a depth of 30% of the measured wall thickness. Samples were then subjected to unreinforced pressure cycling to form a crack at the tip of the notch. After crack formation, select samples were reinforced with WrapMaster's PermaCarbon carbon-epoxy system and subject to both burst testing and pressure cyclic fatigue.

The remainder of this paper comprises of a *Test Methods* section, which provides further information on the process used to create the crack-like features and details on all of the testing samples were subjected to, a *Test Results* section that provides results from pressure testing and the post-test

metallurgical analysis, and a *Conclusions* section that provide commentary on how the PermaCarbon system performed in this programs.

Test Methods

Provided in this section are four subjects including the installation of the EDM notches, instrumentation used for the formation of cracks, the design of the composite repair, and pressure loading conditions.

Installation of EDM Notches

While the relatively low fracture toughness associated with LF-ERW seams is well suited for the propagation of axial cracks, the time required for their formation is prohibitive and unnecessary for a program such as this. Acuren, Magnolia utilizes EDM to form a starter notch in the LF-ERW bondline. This allows for the formation of a crack to be accelerated and for the crack's location to be controlled.

The process consists of taking a graphite electrode that has been formed into a know length and width and plunging it into the bondline. In this specific application, the electrode was 0.015-in in thickness and 3-in in length. An example of the setup used for plunging the electrode into the pipe can be seen in **Figure 1** and an example of an installed EDM notch can be seen in **Figure 2**. Notches were made to be 30% the measured wall thickness of the test samples.

Crack Formation

An EDM notch differs from a crack-like feature in that it lacks a sharp tip and is instead relatively blunt. In order to capture the severity of a crack-like feature, the tip must be generated prior to the installation of a repair. Crack's can be started and propagated by subjecting the EDM notch to tensile fatigue via pressure cycles.

All six reinforced samples were subjected to continuous pressure cycling at a range of 100 psig to 1,045 psig, which corresponds to 7% to 72% SMYS. 72% SMYS was selected as the top end pressure due to it being the maximum allowable operating pressure for pipelines in the United States. The notches were monitored for growth through the use of clip-on displacement gages that were installed over the center of the feature. **Figure 3** shows an example of a sample during pre-cycling with the clip gage installed. Crack growth can be inferred from this reading when an exponential increase in the flexing of the notch opening initiates as this indicated the depth of the feature is increasing. **Figure 4** shows the reading of the clip-on displacement gage versus number of pressure cycles for one of the samples during pre-cycling.

Composite Repair Thickness Design

To properly reinforce an axial crack for long-term operation, the crack propagation must be mitigated. This is done by both considering the fracture toughness of the material being reinforced and by ensuring the repair is comprised of a material with high stiffness. Limiting the amount of flexing that occurs in the hoop direction during pressure cycling is critical for limiting the growth of the crack. Acuren has developed a methodology for designing a composite repair that addresses both of these

considerations. Consider the following equation for the thickness of a composite repair used to repair an axial crack.

$$t_c = t_s \left(\frac{E_s}{E_c} \right) \left(\frac{PR}{\sigma_s t_s} - 1 \right)$$

The required composite thickness, t_c , is calculated using this equation with the appropriate inputs for pipe radius, R , remaining wall thickness of the steel substrate, t_s , the elastic modulus of both the steel substrate and the composite repair, E_s and E_c respectively, the maximum operating pressure, P , and the desired stress state, σ_s . That last term is used to incorporate fracture mechanics into calculations for the repair through the use of full-scale testing results. A short-term burst of an unreinforced sample was conducted after the completion of pre-cycling. This burst pressure is equated to a stress, which with a factor of safety of 2.25 applied, is converted to an optimal operating stress state. As full-scale test results are rarely available, a theoretical stress value can be calculated using material properties of the pipeline.

Utilizing all of these inputs, a target thickness of 0.221 inches was calculated, which equates to 11 layers of the PermaCarbon carbon-epoxy repairs system. All of the inputs used in these calculations can be found in Figure 5.

