Test V Stress Corrosion Cracking Evaluation of ASTM A354 Grade BD Rods

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LRA Report **#TYL'13-0901 Test V**

Prepared for

Caltrans
333 Burma Road
Oakland, CA 94607

Prepared By:
LRA
Mailing Address: POB10239
Newport Beach, CA 92658
Location: 20261 SW Acacia St., Suite 120
Newport Beach, CA 92660
Phone: 949 474-0218
LRA@LouRaymond.com

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Executive Summary

In March 2013, ninety-six high-strength steel rods installed on the lower housing of Shear Key S1 and Shear Key S2 at Pier E2 of the San Francisco-Oakland Bay Bridge, SFOBB, were loaded to their design load of 70% of their specified minimum ultimate tensile strength or Force ultimate, Fu. Within fourteen days, 32 of the 96 ASTM A354 Grade BD rods fractured. A metallurgical investigative team was tasked with examining the cause of the failures of the high-strength steel rods. Based on an examination on two of the extracted high-strength steel rods, the metallurgical investigation team on 07 May 2013 attributed the rod failures to hydrogen embrittlement, HE; that is a time-delayed crack growth mechanism following exposure to hydrogen and results in an in-service fracture of the rods. **(1)**

Subsequently, an extensive six part testing program was developed and performed to address the condition of the remaining bolts on the bridge. Test I, Test II, and Test III were performed to evaluate the mechanical properties of sample rods. Test IV was performed to evaluate the full-size performance of sample rods tested in tension when subjected to a HE environment. Test V was performed to provide statistical substantiation to Test IV. Small, single edge notched fatigue pre-cracked, fpc, and threaded, Thd, specimens were tested in bending, SEN(B), in accordance with ASTM F1624/F2660 when subjected to a stress corrosion cracking, SCC, environment. Test VI used long-term sustained load tests, SLT, in accordance with ASTM E1681 to further substantiate the environmental hydrogen embrittlement, EHE**,** stress intensity thresholds determined by the Rising Step Load, RSL™, slow strain rate test method in Test V. **(2)**

The specific objectives of Test V were to determine the SCC threshold stress intensity factor for the material (**KIscc**) and thread root (**KIρ-EHE**) of the various groups of rods and use this information to independently determine the threshold loads for the Self-Anchored Suspension Span, SAS, rods. *This report lists the findings from the testing performed at L.Raymond & Associates, LRA, in Newport Beach, CA for Test V.* **(3)(4)(5)(6)**

Test V showed that since many specimens can be obtained throughout a cross section of a 2.5-inch long threaded rod segment, the effects of varying manufacturing and environmental variables, such as the effect of potential on the EHE stress intensity threshold, can be evaluated. Additional fractographic analysis was conducted by using a Scanning Electron Microscope (SEM) on the tested specimens whose fracture surfaces were produced under known testing conditions, for comparison to the results of the post fracture analysis (PFA) of the threaded rods in Test IV.

The rods were thoroughly characterized metallurgically relative to Rockwell C Hardness Scale (**HRC**) Open Circuit Corrosion Potential (**OCP**) of the coating, fast fracture strength (**Kmax**), fracture toughness (**KIc**/**KIctod**), internal hydrogen embrittlement, IHE, and EHE at the mid-radius, MR, and outside diameter, OD, of the rod samples when exposed to a 3.5% salt water environment with an applied potential simulating the galvanic coupling effect of the hot-dipped galvanized zinc coating. The centers, C, of the rods were characterized metallurgically relative to HRC and KIc/KIctod.

IHE is hydrogen embrittlement due to processing that is measured when testing in air. EHE is hydrogen embrittlement due to environmental exposure that is measured when testing in a hydrogen-charging environment under conditions of galvanic coupling such as in the salt water under an imposed cathodic potential versus a Saturated Calomel Electrode, SCE. SCC and Environmentally Assisted Cracking, EAC, are generic expressions often used interchangeably for cracking in a corrosive environment, most often under stress. For the purpose of this report, SCC will be used.

Different loading rates were analyzed with the RSL testing rig. Fast fracture strength, FFS, incremental step loading, ISL, in air and in a corrosive environment were performed on a bend or tensile RSL frame in accordance with ASTM F1624 test procedure that provides an accelerated method to measure the threshold stress or threshold stress intensity factor for the onset of SCC in steel (designated K_{Iscc}, $\mathbf{K_{I\text{-}IHE}}$, or with the prefix $\mathbf{K_{I\rho}}$ for Thd specimens with root radius, ρ, in Test V). **(7)** The procedure conforms to and is based on determining the onset of subcritical crack growth with a step-modified, progressively decreasing strain rate test under displacement control.

Throughout testing, many additional topics surfaced that did not fit into the procedures of Test V. These topics are introduced as special projects in supplementary Section 4.5. This section is set up with individual topics that are addressed with their own results, discussion, and conclusion. Some of the special projects included are on the evaluation of zinc cracking, OCP, SEM comparisons of fractographic features, and other noteworthy matters.

Of the 18 rod samples provided to LRA for Test V, it was concluded that the rod failure was due to SCC from the service environment instead of galvanizing inducing IHE. Correlations found in Test V for variation in both hardness and applied potential allowed Test V results to be adjusted to Test IV conditions. As a result, the Test IV results were successfully verified from the adjusted Test V results, thus validating the Test V protocol and analysis.

Respectfully,

L.Raymond & Associates
A Professional Consulting Corporation

William Crumly, P.E. (CA)
***Manager of Technical Operations* / LRA Labs**

L.Raymond & Associates
A Professional Consulting Corporation

Louis Raymond, Ph.D., P.E., FIAE, FASTM
***Director of Technical Operations* / LRA**

1 Objective

The objectives of Test V were to determine the fracture toughness and IHE and EHE stress intensity thresholds of the materials supplied to LRA from the various groups of rods to independently determine the threshold load for hydrogen induced stress cracking in SAS bridge rods.

1.1 Test V Rods

The rods tested as part of Test V varied in diameter from 2-inches to 4-inches so that the cross section of the rods was large enough to allow many specimens to be obtained throughout a cross section of a 3-inch-long threaded rod segment allowing the effects of varying manufacturing and environmental variables, such as the effect of potential on the HE threshold of the full sized threaded rods can be evaluated.

Table 1.1-1 SAS A354 Grade BD Test V Bolt Sampling (2)

ID	Structural Component	Number of Bolts	Nominal Bolt Diameter [in]	Sustained Bolt Tension % Fu (UTS)	Threads (Cut or Rolled)	Test V RSL Technique
1	Shear Key Anchor Bolts- Bottom (S1/S2)	96	3	0.7	Cut	**2**
2	Shear Key Anchor Bolts- Bottom (S3/S4)	96	3	0.7	Cut	
	Pier E2 Bearing Bolts- Bottom Housing (B1, B2, B3, B4)	96	3	0.7	Cut	
3	Shear Key Anchor Bolts-Top (S1/S2)	160	3	0.7	Cut	**4** (spares)
	Shear Key Anchor Bolts-Top (S3/S4)	160	3	0.7	Cut	
4	Pier E2 Bearing Bolts- Top Housing (B1,B2,B3,B4)	224	2	0.7	Rolled	**2** (spares)
5	Spherical Bearing Bushing Assembly Bolts	96	1	0.61	Cut	
6	Bearing Retainer Ring Plate Assembly Bolts	336	1	0.4	Cut	
7	PWS Strand Anchor Rods (Main Cable)	274	3.5	0.32	55 Cut, 219 Rolled	**4*****
8	Tower Saddle Tie Rods	25	4	0.68	Rolled	**1** (spare)
9	Tower Saddle Turned Rods (@ Splices)	100	3	0.45	Cut	
	Tower Saddle Turned Rods (@ Splices)	8	3	0.1		
10	Tower Saddle Grillage Bolts	90	3	0.1	Cut	
11	Tower Outrigger	4	3	0.1	Cut	
12	Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts)	388	3	0.48	Cut	**2**
13	Tower Anchorage Anchor Bolts (100 Dia. Anchor Bolts)	36	4	0.37	Cut	**1**
14	East Saddle Anchor Rods	32	2	0.1	Cut	
15	East Saddle Tie Rods	18	3	0.2	Cut	
16	Cable Bracket Anchor Rods	24	3	0.16	Rolled	
17	Bikepath Anchor Bolts at Pier W2	43	3	0.1	Cut	
18	E2 2013 Replacement Rods (CCO 312)	40	3	0.7	Cut	**2** (spares)

*** samples with rolled thread and cut thread

Fractographic analysis was conducted by using a SEM on the tested specimens whose fracture surfaces were produced under known testing conditions, as supplementary information to the results of the PFA of the threaded rods in Test III and Test IV. **Table 1.1-1** summarizes the ASTM A354 Grade BD bolt locations on the SFOBB and information used in Test V. **(2)** In addition, the rod samples were thoroughly characterized metallurgically relative to HRC, OCP of the coating, KIc/KIctod, IHE, and EHE at the MR and OD of the rod samples when exposed to a 3.5% salt water environment with an applied potential simulating the galvanic corrosion effect of zinc coating. The centers of the rods were characterized metallurgically relative to HRC and KIc/KIctod.

2 Test V Test Protocol and Test Rigs

The current ASTM standards were used unless noted otherwise for each rod sample provided for Test V:

1. ASTM E8 (fast fracture strength),
2. ASTM E18 (HRC),
3. ASTM E23 (notched bar impact testing of metallic materials) ,
4. ASTM E399/E812/E1290 (fracture toughness),
5. ASTM F1624 (IHE, EHE, and SCC threshold),
6. ASTM F2078 (HE terminology),
7. ASTM G3 (Electrochemical cell) and
8. ASTM G129 (Strain rate for EAC)

Fatigue pre-cracked specimens were used to determine the material Fracture Toughness properties (KIc/KIctod/KIscc) in accordance with ASTM F1624 and the other referenced specifications. Tests to determine KIp, the effective threshold stress intensity factor in a salt-water environment for the threaded and galvanized conditions used a specimen with the threads intact. The KIp tests conformed to all other F1624 requirements and were used to directly predict the performance of the threaded rod in service and in Test IV.

2.1 Terminology and Symbols

The terminology used throughout this report can be found in ASTM F2078 HE terminology and Section VI Abbreviations, Acronyms, and Symbols.

2.2 Testing Equipment

2.2.1 Test Machine

Testing was conducted using a computerized, four-point bend, digital displacement controlled loading frame that is capable of stepping in 0.5% load steps and is programmed to increase incrementally in steps of load and time to vary the strain rate at the root of the notch between 10^{-4} and 10^{-9} s^{-1}. RSL bend test machines manufactured by Fracture Diagnostics International, FDI, were used for this test program (see **Figure 2.2-1**).

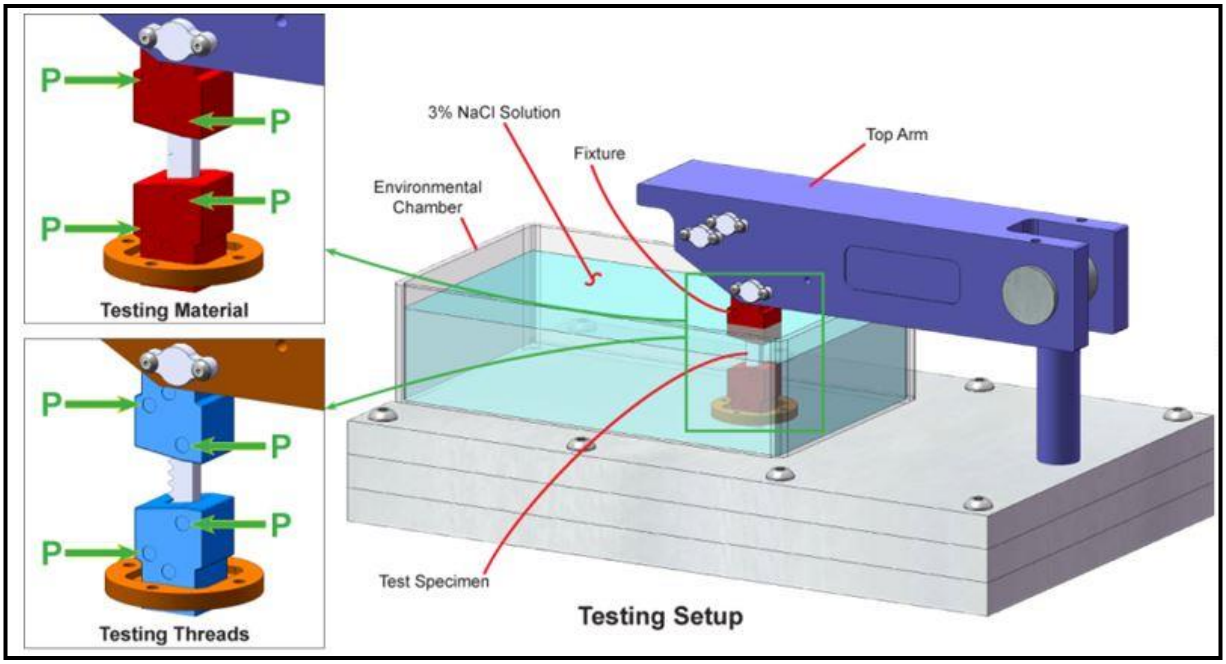

Figure 2.2-1: RSL Bend Test Machine, Manufactured by www.FractureDiagnostics.net

2.2.2 Fixtures

A schematic of the adapters used during this study is shown in **Figure 2.2-1**. The adapters transmit the measured load applied by the testing equipment to the fpc and thread modified ASTM E1290 SEN(B) test specimen.

2.2.3 Test Environment

Testing was conducted in two environments. FFS tests and IHE tests were conducted in air. The EHE test specimens were immersed into a 3.5% NaCl solution under potentiostatic control by imposing a galvanic cathodic potential in 3.5% NaCl solution contained in an appropriate inert container.

2.2.4 Potentiostatic Control

The corrosion potential of the specimen was controlled with reference to a Saturated Calomel Electrode (SCE), and the potential is referred to as Vsce. The imposed potential was cathodic and ranged from -0.85 Vsce to -1.2 Vsce in a 3.5% NaCl solution with the majority of the testing performed at -1.106 Vsce. The manufacturer's recommended allowable variation between SCE reference electrodes is 50 mV, however LRA experience is that if the current flowing through the electrode is minimized, the variation will be less than 10 mV. The auxiliary or counter electrode used for the testing was a length of platinum wire located at the end of the chamber opposite of the specimen. The reference electrode was located so that the end of the electrode was within 1-inch of the specimen under test. Analysis of the test chamber utilizing Ohm's law, V = IR, found that the voltage drop due to solution resistance for a typical test was less than one mV when the SCE electrode is located within 1-inch of the specimen. **Figure 2.2-2** shows the IR voltage drop distribution within the test solution for a test in the RSL test chamber when test current is 5 mA, which is the typical current for EHE test in 3.5% NaCl.

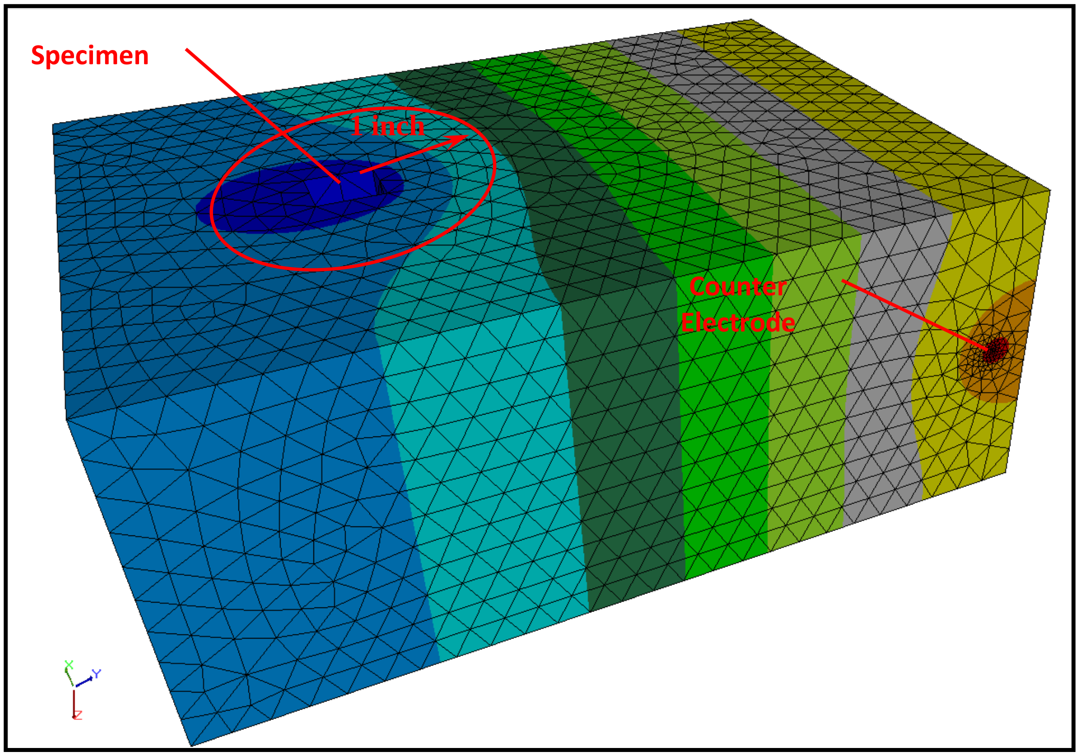

Figure 2.2-2: FEM Analysis of IR Drop

2.3 Test Protocol Details

2.3.1 Specimen Machining

Rod samples were received at LRA and visually examined for general condition and major defects. Full diameter rod samples varied in length from 6-inches to 24-inches. Charpy-sized specimens were cut from 2.5-inch long rod segments using electric discharge machining, EDM.

Two types of specimens were prepared. One type of specimen was cut from the interior of the segment. ASTM E1290-99, single edged notched bend, 0.4W SEN(B) specimens were cut from the interior of the rod to Charpy-sized dimensions of 0.4 inch wide by 0.4 inch thick by 2.25 inches long. A slot, 0.1 inch deep, was cut by EDM in the center of each specimen as a starter slot for fatigue pre-cracking. The location from which an interior specimen was removed was noted and specimens were tested as outer diameter, mid-radius, or center specimens (OD, MR, and C).

The second type of specimen was cut from the outer edge of the segment and included the thread and the hot dipped galvanized zinc, HDG-Zn, coating. These threaded specimens were cut from both spare rods and remnants from Test IV. The nominal dimensions of the threaded specimens were 0.61 inch wide (0.61W) by 0.4 inch thick (0.4B) by 2.5 inches long. A section was removed from the backside of the specimen to reduce the specimen width at the thread root to 0.55 inch. The two types of specimens are shown in **Figure 2.3-1** and **Figure 2.3-2**.

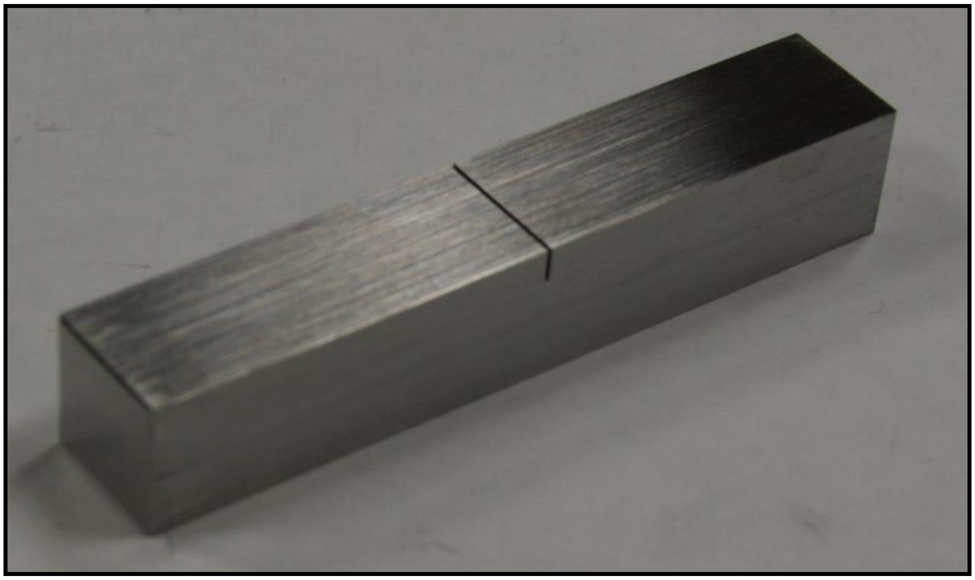

Figure 2.3-1: ASTM E1290, 0.4W-SEN(B), fpc

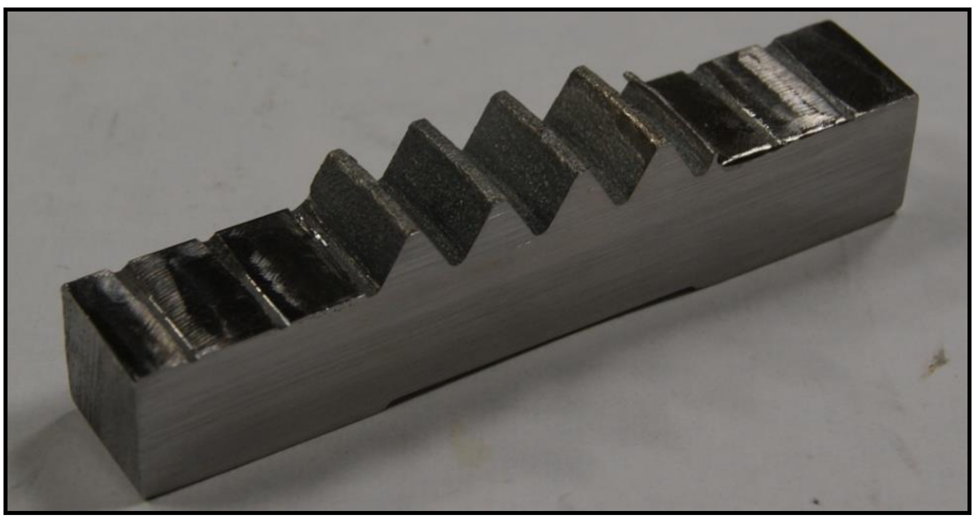

Figure 2.3-2: Modified ASTM E1290 SEN(B), Thd

The Rod identification is as follows: "location ID"-"test number"-"rod sample identification". For example Rod ID, 3-V-9, is an E2 shear key upper rod (location ID #3, see **Table 1.1-1**), used in Test V, identified as rod sample 9. Each specimen cut from a Rod ID has a sample number, S/N. Rod ID can consist of S/N's such as OD1, MR2, C1, and Thd4. Since there are two specimens cut from the outer diameter, one fpc, OD_{fpc}, and one Thd, OD_{Thd}, the term OD without a subscript refers to an OD fpc specimen, and the term Thd refers to an OD Thd specimen. The distribution of specimens in a 3 inch rod is illustrated in **Figure 2.3-3** and **Figure 2.3-4**.

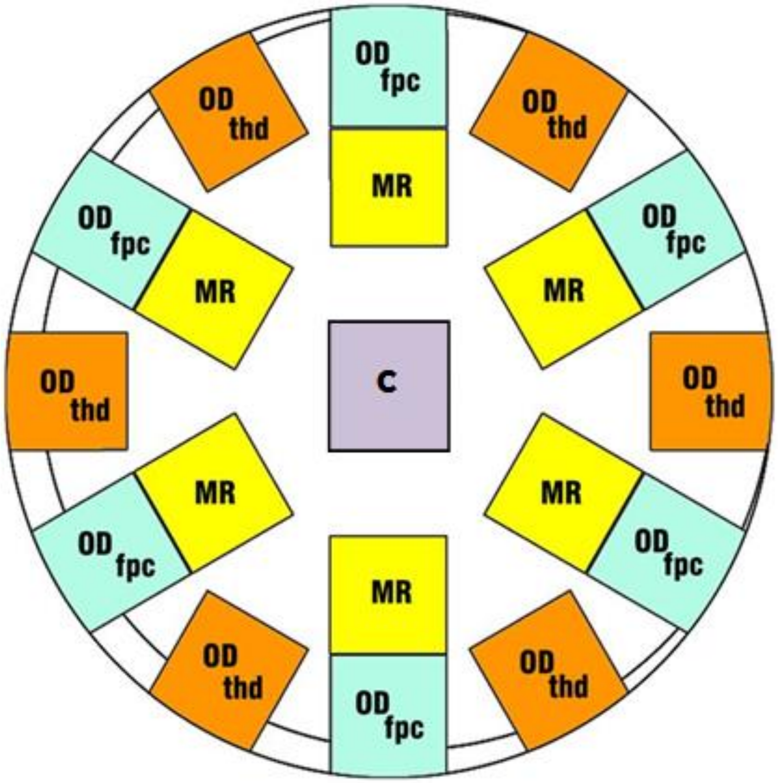

Figure 2.3-3: Machining Plan for a 3-inch Diameter Rod

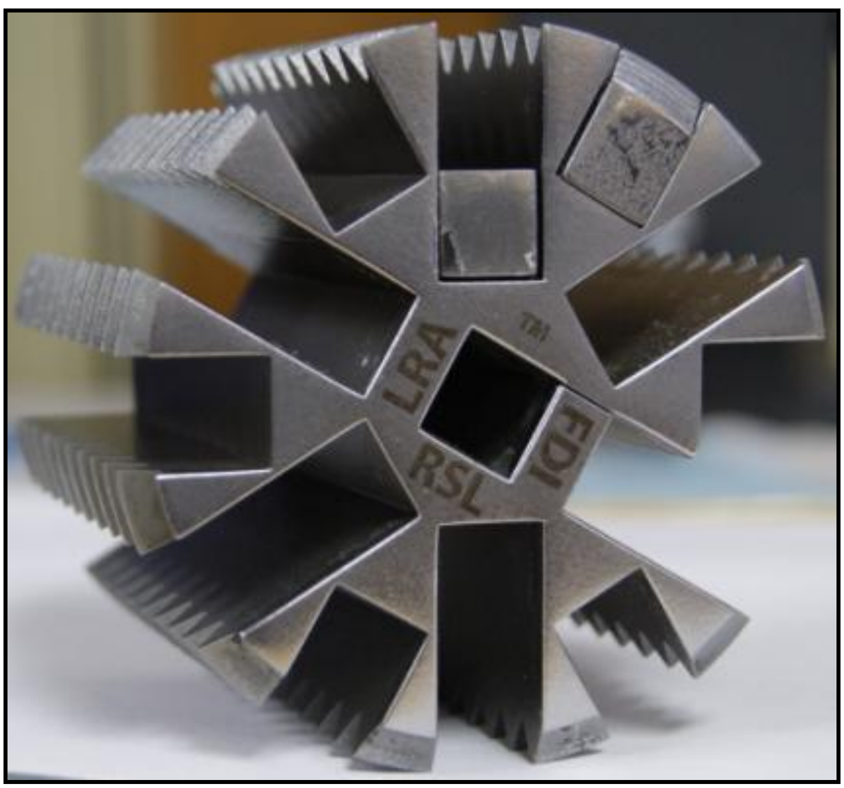

Figure 2.3-4: Rod Segment with Specimens Removed

2.3.2 Specimen Preparation

After the specimens were removed from the rod by EDM, they were lightly sanded and cleaned. The SEN(B) specimens were wet sanded with 240, 320 and/or 600 grit sandpaper to remove EDM recast (a thin coating of molten material re-deposited on the specimen during the EDM process). Specimens were then cleaned in an Alconox cleaning solution, rinsed in acetone, and dried.

2.3.3 Hardness Test

The hardness of each specimen was measured using a Rockwell Hardness Tester (Wilson Instrument Division, American Chain and Cable Co.). A Rockwell Hardness C (**HRC**) scale was used in accordance with ASTM E18. The hardness was measured at six points on the side of the specimen spanning its length. The highest and lowest readings were discarded and the remaining four measurements were averaged. The hardness was used to estimate the ultimate tensile strength of the specimen using ASTM E140.

2.3.4 Fatigue Pre-cracking

Prior to testing, 0.4W-SEN(B) Charpy-sized bend specimens were fatigue pre-cracked. The EDM slot was extended by fatigue approximately 0.08 to 0.10 inches to an $a/W \approx 0.5$. The precise depth of the pre-crack was measured following testing. The final stress intensity factor used during fatigue pre-cracking (typically 15 ksi√in) was less than 60% of the measured stress intensity factor for crack initiation (which is typically 25 ksi√in to 35 ksi√in). A Physmet FCM-300B pre-cracking machine was used to pre-crack the specimens as required. This unique piece of equipment uses constant displacement rings to produce cracks ranging from 0.005 inches to 0.250 inches in fewer than 10 minutes. Threaded specimens were not fatigue pre-cracked.

2.3.5 Fast-Fracture Testing

To provide baseline reference data for each rod and specimen type, a specimen of each rod and type is tested to rupture using a rate consistent with ASTM E8. This establishes a fast-fracture strength, load (**P_{FFS}**), and stress intensity factor for a given specimen geometry. These variables are noted by FFS or max and are obtained from the maximum value achieved in the FFS test for the fpc and Threaded specimens.

2.3.6 RSL™ Testing

The test procedure provides an accelerated method to measure the threshold stress or threshold stress intensity factor for the onset of SCC in steel. The procedure conforms to ASTM F1624 and is based on determining the onset of subcritical crack growth by a load drop during a step-modified, progressively decreasing strain rate test under displacement control. The threshold load, P_{th}, is obtained on completion of a minimum of two tests. The threshold is the lowest value of two consecutive tests when the difference between them is within 5% of the fast-fracture strength, FFS. Once an invariant value is obtained, no further tests are required. Otherwise, additional tests must be performed following the protocol of Section 8.1.6 in ASTM F1624 until an invariant value within 5% of FFS is obtained from two consecutive tests. Of the two tests, the lowest value will be used. For example, if the FFS of a specimen is 100 lbs and the first EHE test had a load of 35 lbs and the second EHE test had a load of 32 lbs, the threshold load would be 32 lbs, because the two EHE tests were within 5 lbs (5% of FFS) of each other. Since an invariant value was obtained, no further tests would be required.

A typical (10/5/2,4) step load profile progression of tests to determine the threshold for steel ≥ 33 HRC to 45 HRC from Section 8.1.6 in ASTM F1624 is shown **Figure 2.3-5**. With the loading profile of (10/5/2,4), a specimen is loaded to reach a target load, P_{target}, in 10 steps with a dwell time of 2-hours between each step and 10 steps with a dwell time of 4-hours between each step, resulting in 20 steps each with a magnitude equal to 5% of P_{target}.