WrapMaster performed the installation of the repair, Acuren provided no guidance on their installation procedure. The surface profiles of the pipe samples were prepared via sandblasting; a NACE 2 specified profile was used.

Pressure Loading Conditions

Two forms of pressure loading were used to test the performance of the reinforced samples, short-term burst and pressure cycling. A single unreinforced sample was used in both of these load cases to provide a baseline for comparing reinforced results to. A single reinforced sample was subjected to short-term burst testing with no additional pressure cycling. The remaining three reinforced samples were all subjected to a runout of 25,000 pressure cycles at a pressure range of 100 psig to 1,045 psig, which corresponds to 7% to 72% SMYS. 72% SMYS was selected as the top end pressure due to it being the maximum allowable operating pressure for pipelines in the United States. An example of one of Acuren's pressure cycle units can be seen in Figure 6.

After the success of the initial reinforced sample reaching the original target runout of 25,000 cycles, the remaining two were given an extended runout of 50,000 cycles to further push the repair. One sample failed after 43,265 cycles, while the other completed the extended runout. The two reinforced samples that survived their runout were subjected to a short-term burst test after.

Test Results

The following sections details the results from the test program. Table 1 provides a summary of the results of this test program. All six of the test samples' initial loading condition was pre-cycling, where the samples were pressure cycled until indications of crack formation were detected. Two samples, one unreinforced (1-UR-B) and one reinforced (2-R-B), were subjected to short-term burst after the formation of their crack. One unreinforced sample (3-UR-C) was pressure cycled to failure. The three remaining samples were all subjected to an additional runout of fatigue cycles after the formation of the crack and installation of their repair.

Table 1: Results Summary

Sample ID	Sample Type	Repair Thickness (in)	Number of Pre-cycles	Number of Fatigue Cycles	Burst Pressure (psig)	Moderately Cycled Years of Service	Lightly Cycled Years of Service
Unreinforced Samples							
1-UR-B	Unreinforced -Burst Only	N/A	8,574		1,992	33	82
3-UR-C	Unreinforced - Fatigue Only	N/A	7,356		N/A	28	70
Reinforced Samples							
2-R-B	Reinforced - Burst Only	0.20	4,457		2,695	17	42
4-R-C	Reinforced - Fatigue + Burst	0.18	8,373	50,000	2,500	192	476
5-R-C	Reinforced - Fatigue + Burst	0.20	6,514	25,000	2,817	96	238
6-R-C	Reinforced - Fatigue + Burst	0.21	4,152	43,265	N/A	166	412

The original target runout for this program was 25,000 cycles, sample 5-R-C was cycled to this runout separate from the other two samples to test whether the relatively low repair thickness was adequate for the program. 4-R-C and 6-R-C were cycled in parallel and had their runout extended to 50,000 cycles to further test the bounds of the designed repair.

Table 1 also provides estimates of the equivalent years of service to the achieved runout for each sample. A “Moderately Cycled” service condition would be representative of typical liquid pipeline operation, whereas a “Lightly Cycled” service condition would correlate with gas pipeline operation. These estimates are based on available pipeline data (2) with a factor of safety of 5 included. Note that the reinforced cycle sample’s estimates (4-R-C, 5-R-C, and 6-R-C) are only based on their fatigue cycles or the cycles they experienced after their repair was installed.

Of the four burst samples, only the unreinforced sample (1-UR-B) experienced failure in the crack like feature. All three reinforced samples experience failure in the unreinforced steel outside of the repair. A photo of the unreinforced failure and the reinforced failure of samples 5-R-C can be found in Figure 7.