The curve at the left labeled "ASTM E8" shows the load/time curve for the fast-fracture test that determines the FFS and P_{FFS}. The first RSL test is performed at 5% steps of P_{FFS} (which is P_{target}) initially 10 each, two-hour steps followed by four-hour steps until the specimens fracture (labeled $P_{i\text{-}1}$) and the step before the fracture step is the threshold load (labeled $P_{th\text{-}1}$). The next test is performed with steps of 5% of P_{target}, which is 1.1 times $P_{th\text{-}1}$ to find $P_{th\text{-}2}$, and so on as shown in **Figure 2.3-5** from ASTM F1624.

ASTM F1624 was originally developed for testing aerospace steels with a hardness of 50 HRC. Because of the low-strength steel being tested, the net-section stress in bending at which the sub-size specimen cracks is likely to be above the yield stress of the steel. At these stress levels, significant plastic deformation at room temperature is possible and will produce a load drop that can be confused with crack extension. **Figure 2.3-6** shows the load drop curvature that can be used to separate the crack initiation load from yielding from ASTM F1624.

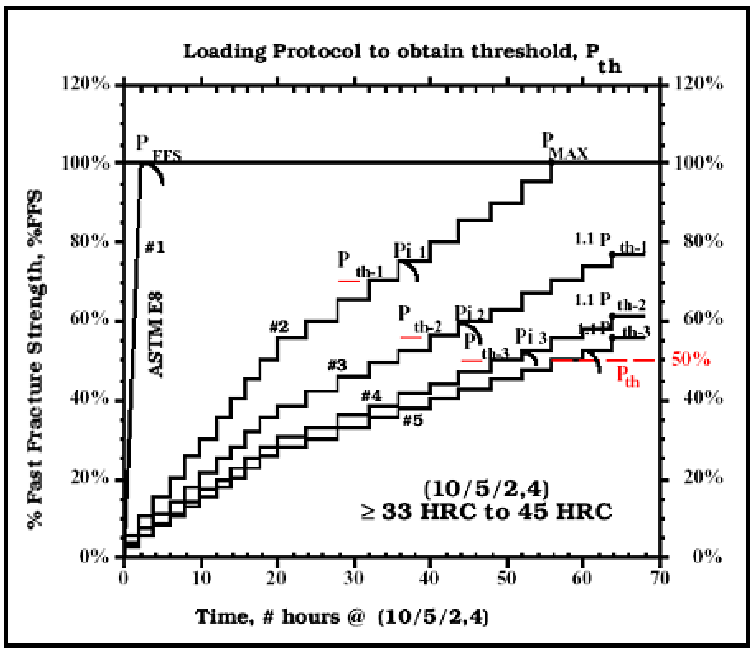

Figure 2.3-5: Schematic of a (10/5/2,4) Step Load Profile

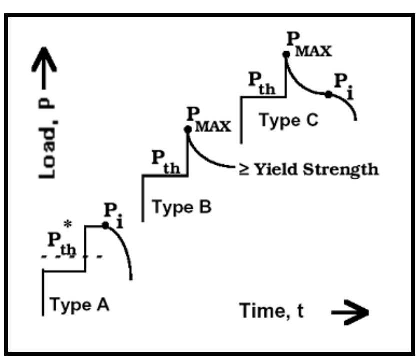

Figure 2.3-6: Definition of Crack Initiation Load, Threshold Load, and Yielding

Hydrogen embrittlement or stress corrosion cracking will produce an accelerating curve that appears as a concave downward Type A load time curve as shown in **Figure 2.3-6:** . On the other hand, yielding will produce a Type B load time curve that is concave upwards.

Often, cracking will initiate after some delay in a step and after yielding starts. When this occurs, the curve will take on a sigmoidal shape as shown in **Figure 2.3-6** as a Type C curve. If the test does not attain a load drop of 5%, the test will increase to the next load step, generating a serrated load-time curve above the threshold. To separate the threshold load from yielding, a change in specimen compliance is measured.

Multiple specimens are tested per ASTM F1624. By decreasing the load step, the strain rate is decreased from specimen to specimen. The minimum or invariant value of the stress intensity factor (K_{Iscc}, $K_{I\text{-}IHE}$, $K_{I\rho\text{-}EHE}$ or $\mathbf{K_{I\rho\text{-}IHE}}$) or stress for a given geometry with regard to the loading rate before the onset of crack growth is defined as the threshold for the onset of crack growth due to HE.

2.3.7 Impact after Test

After RSL testing has been completed, the specimen is ultrasonically cleaned in Alconox followed by acetone and dried in air. The specimen is then baked at 400°F for one hour to heat tint the cracked surface and then broken by impact per ASTM E23 to expose the fracture face using the CIM-24 Physmet Charpy Impact Machine. This machine is capable of testing materials with energy capacities up to 24 ft-lbs at room temperature. Heat tinting aids any subsequent SEM examination by marking the extent of SCC cracking.

For fatigue pre-cracked specimens, the actual length of the pre-crack cannot be measured until after the test is complete and the specimen is broken open. In addition, for the fatigue pre-cracked FFS test, heat tinting allows the extent of crack tearing to be measured to ensure that a valid crack tip opening displacement, CTOD, test was performed.

For threaded specimens, the energy capacity to break an EHE test specimen at room temperature was more than 24 ft-lbs. This resulted in the threaded test specimens being immersed in liquid nitrogen (LN_2) before being impacted to reduce the energy needed to fracture.

2.4 Test Method Validation

The threshold load measured with Charpy-sized specimens for the rods in Test V can be used to calculate a threshold load for full size rods as a ratio to Fu for the rods. This calculation was validated three ways:

1. Fracture mechanics was used to relate a measured threshold stress intensity factor for the threaded specimens loaded in bending to the threshold load for the corresponding full size threaded rod loaded in tension. **(2)**

2. Finite Element Analysis was used to relate the local maximum Strain Energy Density, SED, of threaded Charpy-sized specimens loaded in bending to the local maximum SED for the corresponding full size threaded rod loaded in tension. **(2)**

3. Test V data for rods corrected for applied potential and hardness predicted failure loads for corresponding rods tested as part of Test IV. **(2)**

All three methods are independent from each other and each validated the use of threaded Charpy-sized specimens loaded in bending to determine the threshold load for full size threaded rods loaded in tension.

2.5 Fracture Mechanisms

During the testing of the rods with cut threads it became apparent that the failure mechanism during the RSL test was more complex than anticipated.

Examination of the RSL load/time curve for the threaded specimens found that the system spring rate (measured as the inverse of compliance) changed significantly at a load step that was typically well below the load at which visible cracking was detected. **Figure 2.5-1** shows a typical RSL test curve. The blue curve shows the change in spring rate or stiffness (**k**) at each step and the red plot is the stress intensity factor vs time. The spring rate starts to fall at the load where the stress is approximately the yield strength and is most likely caused by local yielding of the specimen at a hydrogen susceptibility ratio (**Hsr**) of 0.7 of 118 ksi. However, the spring rate changes again at 172 ksi. This spring rate change can only be explained by the formation of cracks at the thread root of the specimen. The RSL software automatically performs the calculations necessary to determine the threshold load step using this spring rate (or compliance) method for detecting cracking and the threshold loads reported in this report were determined using this digital analysis technique.

The Hsr is a ratio of the local net section stress under SCC relative to the steel's tensile strength. Low alloy steel yields at values of around 0.7 Hsr. When the Hsr is greater than 0.7, yielding will occur before SCC.

The onset of cracking corresponding to the change in spring rate was verified by performing tests with longer dwell times allowing visual confirmation of cracking. When the test dwell time is 8-hours or longer, the onset of EHE cracking is at the same step as this break in the spring rate for a test with 4-hour steps. This verifies that the break in spring rate for the testing performed with 4-hour steps was due to crack initiation.

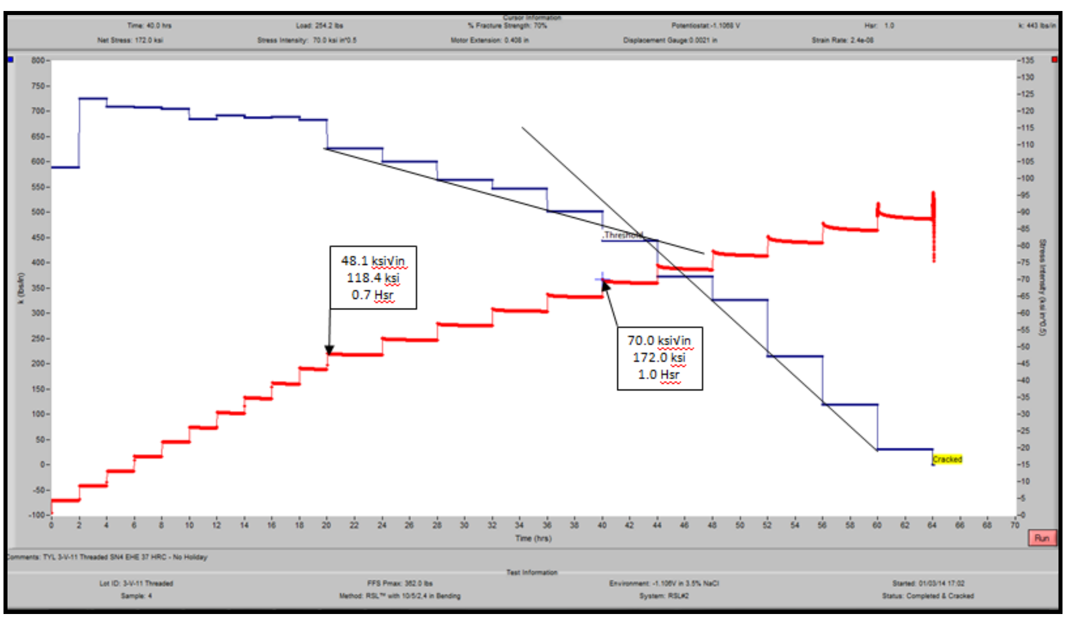

Figure 2.5-1: RSL Software Test Results for Specimen 3-V-11 Thd 4

During the testing of some of the rods with rolled threads it became apparent that the failure mechanism during the RSL test was more complex than the failure mechanism for the cut threads. For rolled threads, the case or hardener outside layer is typically greater than 20 mils thick at a hardness that may be 40 HRC to 45 HRC.

It appears that cracking extends through the rolled microstructure in steps, arresting as it reaches lower hardness material and then extending parallel to the thread root forming a crack blunting mechanism. At the next load step the crack would extend a short distance and then arrest again. **Figure 2.5-2** shows the appearance of a crack progressing through the lamellar microstructure at the thread root of a rolled thread. Photo a) of **Figure 2.5-2** shows the thread root splintering and crack lifting away, photo b) shows the thread root magnified 50X showing splintering and lifting of the crack, photo c) shows the thread root magnified 500X showing the crack extending through the steel in steps forming a structure that looks like a brick wall, and photo d) shows cracks propagating through the rolled structure magnified 800X. The rolled grain structure causes small cracks to arrest and extend parallel to the direction of the rolled microstructure creating cracks similar to a “Smiley Face — ☺” that have a crack blunting effect. Cracking will continue only upon increasing load during the following load step. Eventually cracking will extend through the rolled microstructure sufficiently to initiate cracking in the more equiaxed microstructure (grains of equal length) of the bulk of the specimen, showing as a continuous load drop in the test curve.

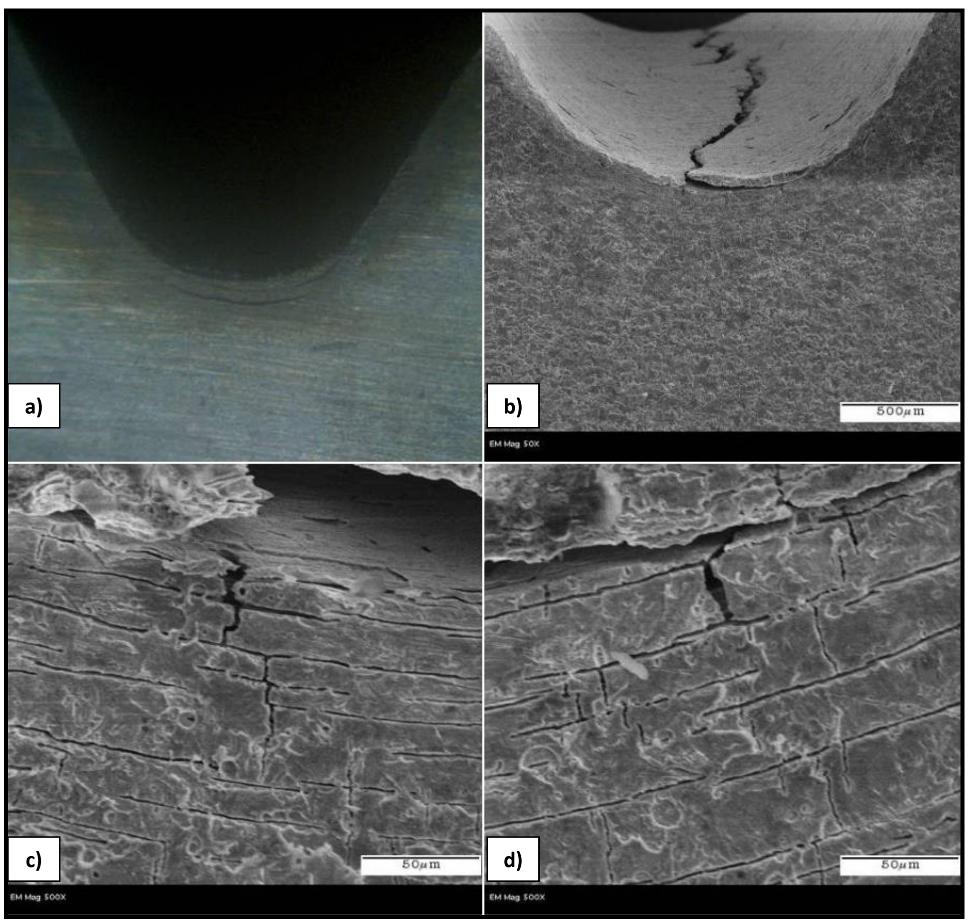

Figure 2.5-2: Cracking of a Rolled Thread: a) Side Profile of Thread Root, b) Thread Root Magnified 50X, c) Thread Root Magnified 500X , d) Crack Propagation Magnified 500X

Figure 2.5-3 shows a typical RSL curve for a specimen with rolled threads showing minor load drops consistent with small crack extensions. This specimen initiated cracking at a stress intensity factor around 80 ksi√in. Two load drops of about 1-pound can be seen as delineated by the arrows. Compliance analysis of the RSL load frame and threaded specimen found that a 1-pound load drop corresponded to a crack extension of approximately 0.001 inch.

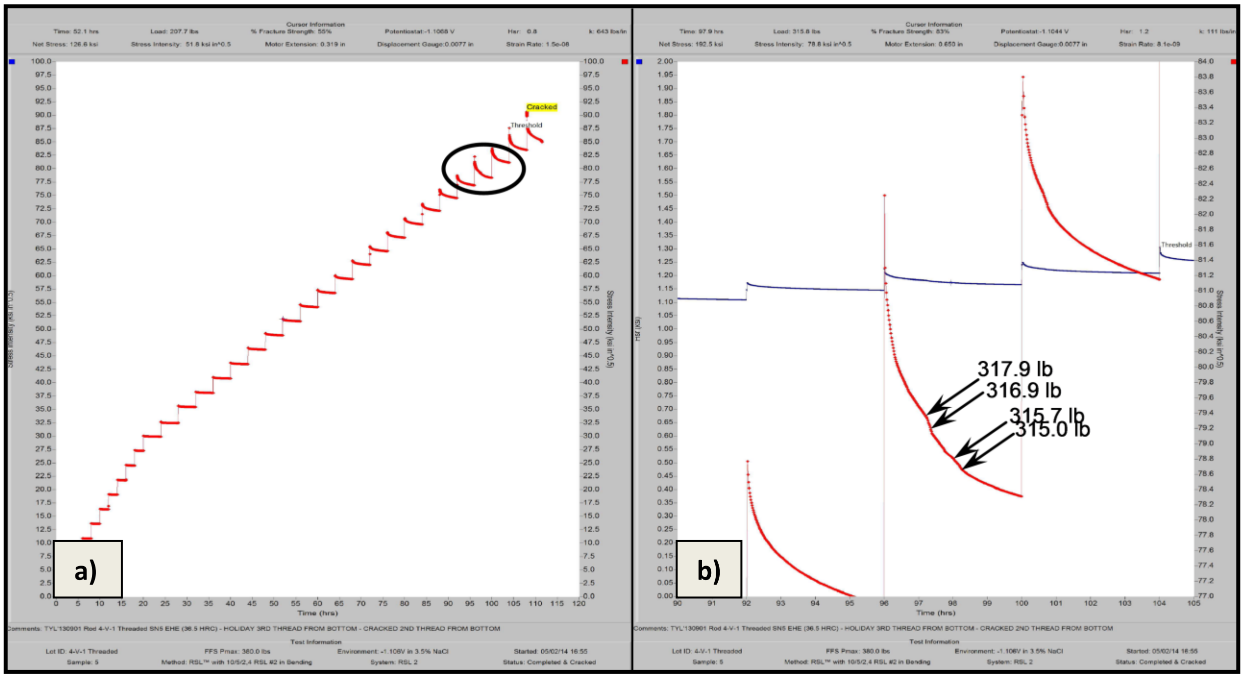

Figure 2.5-3: a) RSL curve for Rod 4-V-1, SN Thd 5, b) Magnified Load Drops

Specimens displaying these small load drops showed no other evidence of cracking until cracking initiated that was detected by a visual load drop. Not all specimens with rolled threads displayed this phenomena. The rods that did were identified with rods that had an M-shaped hardness profile (hardness profile across the cross section where the hardness decreased near the rod outside diameter) and had significantly improved threshold Fu. Rods that did not have an M-shaped hardness profile did not display this cracking/arrest load profile, but still had a threshold Fu that was slightly superior to rods with cut threads.

3 Test V Results

The stress intensity factor threshold test results for the eighteen bolt samples and additionally six remnant samples were machined from remnant rod samples in Test IV (introduced in Specimen Machining, Section 2.3.1) are listed in **Table 3.1-1** through **Table 3.5-1**. The significance of the tabulated results is discussed in Section 4.1 through Section 4.4.

The grey cells in the tables represent specimens with machining defects and 2-inch diameter rods that could not machine an OD fpc specimen.

The maximum stress intensity values, Kmax, calculated from the maximum load achieved in the Fast Fracture Strength test, FFS, for the fpc and Threaded specimens from Test V are listed in **Table 3.1-1**. Kmax is a measure of the maximum stress intensity that can be measured by the specimen.

Table 2.5-1: Results of Fast Fracture Test Showing Kmax

LRA-Fast Fracture Strength Kmax												
ID	Structural Component	Dia.	Rod ID	Comment	Fatigue Pre-cracked (fpc)						Threaded	
					Center		MR		OD		Thd	
					HRC	Kmax	HRC	Kmax	HRC	Kmax	HRC	Kmax
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-1	2010 Material Rolled Threads	33.5	86.1	36.0	85.4			36.0	96.6
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-2	2010 Material Rolled Threads	33.0	83.2	35.5	84.3			36.0	98.1
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-A	2008 Material Top of Rod (Live End)	31.5	74.1	35.5	78.9	37.0	84.9	36.5	98.5
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-D	2008 Material Near Fracture (Dead End)			32.0	78.0	36.0	84.3	36.0	95.1
3	Shear Key Rods - Top (S1/S2)	3"	3-V-9	2010 Material Machined Threads	30.5	80.9	32.5	81.6	36.0	86.4	35.5	99.9
3	Shear Key Rods - Top (S1/S2)	3"	3-V-10	2010 Material Machined Threads	31.5	77.2	31.5	79.4	36.0	85.3	36.0	98.9
3	Shear Key Rods - Top (S1/S2)	3"	3-V-11	2010 Material Machined Threads	28.0	72.2	33.0	80.9	35.0	86.2	35.5	99.8
3	Shear Key Rods - Top (S1/S2)	3"	3-V-12	2010 Material Machined Threads	31.0	77.1	34.0	79.2	36.0	85.3	36.0	99.4
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-b2E-4	2006 Material Machined Threads	30.0	79.5	37.0	86.2	37.5	90.7	36.5	97.5
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-E109	2006 Material Machined Threads	31.5	82.1	37.0	86.2	38.0	92.1	38.0	89.7
18	2013 E2 Replacement Anchor Rods Non-Galvanized	3"	18-V-1	2013 Material Machined Threads	33.5	84.9	35.5	88.8	35.5	91.1	35.5	100.0
18	2013 E2 Replacement Anchor Rods Galvanized	3"	18-V-2	2013 Material Machined Threads	33.0	87.0	35.0	88.5	35.0	91.4	35.5	96.8
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E012	2010 Material Machined Threads	28.5	77.6	32.5	78.6	38.0	87.0	38.0	107.2
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E027	2010 Material Rolled Threads	29.0	76.1	32.5	79.5	36.0	87.0	36.5	101.9
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E093	2010 Material Machined Threads	29.0	75.9	34.0	79.2	37.5	88.6	38.0	106.7
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E096	2010 Material Rolled Threads	28.5	73.5	30.0	80.2	35.5	84.0	35.0	95.3
8	Tower Saddle Tie Rods - Top	4"	8-V-1	2010 Material Rolled Threads	31.5	77.1	34.5	81.5	32.5	86.8	31.0	88.7
13	Tower Anchorage Anchor Rods 102mm Diameter - Bottom	4"	13-V-CW-4	2010 Material Machined Threads	30.5	76.3	35.0	79.8	37.0	92.8	35.5	96.6

3.1 KIc

With proper instrumentation during the fast fracture testing of fpc specimens, a valid estimate of the stress intensity can be made from crack tip opening displacement, KIctod, measurement. KIctod was measured using the methods described in ASTM E1290-99 where the test is interrupted as soon as the maximum load is reached. The KIctod measured is analogous to fracture toughness, KIc, and is often used to provide an estimate for KIc when there is not enough material for a valid KIc measurement. KIctod values are listed on **Table 3.2-1.**

The fracture toughness of the 2010 rods is clustered around 146 ksi√in. The fracture toughness of the 2008 rods is significantly lower at about 123 ksi√in.

It was found that the dynamic tear modulus displays a strong correlation with hardness and the environmental stress intensity factor. This correlation can allow KIscc and $KI_{\rho\text{-EHE}}$ to be estimated from a simple T_d measurement. Thus, an inexpensive T_d test of small samples from a rod could provide an inexpensive quality control test for threaded rods allowing the rapid development of KIscc and $KI_{\rho\text{-EHE}}$ estimates.

Table 3.1-1: Results of Fast Fracture Test Showing KIctod

LRA-Fast Fracture Strength KIctod ≈ KIc													
ID	Structural Component	Dia.	Rod ID	Comment	Fatigue Pre-cracked (fpc)								
					Center			MR			OD		
					HRC	Td	KIctod	HRC	Td	KIctod	HRC	Td	KIctod
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-1	2010 Material Rolled Threads	33.5	11.3	158.9	36.0	8.1	145.7			
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-2	2010 Material Rolled Threads	33.0	12.1	152.0	35.5	9.7	149.3			
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-A	2008 Material Top of Rod (Live End)	31.5	1.9	141.5	35.5	0.6	122.2	37.0	0.9	132.7
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-D	2008 Material Near Fracture (Dead End)				32.0	1.0	121.9	36.0	1.7	121.0
3	Shear Key Rods - Top (S1/S2)	3"	3-V-9	2010 Material Machined Threads	30.5	14.1	140.4	32.5	12.8	144.6	36.0	7.3	123.7
3	Shear Key Rods - Top (S1/S2)	3"	3-V-10	2010 Material Machined Threads	31.5	12.5	159.1	31.5	13.4	138.8	36.0	7.4	147.2
3	Shear Key Rods - Top (S1/S2)	3"	3-V-11	2010 Material Machined Threads	28.0		148.4	33.0	12.3	147.8	35.0	8.5	132.7
3	Shear Key Rods - Top (S1/S2)	3"	3-V-12	2010 Material Machined Threads	31.0	12.8	138.8	34.0	11.3	139.0	36.0	13.9	143.1
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-b2E-4	2006 Material Machined Threads	30.0	21.9	141.6	37.0	8.2	143.4	37.5	7.0	152.3
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-E109	2006 Material Machined Threads	31.5	13.7	147.4	37.0	8.5	152.9	38.0	6.3	157.5
18	2013 E2 Replacement Anchor Rods Non-Galvanized	3"	18-V-1	2013 Material Machined Threads	33.5	14.8	143.5	35.5	12.5	149.0	35.5	10.2	145.0
18	2013 E2 Replacement Anchor Rods Galvanized	3"	18-V-2	2013 Material Machined Threads	33.0	15.9	146.8	35.0	12.6	149.0	35.0	11.2	149.6
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E012	2010 Material Machined Threads	28.5	10.9	152.0	32.5	9.8	161.4	38.0	4.6	138.3
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E027	2010 Material Rolled Threads	29.0	18.0	142.3	32.5	13.9	149.2	36.0	6.9	143.9
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E093	2010 Material Machined Threads	29.0	10.3	149.7	34.0	8.1	143.7	37.5	5.8	139.0
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E096	2010 Material Rolled Threads	28.5	22.0	143.9	30.0	17.7	137.6	35.5	9.0	144.2
8	Tower Saddle Tie Rods - Top	4"	8-V-1	2010 Material Rolled Threads	31.5	4.6	128.9	34.5	2.2	145.1	32.5	2.0	154.9
13	Tower Anchorage Anchor Rods 102mm Diameter - Bottom	4"	13-V-CW-4	2010 Material Machined Threads	30.5	7.0	146.3	35.0	3.4	129.5	37.0	5.5	132.5

3.2 IHE Threshold

The IHE threshold stress-intensity values for both threaded and fpc specimens are listed in **Table 3.3-1**. Based on this limited data, neither the 2008 nor the 2010 specimens tested exhibit IHE. The possibility exists that process hydrogen could have diffused out of the uncoated surfaces of samples since the rod samples were removed from the bridge and in storage at room temperature for up to six months before testing was considered. Extra precautions were taken with the freshly galvanized 2013 rods to minimize any escape of hydrogen by storing specimens in a freezer and the results of these specimens further supported the original conclusions.

Table 3.2-1: Results of IHE RSL Tests Showing $K_{I\text{-}IHE}$ and $K_{I\rho\text{-}IHE}$

LRA-IHE Testing in Air										
ID	Structural Component	Dia.	Rod ID	Comment	Fatigue Pre-cracked (fpc)				Threaded	
					MR		OD		Thd	
					HRC	$K_{I\text{-}IHE}$	HRC	$K_{I\text{-}IHE}$	HRC	$K_{I\rho\text{-}IHE}$
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-1	2010 Material Rolled Threads	35.0	92.7			36.0	94.4
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-2	2010 Material Rolled Threads	35.5	95.9			35.5	97.4
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-A	2008 Material Top of Rod (Live End)	32.0	80.9	36.5	77.7	36.0	96.9
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-D	2008 Material Near Fracture (Dead End)			36.0	77.0	36.0	92.9
3	Shear Key Rods - Top (S1/S2)	3"	3-V-9	2010 Material Machined Threads	33.5	95.8	36.0	86.2	35.0	100.8
3	Shear Key Rods - Top (S1/S2)	3"	3-V-10	2010 Material Machined Threads	33.0	92.1	35.5	85.2	36.0	99.0
3	Shear Key Rods - Top (S1/S2)	3"	3-V-11	2010 Material Machined Threads	32.5	86.4	36.0	84.4	36.0	97.3
3	Shear Key Rods - Top (S1/S2)	3"	3-V-12	2010 Material Machined Threads	33.0	92.1	35.5	88.7	35.0	95.8
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-b2E-4	2006 Material Machined Threads	35.5	89.9	37.0	86.8	37.0	96.5
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-E109	2006 Material Machined Threads	35.5	86.6	38.0	89.8		
18	2013 E2 Replacement Anchor Rods Non-Galvanized	3"	18-V-1	2013 Material Machined Threads					35.5	99.3
18	2013 E2 Replacement Anchor Rods Galvanized	3"	18-V-2	2013 Material Machined Threads					35.5	97.4

3.3 EHE Threshold

The EHE threshold stress-intensity values for both fpc and Thd specimens tested at -1.106 Vsce are given in **Table 3.4-1**. For the fpc specimens the results are listed as KIscc. However, the Thd specimens have a thread acting as a notch rather than a fatigue pre-crack so the measured stress intensity factor is an "effective" stress intensity factor that is not a material property but includes the effect of the notch root radius. Since the symbol, ρ, is typically used to indicate a root radius in literature, KIρ-EHE was used to differentiate the stress intensity factor measured using threaded specimens from KIscc for fpc specimens. The highest threaded KIρ-EHE data achieved were obtained from the 2013 rods followed by the 2010 rods, and lastly the 2008 rods. The KIρ-EHE data for rod samples with rolled threads are higher than the KIρ data for the cut-thread rod samples, excluding the 2013 rods. Although the 2013 rod has cut threads, the non-galvanized threaded specimens achieved the highest threshold (higher than rolled threads). The fpc specimens indicate the 2013 material is the most environmental corrosion-resistant of the rods obtained for Test V.