After samples had been tested to failure, the features were broken open for a post-test metallurgical analysis to help determine the amount of crack growth that had occurred throughout testing. EDM notch depth and crack growth can be determined by observing side profiles of the feature. Cracks were heated past 400 °F after they completed pre-cycling to form a bluish hue on the exposed portions of the feature. This process allows for the regions of crack growth that were before and after the installation of the repairs to be distinguishable. Metallurgical macrographs of an unreinforced (1-UR-B) and reinforced (5-R-C) sample can be found in Figure 8.

Table 2 summarizes the relevant measurements of all the features. Note that samples 2-R-B and 4-R-C did not show a clear enough difference in their crack growth to differentiate between the “Precycle Growth” and “Reinforced Growth” phases of testing, so their “Precycle Growth” measurement is a combination of the two. The “Crack Depth” is representative of the feature’s depth prior to the installation of the composite. In other words, the “Crack Depth” is the combination of the “Notch Depth” and the “Precycle Growth”

Table 2: Crack-like feature measurements

Sample #	Wall Thickness (in)	Notch Depth (in)	Pre-cycle Growth (in) ¹	Crack Depth (% Wt)	Reinforced Growth (in)
1-UR-B	0.215	0.063	0.054	54.4%	N/A
2-R-B	0.207	0.068	0.053	N/A	N/A
3-UR-C	0.220	0.064	0.146	N/A	N/A
4-R-C	0.231	0.058	0.052	N/A	N/A
5-R-C	0.199	0.069	0.033	51.2%	0.023
6-R-C	0.224	0.069	0.037	47.3%	0.059

Conclusions

This full-scale test program as presented in this paper demonstrates that carbon-epoxy composite reinforcement, specifically the PermaCarbon system, can effectively and reliably reinforce axial crack-like defects in vintage LF-ERW pipe. Controlled EDM notching and pre-cycling successfully produced realistic crack geometries, enabling a meaningful assessment of repair performance. A fracture-mechanics-based design methodology, calibrated using the failure pressure of an unreinforced crack, accurately predicted the required composite thickness for long-term crack mitigation.

Across burst and fatigue testing, all reinforced samples exceeded the performance of the unreinforced controls. In every reinforced burst test, failure occurred in the unreinforced steel outside the repair,

¹ Sample 2-R-B and 4-R-C did not show a clear enough transition to differentiate pre-cycling from reinforced cycling, so pre-cycle growth is actually a combination of the two phases of testing.

confirming that the composite system fully restored hoop strength at the defect location. Fatigue testing further validated long-term durability: reinforced samples achieved the target 25,000-cycle runout, and two samples were pushed to 50,000 cycles, representing a minimum design life of 100 years under moderate cyclic conditions.. Metallurgical analyses confirmed minimal crack extension after reinforcement, demonstrating the system's ability to arrest crack growth.

Overall, this study provides strong validation for a fracture-mechanics-based design approach for composite crack reinforcement and confirms that the PermaCarbon carbon-epoxy system can provide a minimum design life of 100 years for aging LF-ERW pipelines operating under typical cyclic conditions.

References

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- (3) Alexander, C. and Denowh, C., The Role of Full-Scale Testing in Managing Pipeline Integrity, Pipeline Pigging and Integrity Management Conference, Houston, Texas, February 12-16, 2024.