Table 3.3-1: Results of EHE RSL Tests Showing KIscc and KIρ-EHE

LRA-EHE Testing in 3.5% NaCl Water at -1.106 Vsce											
ID	Structural Component	Dia.	Rod ID	Comment	Fatigue Pre-cracked (fpc)				Threaded		
					MR		OD		Thd		
					HRC	KIscc	HRC	KIscc	HRC	KIρ-EHE	Fu-EHE
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-1	2010 Material Rolled Threads	35.5	23.3			36.5	85.0	1.00
4	Pier E2 Bearing Rods - Top Housing (B1,B2,B3,B4)	2"	4-V-2	2010 Material Rolled Threads	36.0	27.5			36.0	84.6	0.99
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-A	2008 Material Top of Rod (Live End)	35.0	24.1	37.5	19.2	36.5	55.0	0.62
1	Shear Key Anchor Rods - Bottom (S1/S2)	3"	1-V-S2-A2-D	2008 Material Near Fracture (Dead End)	34.0	29.1	35.0	29.1	36.0	51.9	0.59
3	Shear Key Rods - Top (S1/S2)	3"	3-V-9	2010 Material Machined Threads	33.5	35.1	35.5	28.2	35.0	62.3	0.70
3	Shear Key Rods - Top (S1/S2)	3"	3-V-10	2010 Material Machined Threads	33.0	35.0	36.0	26.5	35.0	66.3	0.75
3	Shear Key Rods - Top (S1/S2)	3"	3-V-11	2010 Material Machined Threads	33.0	36.9	34.5	32.1	36.0	69.9	0.79
3	Shear Key Rods - Top (S1/S2)	3"	3-V-12	2010 Material Machined Threads	33.0	33.6	35.5	23.1	35.5	66.3	0.75
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-b2E-4	2006 Material Machined Threads	34.0	39.8	37.0	22.6	37.5	63.6	0.72
12	Tower Anchorage Anchor Rods 76mm Diameter - Bottom	3"	12-V-E109	2006 Material Machined Threads	37.5	24.3	38.0	19.2	37.5	61.0	0.69
18	2013 E2 Replacement Anchor Rods Non-Galvanized	3"	18-V-1	2013 Material Machined Threads	35.5	43.2	35.5	42.9	35.5	91.5	1.03
18	2013 E2 Replacement Anchor Rods Galvanized	3"	18-V-2	2013 Material Machined Threads	35.0	44.4	35.5	42.7	35.5	86.7	0.98
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E012	2010 Material Machined Threads	34.0	28.4	38.0	20.5	37.5	52.1	0.58
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E027	2010 Material Rolled Threads	31.0	34.4	36.5	24.0	36.5	65.1	0.72
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E093	2010 Material Machined Threads	32.5	41.4	37.5	22.2	38.0	54.5	0.60
7	PWS Strand Anchor Rods (Main Cable)	3.5"	7-V-E096	2010 Material Rolled Threads	33.5	31.5	35.0	26.5	35.0	87.5	0.97
8	Tower Saddle Tie Rods - Top	4"	8-V-1	2010 Material Rolled Threads	33.5	30.7	32.5	33.9	34.0	78.0	0.85
13	Tower Anchorage Anchor Rods 102mm Diameter - Bottom	4"	13-V-CW-4	2010 Material Machined Threads	36.5	24.1	36.5	21.4	37.0	58.0	0.63

3.4 Remnant Thresholds

Remnants of some of the rods that were tested in Test IV were provided for testing at LRA. The remnants from Group ID #2 were cut from the dead end stick-out portion of the rod both as installed on the bridge and as tested in Test IV. The remnants from Group ID#7 were cut from the dead end stick out as tested in Test IV. Remnant 7-V-TR-9-E was from a rod made with rolled threads. Remnant 7-V-R-10-G was from a rod made with machined threads. Results of testing the threaded specimens for these remnants are listed in **Table 3.3-5**.

Table 3.4-1: Results of Remnant FFS and EHE RSL Tests Showing Kmax and KIρ-EHE

Test V Remnant Results								
ID	Remnant Rod ID	Dia.	Structural Component	Threaded FFS		Threaded EHE		
				HRC	Kmax	HRC	KIρ-EHE	Fu-EHE
2	B1-F4	3"	Shear Key and Bearing Anchor Rods - Bottom (S1/S2)	**36.0**	**99.5**	**36.5**	**61.5**	**0.69**
2	B2-F5	3"	Shear Key and Bearing Anchor Rods - Bottom (S1/S2)	**36.0**	**97.8**	**35.5**	**63.5**	**0.72**
2	S3-D2	3"	Shear Key and Bearing Anchor Rods - Bottom (S1/S2)	**35.5**	**98.7**	**36.0**	**65.0**	**0.73**
2	S4-E2	3"	Shear Key and Bearing Anchor Rods - Bottom (S1/S2)	**35.0**	**91.6**	**35.5**	**61.8**	**0.70**
7	7-V-TR-9-E	3.5"	PWS Strand Anchor Rods (Main Cable)	**37.0**	**101.9**	**37.5**	**68.0**	**0.75**
7	7-V-TR-10-G	3.5"	PWS Strand Anchor Rods (Main Cable)	**35.5**	**100.0**	**36.0**	**57.0**	**0.63**

4 Test V Discussion

The fracture mechanism for rolled threads was found and the difference between the $KI\rho$ threshold between machined and rolled threads was explained. As a result of discovering the EHE fracture mechanism for the cut threads a correlation between $KI\rho_{\text{-IHE}}$ and the material's T_d was proposed and found to exist.

4.1 Kmax

The fast fracture strength values for the samples (including the remnant specimens) are plotted in **Figure 4.1-1** as a function of hardness. Because the specimens are well below the minimum size for fracture toughness testing the values recorded for Kmax do not relate to the material's fracture toughness. However, the value for Kmax does show the maximum measured value possible for the specimen and can be used to compare to the RSL test in air to determine if there is any effect of residual hydrogen as measured by $KI_{\text{-IHE}}$. Some initial conclusions that can be drawn from this data are: (1) Kmax increases with hardness, increasing in groups from Center (C), Mid-Radius (MR), Outer Diameter (OD), to Threaded, (2) K_{max} for the threaded specimens is higher than the Kmax for fpc specimens, (3) All rolled thread specimens reached test limit without cracking, and (4) The 2008-fpc specimens are at the minimum values of the 2010-fpc specimens and the 2008 threaded-cut specimens are within range of 2010 threaded-cut specimens.

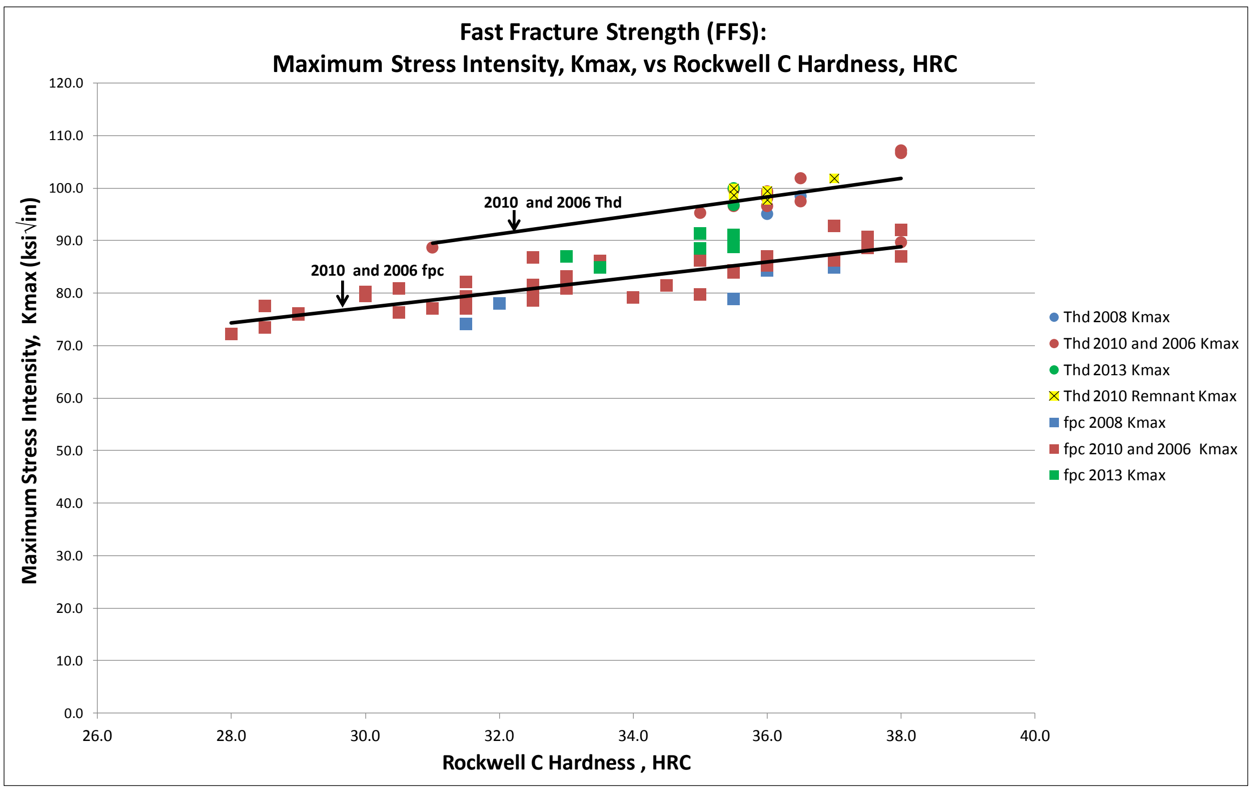

Figure 4.1-1: Maximum Achieved Stress Intensity Factors During Fast Fracture Testing

4.2 KIc

Fracture toughness of steel is measured by determining the critical stress intensity factor at which a sharp crack initiates. KIctod is an estimate for the fracture toughness of the material. LRA's experience is that the estimate from KIctod closely matches linear elastic results and certainly can be used for comparison between rods. The fpc specimen KIctod values calculated from the fast fracture test data listed in **Table 3.1-1** are plotted in **Figure 4.2-1**. The fracture toughness of the 2010 rods is clustered around 146 ksi√in. The fracture toughness of the 2008 rods is about 123 ksi√in. In general, for high-strength, low-alloy 4140 steel, the fracture toughness should decrease with increasing hardness. For microstructures other than martensite the fracture toughness should be less than the fracture toughness of martensite at the same hardness. The lower hardness MR specimens were mostly from the low hardenability of 4140 steel as compared to 4340 steel MR specimens. Additionally, the range of hardness displayed by the specimens from the OD of the rods is small so the fracture toughness should not change by much. The 4140 rods delivered in 2008 have fracture toughness values that are below the fracture toughness correlation for the 2010 material. The rods delivered in 2013 made from 4340 steel have a facture toughness that is approximately the same as the 2010 rods.

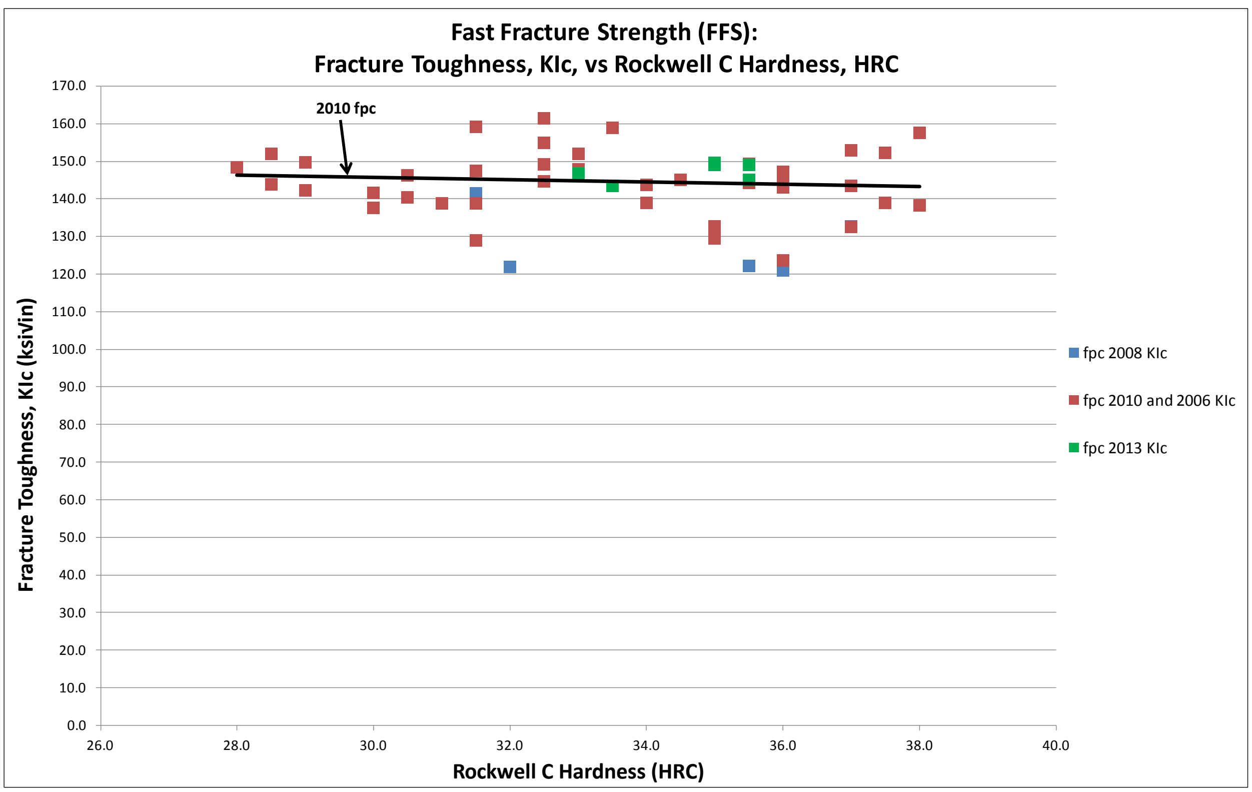

Figure 4.2-1: KIctod Estimates for Fracture Toughness

4.3 IHE Thresholds

The RSL IHE tests for the fpc specimens were tested on a fixture that resulted with higher KI-IHE loads than Kmax. However, this issue did not exist for the threaded specimens. The KI-IHE results are plotted in **Figure 4.3-1** along with the trend lines for the Kmax values from the fast fracture tests shown in **Figure 4.1-1**. For the threaded specimens, most of the KI-IHE results are at or slightly below the Kmax line. Most of the fpc specimens are at or slightly above the Kmax line – most likely due to the distortion in the test fixture at the higher loads. SEM examination of the fpc specimens, including the 2008 material, showed no evidence of intergranular cracking, IG, indicating that no hydrogen cracking had occurred. IHE testing was discontinued when it became apparent that no residual hydrogen was present in any of the rods tested.

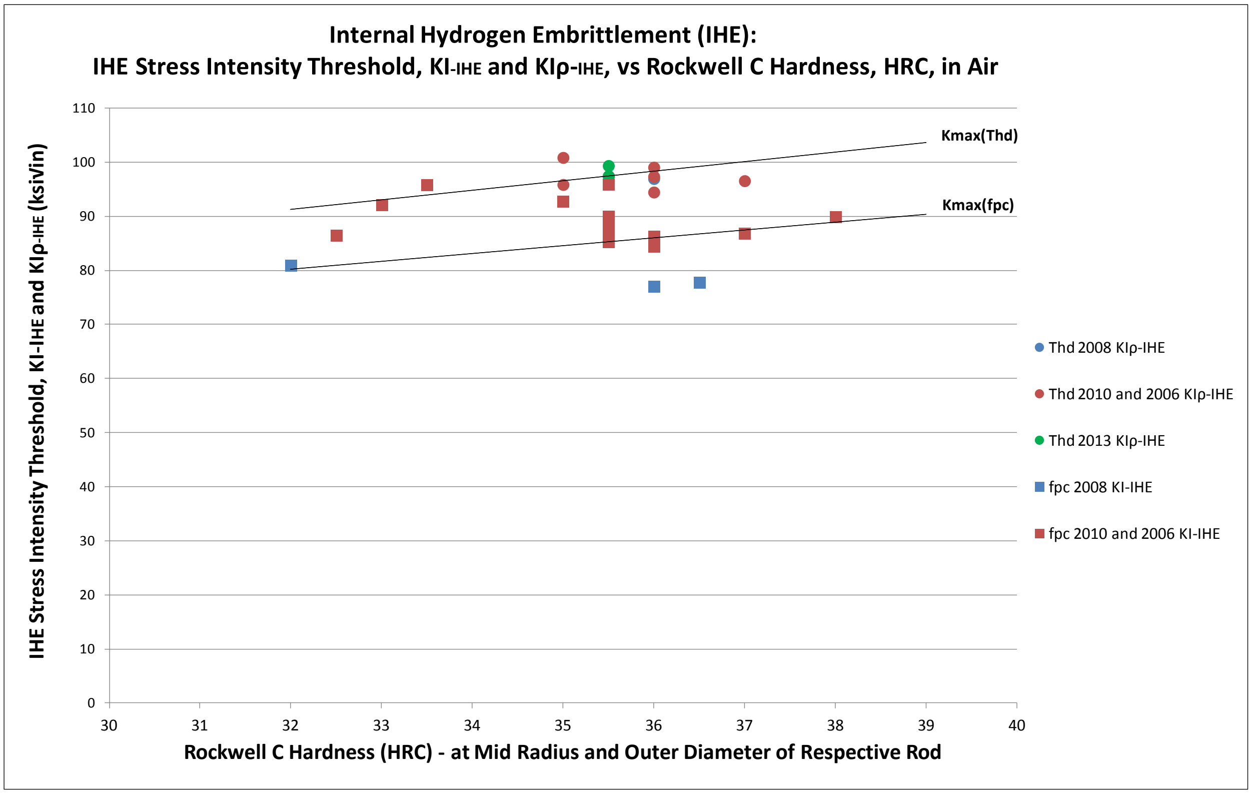

Figure 4.3-1: Results of RSL IHE Testing for Both fpc and Thd Specimens

4.4 EHE Thresholds

The results of RSL testing of threaded specimens (including the threaded specimens from the remnant samples) in 3.5% NaCl in water with an applied potential of -1.106 Vsce is shown in

Figure 4.4-1. The KIρ-EHE measured for the threaded specimens is significantly greater than the fpc specimens showing the effect of the larger root radius. The trend line for the fatigue pre-cracked data is drawn in black and shows the effect of hardness on KIscc. Lines parallel to the fpc trend line are drawn through the data for the threaded specimens to provide an estimate for the effect of hardness on the threaded data. Typically, the rods with rolled threads display KIρ-EHE that are significantly greater than the rods with cut threads. The group of rods with rolled threads that have the higher values for KIρ-EHE and lie above the trend line had an "M" shaped profile from the hardness testing done in Test II and Test III.

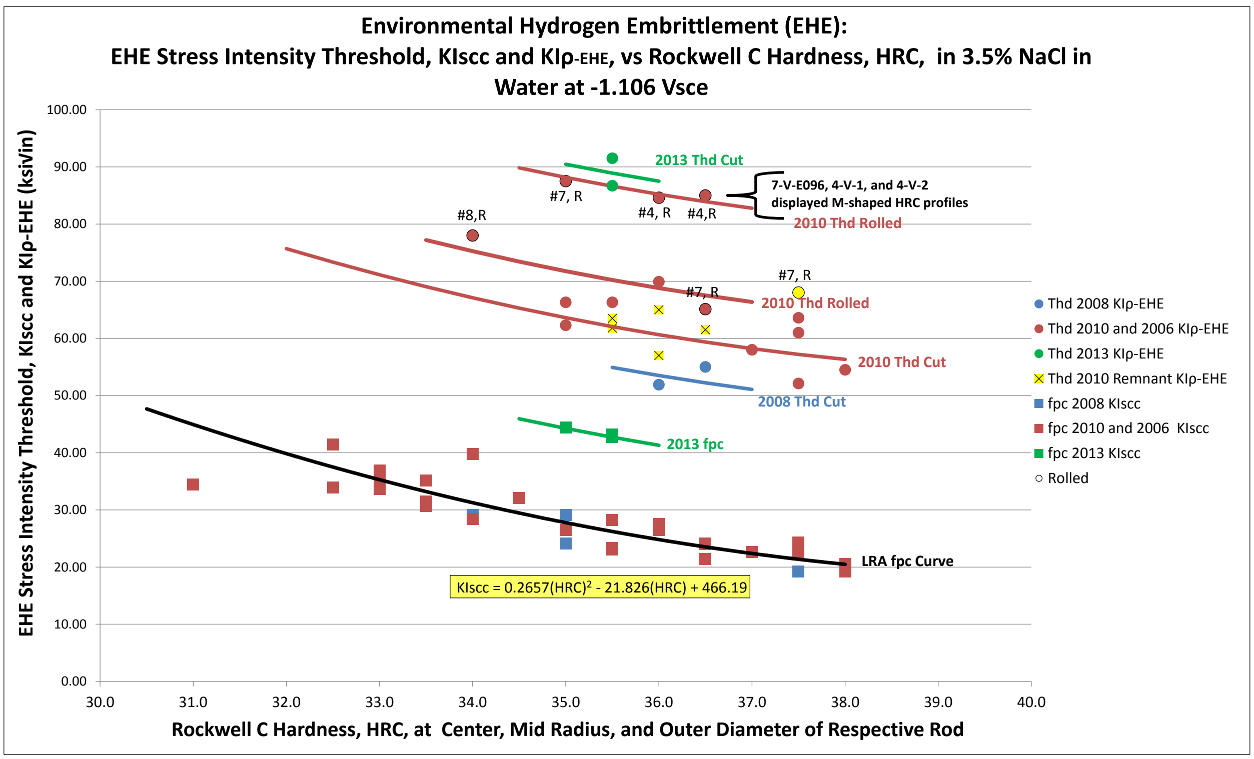

Figure 4.4-1: Results of RSL EHE Testing for Both fpc and Thd Specimens

In Summary:

- The KIρ-EHE and KIscc were determined for each rod sample provided
- The KIscc data are dependent on hardness of the specimen.
- The KIρ-EHE data for the 2010 rods are higher than KIρ-EHE data for the 2008 rods due to a combination of cleanliness and toughness of the steel and the manufacturing quality of the threads.
- The KIρ-EHE data for rod samples with rolled threads are typically higher than the KIρ-EHE data for the cut-thread rod samples.

- The group of rods with rolled threads all lie above the trend line for cut threads. The rolled rods with an "M" shaped hardness profile displayed the highest environmental thresholds for SAE 4140 steel.

4.5 Special Projects

4.5.1 Objective

Since many specimens can be obtained throughout a cross section of a 3-inch-long threaded rod segment, the effects of varying manufacturing and environmental variables, such as potential, on the EHE threshold of the threaded rods can be evaluated. Several ad hoc projects were requested and carried out to evaluate specific concerns raised during testing of the A354BD threaded rods.

1. The Open Circuit Potential was measured for 20 rods being tested as part of Test V,
2. The effect of specimen width, or Plane Strain on the Performance of Threaded Specimens was evaluated,
3. The effect of cracks in the galvanizing as possible sharp crack initiation points was evaluated,
4. SEM Fracture Morphology Comparison in fpc Specimens,
5. Crack Initiation Analysis in 2008 Rod Dead-End,
6. Crack Initiation Analysis on Threaded SEN(B) Specimens.
7. Fractographic analysis was conducted by using a Scanning Electron Microscope (SEM)
   a. On tested specimens whose fracture surfaces were produced under known testing conditions.
   b. This was compared to the results of the post fracture analysis (PFA) of the threaded rods.

4.5.2 Open Circuit Potential

To characterize the galvanic corrosion behavior of the coating relative to the specific grade of steel, the Freely Corroding Corrosion Potential, E_{CORR}, or Open Circuit Potential, OCP was measured in a 3.5 % NaCl solution. The OCP measurements were run in accordance with ASTM G3.

Summary of Protocol:

1. Check the electrode's potential by comparing with a calibration electrode. Both electrodes are placed in 3.5% NaCl solution in beaker.
2. Record the potential. Connect the saturated calomel electrode (SCE) that is to be used, to the Digital Acquisition Unit (DAQ) and remove the calibration electrode from the beaker.
3. Place the specimen to be tested in Alconox and acetone for five minutes each using the ultra-sonic machine.

4. Coat the sample with stop-off lacquer making sure there are no exposed areas of the sample that are to be exposed to the NaCl solution except those that are to be tested.

5. Wait approximately 30 minutes for the lacquer to dry.

6. Attach the clamps to the specimen and adjust the specimen's position in the beaker so that the surface of the solution is in contact with the lacquer.

7. Before beginning the test, measure and record the solution temperature (using a thermometer) as well as its pH level (using pH tape).

8. Open the Tracer DAQ software and begin the test

9. After the test is finished, record the temperature of the solution and the pH level.

10. Record the SCE electrode's potential relative to the calibration electrode by following step number one.

11. Remove the specimen and rinse with deionized water followed by acetone. Once the sample is thoroughly dried, spray with Krylon. Let the sample dry for approximately one hour. Place sample in a sealed bag and store in corresponding job box.

12. Take out the SCE electrode from the solution and rinse with deionized water. Place electrode in KCl solution and store.

Figure 4.5-1 shows the test specimen with the specimen under test immersed in 3.5% NaCl solution along with a SCE. **Figure 4.5-2** shows the test set-up along with the control computer for data acquisition.

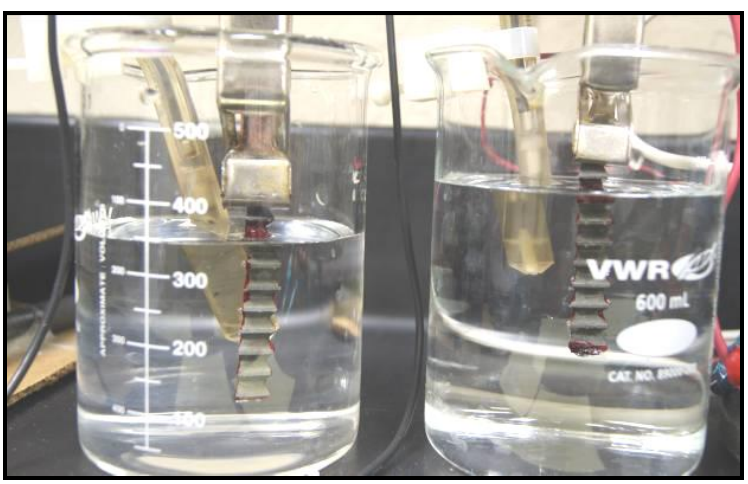

Figure 4.5-1: OCP Measurement in 3.5% NaCl in Beakers

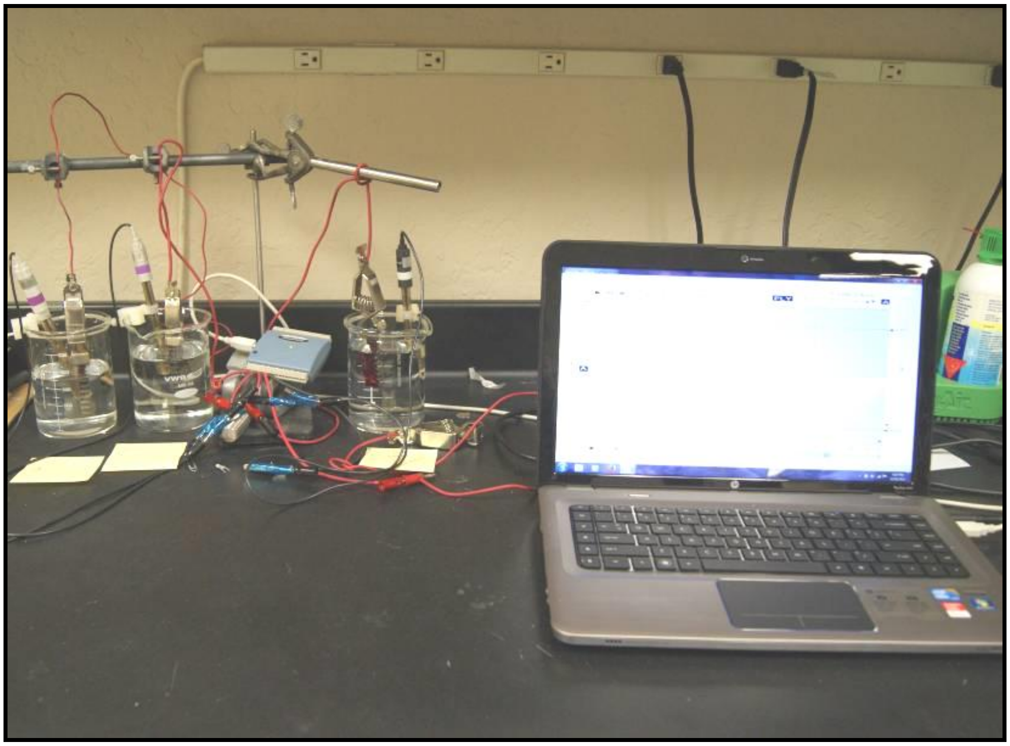

Figure 4.5-2: OCP Measurement Set-up

Results:
For each rod tested at LRA the OCP was measured. For the test, OCP was monitored for 48 hours and the variation in OCP with time was monitored and recorded every 30 seconds. The OCP for three rods was measured for an extended time to monitor how the OCP varied with time and determine if the OCP ever leveled off.

Table 4.5-1 shows results for testing several rods over 48 hours with the curves shown in **Figure 4.5-3**. The measured value for OCP varies significantly over the 48 hour time period and it is not clear if it levels off. The greatest variation occurs in the first two hours.

Table 4.5-1: Typical Values for OCP Over 48 Hours

Sample	Vsce					
	After 2	After 10	After 20	After 30	After 40	After 48
1-V-S2-A2-A	-0.9541	-0.9238	-0.9222	-0.9068	-0.8986	-0.8898
3-V-9	-1.0069	-1.0205	-1.0200	-1.0151	-1.0114	-1.0128
4-V-1	-0.9061	-0.9092	-0.8922	-0.8841	-0.8833	-0.8701

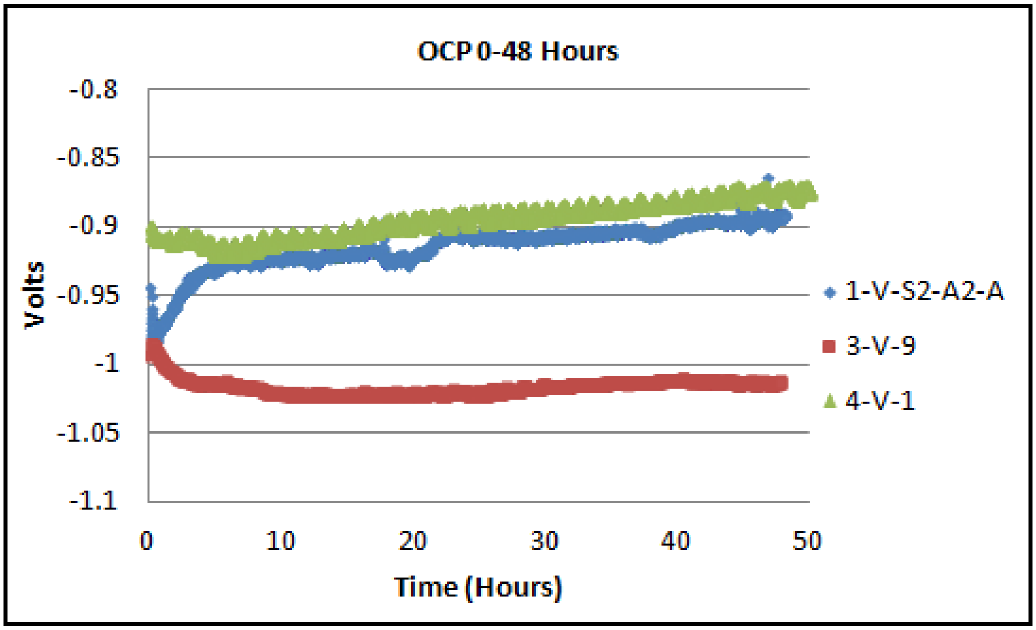

Figure 4.5-3: OCP vs Time for Three Typical Rods

In order to see what the long term variation in OCP was, one of the rods, Remnant B1-F4, was tested for an extended time of over 120 hours. **Figure 4.5-4** shows the resulting curve. Within the first few hours the OCP dropped from -0.950 Vsce to -1.000 Vsce. Over the next 120 hours the OCP gradually increased, approaching -0.900 Vsce at 120 hours. Typically the measured value for OCP would drop rapidly to a minimum within an hour. The measured value for OCP would increase slightly over the next 20 hours and then increase continuously after that.