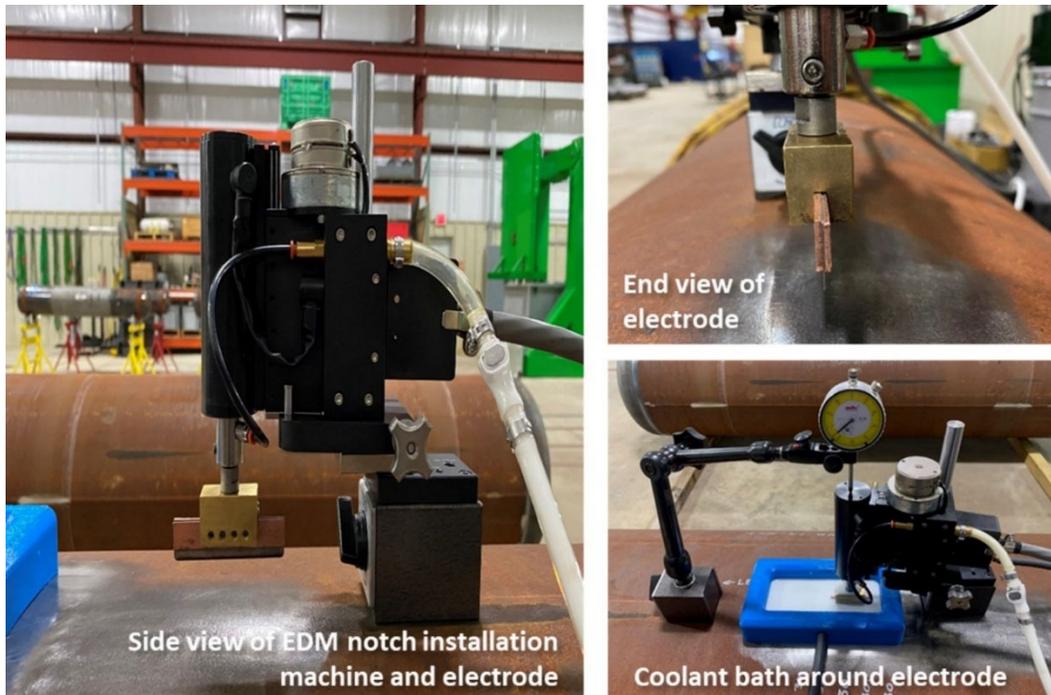


Figure 1. EDM notch installation setup (3)

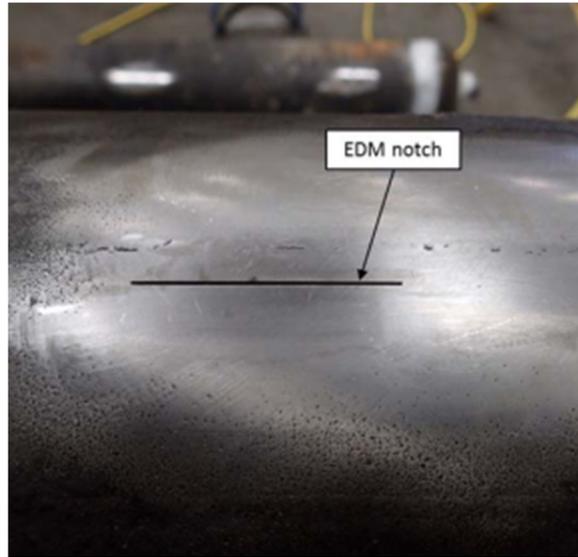


Figure 2: EDM notch installed in external pipe wall (1)

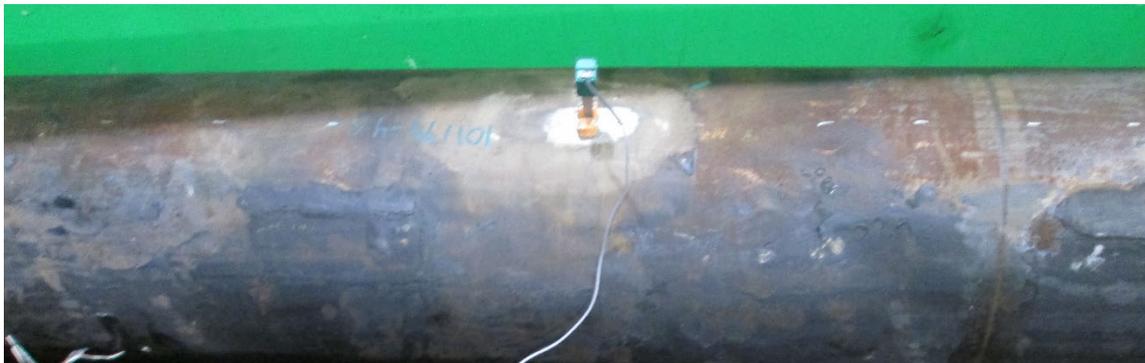


Figure 3: Unreinforced sample during precycling with clip-on displacement gage installed