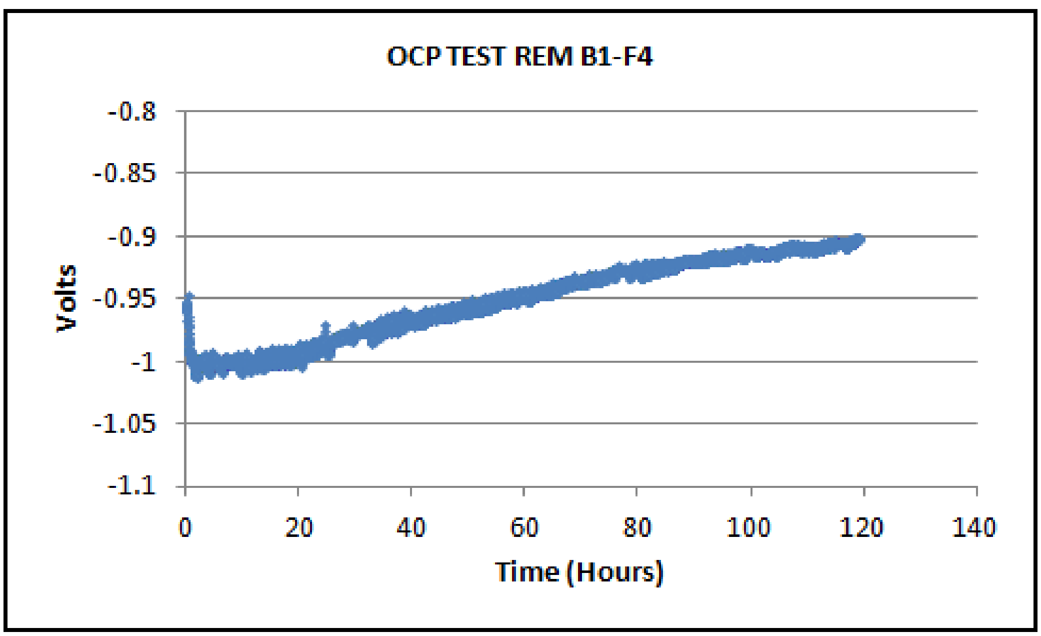

Figure 4.5-4: OCP Results for Remnant B1-F4

The OCP was measured for all the rods tested at LRA over a period of 48 hours. **Table 4.5-2** lists the results of the OCP testing, listing the initial voltage, the minimum voltage and the final voltage.

Table 4.5-2: Test V OCP Results

Sample Number	Initial Voltage	Minimum Voltage	Final Voltage
1-V-S2-A2-A	-0.944	-0.986	-0.893
1-V-S2-A2-D	-1.115	-1.126	-1.073
3-V-9	-0.992	-1.023	-1.013
3-V-10	-1.047	-1.072	-1.052
3-V-11	-1.052	-1.052	-0.965
3-V-12	-1.020	-1.022	-1.003
4-V-1	-0.899	-0.921	-0.867
4-V-2	-0.850	-0.875	-0.827
7-V-E012	-0.985	-1.008	-0.940
7-V-E027	-0.915	-0.946	-0.919
7-V-E093	-1.110	-1.128	-1.071
7-V-E096	-0.962	-1.002	-0.966
8-V-1	-0.920	-0.922	-0.896
12-V-B2-E4	-0.875	-0.876	-0.830
12-V-E109	-0.953	-0.971	-0.887
13-V-CW-4	-0.880	-0.921	-0.893
18-V-1	-0.445	-0.690	-0.685
18-V-2	-1.001	-1.069	-1.021
Rem B1-F4	-0.960	-1.013	-0.902
Rem B2-F5	-0.930	-0.937	-0.886
Rem S3-D2	-0.847	-0.929	-0.817
Rem S4-E2	-1.028	-1.031	-1.009

Environmental testing at LRA was performed at -1.106 Vsce and the difference in applied potential affected the determined KIscc and $KI\rho_{\text{-EHE}}$ threshold. While there are individual differences in the determined OCP value, clearly the OCP for the remnants are significantly different from the potential of -1.106Vsce applied during testing at LRA. Testing at the potential of -1.106 Vsce during Test V resulted in more conservative, lower $KI\rho_{\text{-EHE}}$ values.

4.5.3 Evaluating Plane Strain Performance of Threaded Specimens

Test V used sub-sized specimens for the threaded specimens. Since they did not meet standard fracture mechanics plane strain requirements, a special project was designed to show the relationship of KIρ of the sub-sized specimens to valid plane strain specimens.

Approach:
Two approaches were used to show the relationship of sub-sized Threaded specimen threshold stress intensity factor measurement to valid plane strain values of KIρ.

1. Measuring the environmental threshold of 1.00-inch wide specimens. These specimens were designed having a width (Dimension "B") that met normal plane strain requirements. The 1 inch wide specimen are referred to as 1.0B specimens.
2. Measuring the environmental threshold for specimens of higher hardness that transitioned to normal plane strain requirements.

One inch Specimens:
The specimen had the same dimensions as the standard specimen with the exception of the width. Rather than being 0.40 inches wide the larger specimen was 1.00 inches wide. **Figure 4.5-5** shows a representation of the 1.0B specimen. The specimens were machined from the 3-V-12 rod.

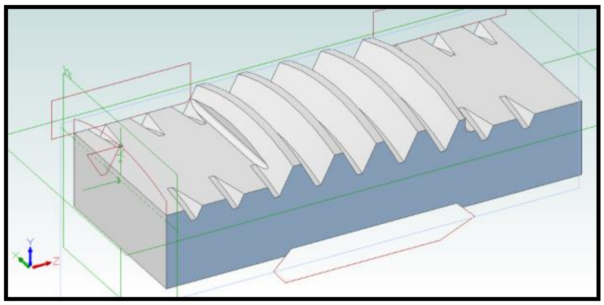

Figure 4.5-5: Specimen Drawing of 1.0B SEN(B)

Figure 4.5-6 shows a picture of the fracture face of a standard 0.4B SEN(B) specimen showing that the EHE crack growth rate stabilized as a flat region near the center for approximately 1/2 of the width, with a shear lip in the remaining area. **Figure 4.5-7** shows the fracture face of a one-inch wide, 1.0B SEN(B) specimen showing the SCC crack to be flat and parallel to the rear face of the specimen – at a contour of relatively constant stress intensity factor – across 90% of the width of the specimen.

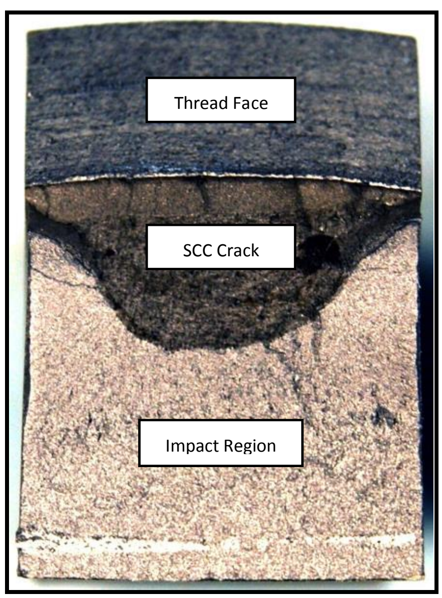

Figure 4.5-6: Typical EHE Fracture Face of 0.4B SEN(B) Specimen

Figure 4.5-7: EHE Fracture Face of 1.0B SEN(B) Specimen

The characteristic of the one-inch wide specimen is that the relationship of the bending stress to the applied stress intensity factor is the same as the standard specimen but the majority of the specimen is in plane strain. See **Table 4.5-3** for the calculated ratio of bending stress to stress intensity factor for both fast fracture specimens from the wide and standard geometries.

Table 4.5-3: Ratio of Applied Stress to Stress Intensity Factor for Wide and Standard Geometry 3-V-12 Threaded Specimens

Specimen	K_{max} (ksi$\sqrt{in}$)	σ_{max} (ksi)	σ_{max}/K_{max}
3-V-12, 1.0B, Thd SN1	95.2	233.8	2.456
3-V-12, 0.4B, Thd SN5	99.4	243.4	2.449

The ratio of bending stress to stress intensity factor is essentially the same for both specimen geometries.

High Hardness Specimens:
When simulating a zinc potential, the concept was to show that at higher hardness, the measured $K_{I\rho\text{-EHE}}$ for these specimens (which were tested under plane strain conditions) would fall along a curve of stress intensity vs hardness, parallel to the Townsend curve and extend into the $K_{I\rho\text{-EHE}}$ data measured in Test V. **(8)**

Specimens were removed from an exemplar threaded rod of the same material (SAE 4140 steel) and size (three inch diameter) as the majority of the rods that were tested at LRA. This rod also had rolled threads. The galvanizing was removed by soaking the specimens in 10% HCl. Then, the specimens were quenched and tempered to varying hardness. Target hardness values were 50 HRC, 45 HRC and 40 HRC.

Summary of Protocol:
Testing was performed using the protocol developed for measuring the value for KIρ for threaded specimens for Test V. For the One Inch specimens, three specimens were tested. One was broken at fast fracture conditions to determine maximum load. The other two were broken under EHE conditions at progressively slower strain rates to find a threshold. Only two EHE tests were required.

The high hardness specimens were also tested under EHE conditions. The hardness for these specimens was sufficiently high that, from previous experience, the strain rate necessary for achieving a threshold was already known.

Results:
Table 4.5-4 lists the results from testing the 1.0B SEN(B) specimens from Rod 3-V-12. Both EHE results are within 5% of the value for KIρ with the lowest value for EHE KIρ being the threshold at 62.1 ksi√in.

Table 4.5-4: Results from Testing 1.0B SEN(B) Specimens from Rod 3-V-12

S/N	Hardness (HRC)	Kmax, KIρ-EHE (ksi√in)
Thd 1, FFS	35.5	95.2
Thd 3, EHE	35.5	63.1
Thd 4, EHE	35.5	62.1

Table 4.5-5 lists comparable results from testing standard size specimens from rod 3-V-12 with the threshold being 66.3 ksi√in. The threshold for the one-inch specimen is lower but within 5% of the threshold found with standard specimens.

Table 4.5-5: Results from Testing Standard Specimens from Rod 3-V-12

S/N	Hardness (HRC)	Kmax, KIρ-EHE (ksi√in)
Thd 5, FFS	36.0	99.4
Thd 2, IHE	35.0	95.8
Thd 3, EHE	35.5	66.3
Thd 6, EHE	36.0	70.0

Table 4.5-6 lists the results from testing the high hardness specimens. The heat treated specimens are seen with notation HT, and the as received specimen is seen with notation AR.

Table 4.5-6: Results from Testing High Hardness Specimens

S/N	Hardness (HRC)	KIρ-EHE (ksi√in)
HT 1000 Thd SN1, EHE	39.0	76.8
HT 800 Thd SN1, EHE	45.5	64.2
AR Thd SN1, EHE	52.0	40.8

Figure 4.5-8 shows the results from the threaded, high hardness, rolled specimens and threaded, rolled specimens, along with the results of all SAE 4140, fatigue pre-cracked specimens. The graphed data is broken into four groups:

1. EHE for the high hardness threaded exemplar rods with rolled threads.
2. EHE for the threaded rods with rolled threads.
3. EHE fatigue pre-cracked specimens from rods made in 2008.
4. EHE fatigue pre-cracked specimens from rods made in 2006 and 2010.

The fpc data was plotted to show how the hardness effected EHE stress intensity thresholds (similar to Townsend's work in 1975) even when threaded specimens were used. **(8)**

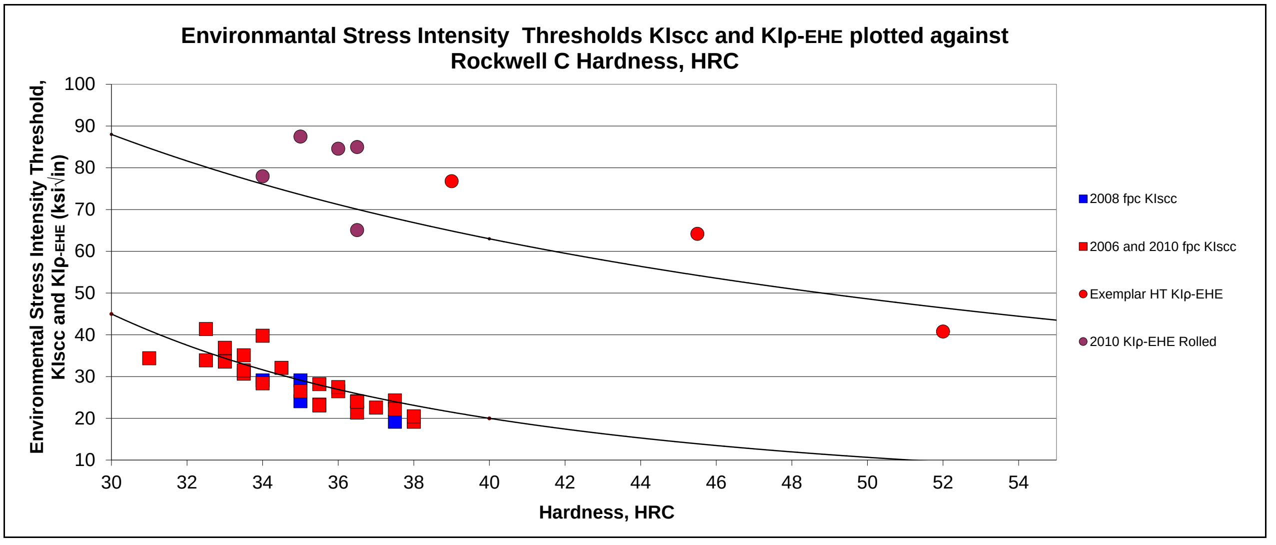

Figure 4.5-8: Effect of Hardness on KIp-EHE and KIscc at -1.106Vsce

This data is for comparison to the high hardness specimens (labeled "Exemplar HT"). Note that the "Exemplar HT" specimens (high hardness specimens) were made from rods that had rolled threads. Austenitizing, quenching and tempering would remove all the deformed microstructure and compressive residual stress from rolling, but the thread profile would still have the benefits of the smooth rounded profile.

Conclusion:
The goal of this project was to verify that the environmental thresholds measured in plain strain conditions matched the environmental thresholds measured in Test V.