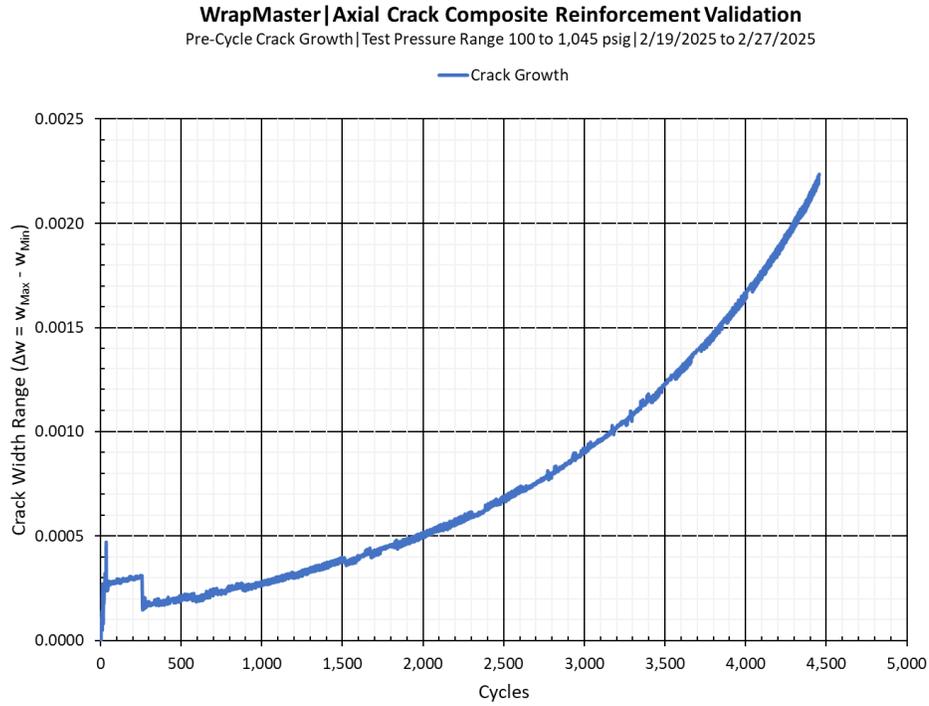


Figure 4: Clip -on displacement gage reading vs number of pressure cycle during pre-cycling

D	14	inches
R	7	inches
t_s	0.219	inches
Crack depth (%)	50%	(Sample 1URC)
t_{s_rem}	0.110	inches
E_s	29,000,000	psi
E_c	18,850,000	psi
σ_y	46,000	psi
σ_{UTS}	63,000	psi
Composite Design Strength: s_{lt}	45,170	psi
Client-given MAOP: P	1,045	psig
MAT-8 P_{burst}	N/A	psig
Experimental P_{burst}	2,033	psig
f	2.25	Safety factor
MAT-8 or Exp. Burst: σ_{burst}	64,982	psi
$\sigma_s (\sigma_{burst} / f)$	28,881	psi
t_c	0.221	inches
Thickness per layer:	0.020	inches
Number of Wraps:	11	
Reinforced Burst Pressure	3,460	psig
Fatigue Calculations (assuming API X' Curve)		
$N(\sigma_s)$	61,827	cycles

Figure 5: Composite repair design calculation inputs



Figure 6. Pressure cycle pumping unit



Figure 7: Sample 1-UR-B (top) and 5-R-C (bottom) post short-term burst test

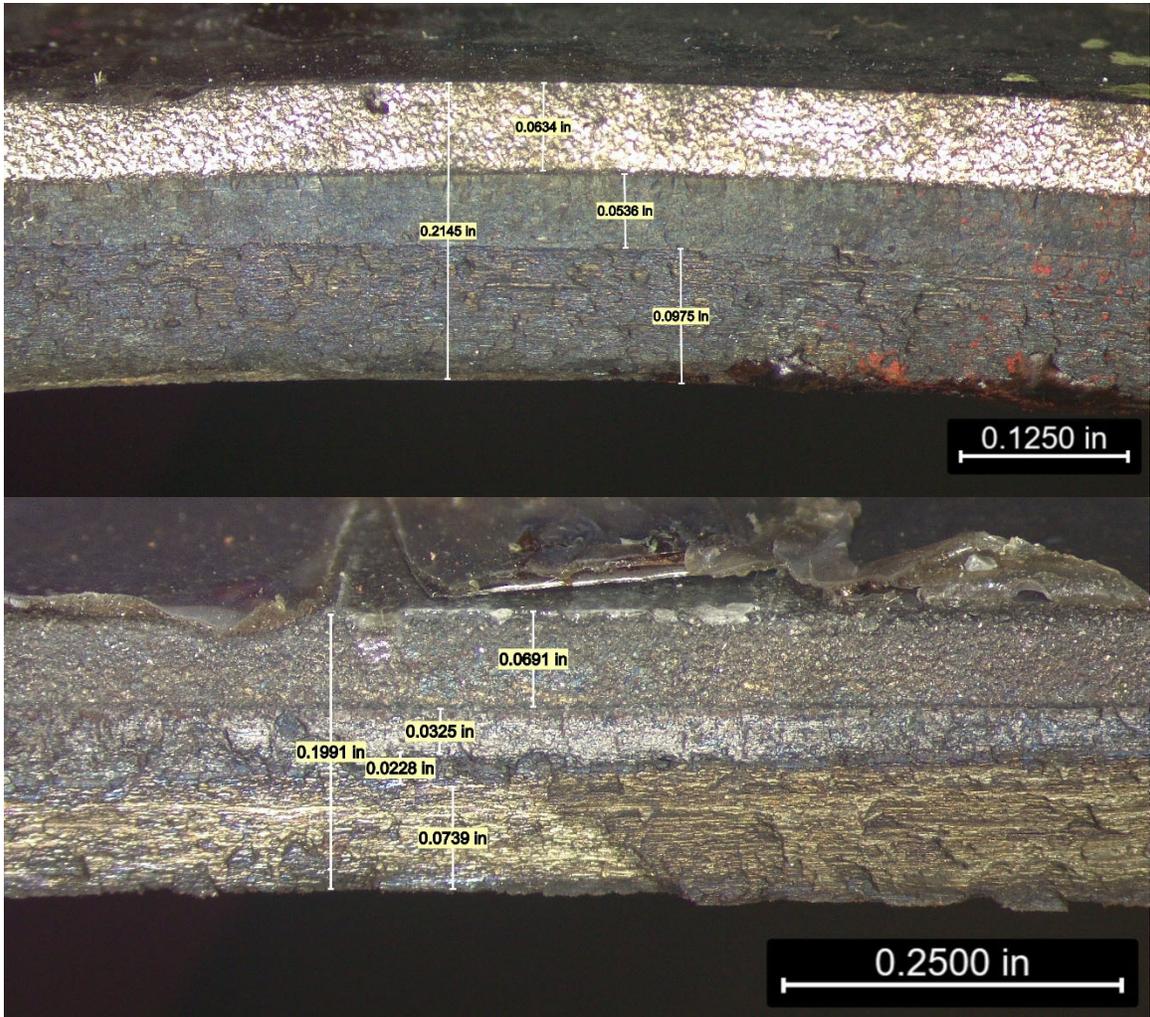


Figure 8: Sample 1-UR-B (Top) and 5-R-C (bottom) macrographs