For the one Inch wide 3-V-12 threaded specimens, the cracking threshold was measured to be 62.1 ksi√in that can be compared to the environmental threshold of 66.3 ksi√in for the standard geometry 3-V-12 threaded specimens. From this, it can be concluded that the threshold determination method used for 0.4B standard geometry specimens, where stiffness analysis is used is equivalent to measuring the 1.0B plane strain environmental threshold.

For the high-hardness standard geometry specimens, **Figure 4.5-8** illustrates that the high hardness data fall along a line that is parallel to the Townsend Curve. **(8)** Being that the threads of the exemplar rod were rolled, the data for these tests is in line with the data for the 2010 Threaded rods with rolled threads supporting the conclusion that the environmental thresholds measured for the 2010 rods are in agreement with the environmental thresholds measured in plane strain conditions.

4.5.4 Zinc Cracking

The experiment was designed to test the hypothesis that cracking in the galvanizing may act as a stress riser at the root of the thread. If the hypothesis is found to be true, it would mean that after the cracks initiate in the galvanizing, it would propagate into the steel, at a lower stress level than the crack would otherwise initiate if the steel were bare. On the other hand, if the hypothesis is shown to be false, then we could conclude that cracking in the galvanizing has no impact on crack initiation in the steel.

Procedure:

To test the hypothesis, two threaded specimens from the same rod piece were prepared: One with the existing galvanizing (Specimen A) and one stripped of all the galvanized coating, i.e. bare (Specimen B), and both are shown in **Figure 4.5-9**. To ensure that stripping the galvanizing from the bare specimen did not drive hydrogen into it, both specimens were baked at 375°F for 24 hours. Since the purpose of the experiment is to test the fracture mechanism and not stress corrosion, the specimens were step loaded using a conveniently fast loading rate.

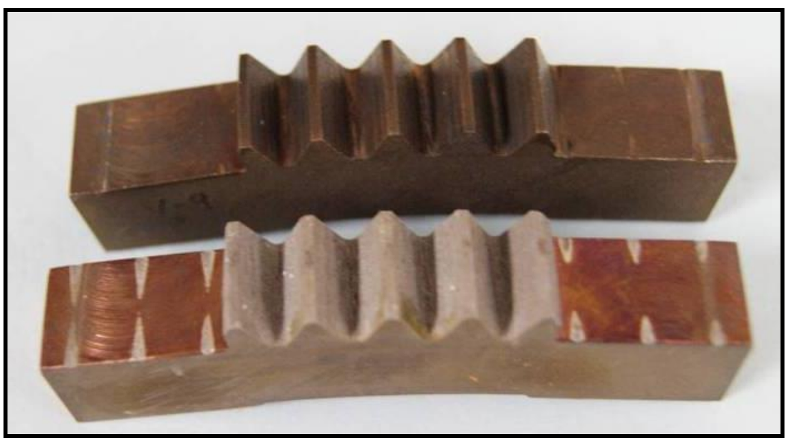

Figure 4.5-9: Bare Specimen (Top) and Galvanized Specimen (Bottom)

Both specimens were installed in a RSL bend machine and loaded using a step protocol with a 1-minute dwell time per step. The specimens were monitored using acoustic emission sensors on the specimens. The middle two thread roots of each specimen were videographed at approximately 30X magnification (see **Figure 4.5-10** and **Figure 4.5-11**) during the entire test.

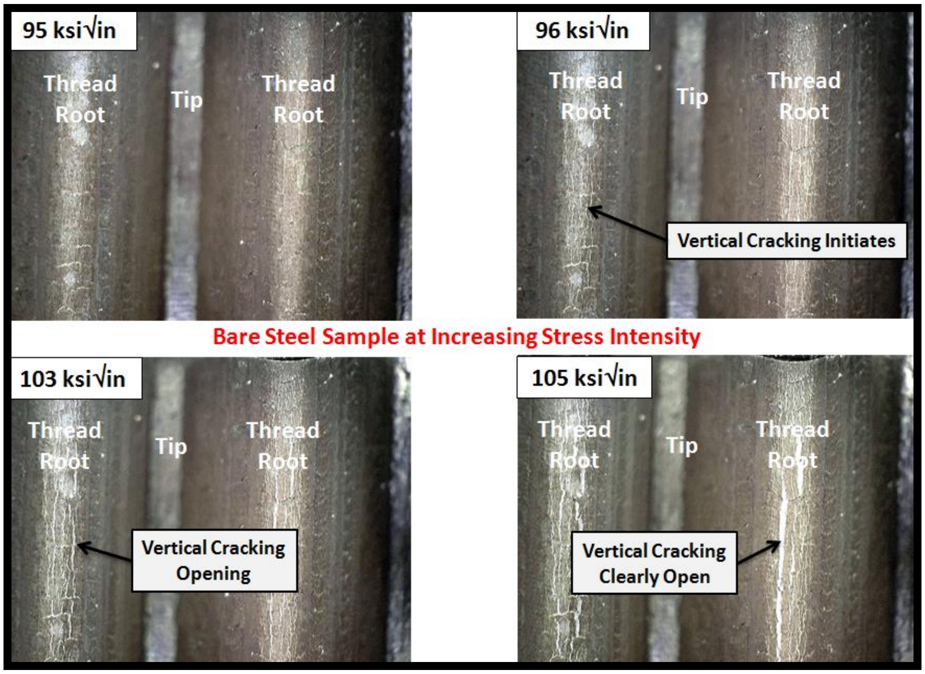

Figure 4.5-10: Crack Progression in Thread Root of Bare Specimen

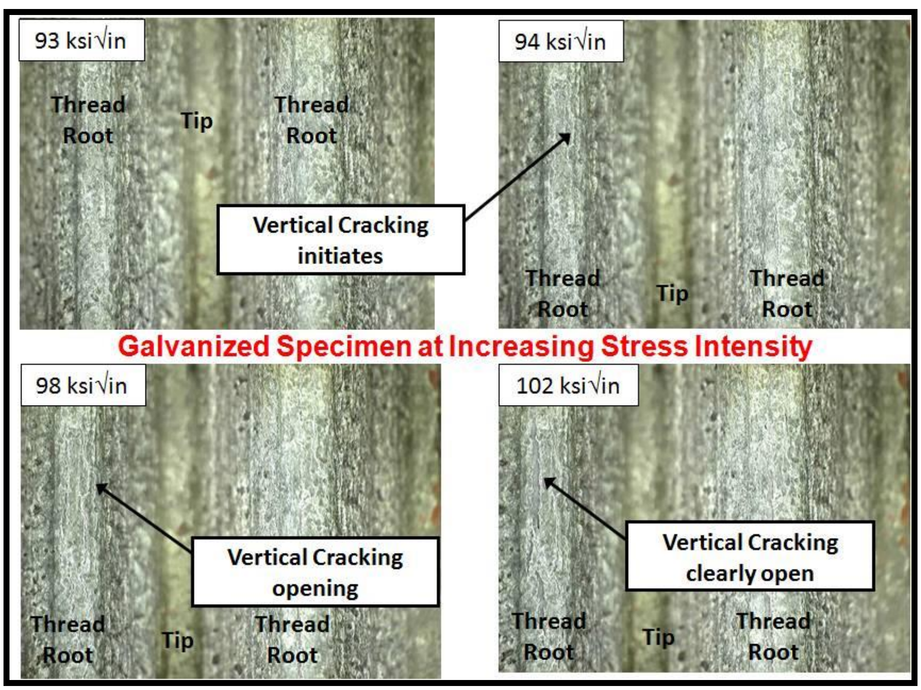

Figure 4.5-11: Crack Progression in Thread Root of Galvanized Specimen

Results:

The audio recording indicates that cracking of the galvanizing in Specimen A started at approximately 25 ksi√in. The cracks in the galvanizing are not visible on the thread root surfaces at the videograph's magnification of approximately 30x until the last few load steps (approximately 95 ksi√in). The emissions from Specimen A consisted of continuous "pops" from 25 ksi√in until failure.

On the other hand, noise in Specimen B, in the form of distinct "pops" initiated at a stress intensity factor above 96 ksi√in. Crack initiation in the steel for both specimens occurred at similar levels (see **Table 4.5-7**).

Table 4.5-7: Results of Zinc Cracking Experiment

Specimen	Stress Intensity (k) when…			
	No Crack	Initiation	Clearly Cracking	Crack Opening
Bare Steel Threaded Specimen	95 ksi√in	96 ksi√in	103 ksi√in	105 ksi√in
Galvanized Threaded Specimen	93 ksi√in	94 ksi√in	98 ksi√in	102 ksi√in

Crack initiation in both specimens was identified by visual examination of cracking. Crack opening in the steel and galvanizing occurred at similar levels.

To verify the results, threaded specimen 3-V-10 Threaded SN6 was tested by RSL according to the following protocol:

1. Remove galvanizing in dilute HCl.
2. Bake at 375°F for 24 hours.
3. Visually examine thread root area to verify absence of galvanizing.
4. RSL test at parameters identical to 3-V-10 Threaded SN3 (10/5/2,4 with strain rate = 2E-10).

Table 4.5-8 lists EHE results of the RSL tests for 3-V-10. The 3-V-10 Threaded SN3 and Threaded SN 4 specimens were tested with their galvanizing intact. The 3-V-10 Threaded SN6 specimen had the galvanizing removed prior to the RSL test. Although galvanizing was present on two specimens and not on another, a potential of -1.106 Vsce was imposed during EHE testing in a 3.5% NaCl solution.

Table 4.5-8: Results of EHE RSL Testing of Bare and Galvanized Specimens

S/N	Galvanized	Strain Rate (in/in/sec)	$KIp_{\text{-EHE}}$ (ksi√in)
3-V-10 Thd SN3	Yes	1.90E-08	66.3
3-V-10 Thd SN4	Yes	1.30E-08	68.6
3-V-10 Thd SN6	No	2.00E-08	67.6

There is no difference in the environmental threshold measured for the three specimens indicating that the presence or absence of galvanizing has no effect on the measured environmental threshold stress intensity factor of the threaded specimens under an externally applied potential.

Conclusion:
At an imposed potential of -1.106 in a 3.5% NaCl solution, the results of this experiment indicate that cracking in the galvanizing does not act as a stress riser or a sharp crack tip at the root of the bolt threads. The implications for the SAS bolts is that cracking in the galvanizing, which may occur at a lower load than the bolt's sustained service load, is not equivalent to a fatigue pre-crack in the steel. Acoustic emission indicates that cracking in the galvanizing may have originated on loading but no cracking was apparent on the surface of the galvanizing until the underlying steel initiated cracking.

Cracking in the galvanizing that exposes the steel surface at the thread root may originate galvanic action that will lead to hydrogen evolution into the steel substrate. However, the threshold for stress corrosion cracking will be higher than that of a pre-cracked specimen with similar properties. This confirms the test results that indicate that threaded fasteners have a higher threshold than fatigue pre-cracked specimens of the same dimensions and material properties.

4.5.5 SEM Fracture Morphology Comparison in fpc Specimens

In Test V, fatigue pre-cracked specimens machined from the rod samples sent to LRA were tested in four-point bending after a sharp crack had been initiated in them. These specimens had fast fracture strength in bending, FFS(B), tests performed on them along with Rising Step Load bending tests in air and in an environment. For the environmental tests, the specimens were tested in 3.5% NaCl solution with an imposed potential of -1.106 Vsce. After the tests were completed to failure, the specimens were fractured on a Charpy impact machine.

Of interest to LRA was the characterization of the fracture morphology for each of the tests performed on the fpc specimens. To perform this characterization, SEM photographs were taken of the fracture face to determine the different fracture modes apparent and match those fracture modes with the tests performed on the specimens. The fracture modes that were found include dimple rupture, hydrogen embrittlement, cleavage and mixed fracture.

Dimpled Rupture:
This fracture mode was found on specimens that had FFS(B) and/or impact tests performed on them. See **Figure 7.10-1** for an image characterizing dimpled rupture. Dimples are characteristic of an overload failure mode due to ductile yielding, tearing or rupture.

Intergranular Fracture:
Intergranular fracture is typical for hydrogen embrittlement. For Test V this mode was exclusively found on the fracture faces of specimens that had been Rising Step Load tested in an environment with an imposed potential. See **Figure 4.5-13** for an image characterizing intergranular fracture.

The clear grain definition and IG cracking in **Figure 4.5-13** is clear evidence of hydrogen embrittlement.

Cleavage:
This fracture mode was mainly found on specimens that were tested at high strain rates characteristic of impact loading. See **Figure 4.5-14** for an image characterizing the failure mode of cleavage. Cleavage was also found in the overload region of specimens from the 2008 material that had failed on the bridge.

The planar, mostly parallel surfaces illustrated in **Figure 4.5-14** are evidence of brittle fracture where the grains of the material get split or severed. The cleavage failure mode occurs with little plastic deformation of the specimen before failure. If a specimen fails with this failure mode under slow strain rate conditions, the cause of failure is most likely due to low fracture toughness (not impact toughness). In the case of the Test V fpc specimens, with the exception fo the 2008 material, this failure mode was found after tests with high strain rates and liquid nitrogen immersion such as the threaded specimens being fractured by impact loading.

Mixed Fracture:
This fracture mode is a mixture of failure modes and was mainly found on specimens that were tested in environments with imposed potentials at higher strain rates. See **Figure 4.5-15** for an image characterizing mixed fracture.

The combination of IG and dimple rupture seen in **Figure 4.5-15** is evidence of a mixed fracture mode. If the ratio of dimple rupture over intergranular fracture is high, the more plastic deformation or yielding occurred.

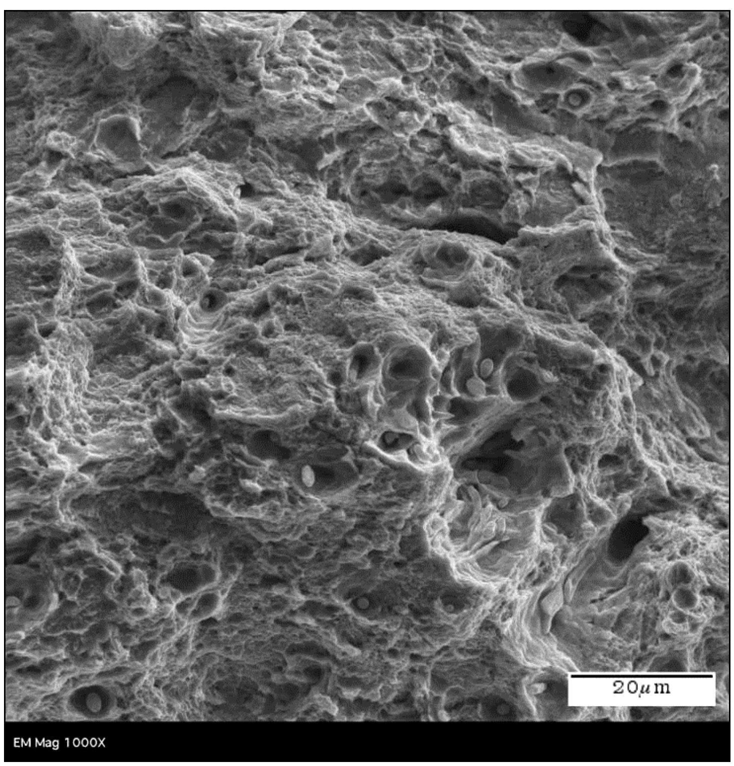

Figure 4.5-12: SEM Photograph of Dimple Rupture Failure Mode

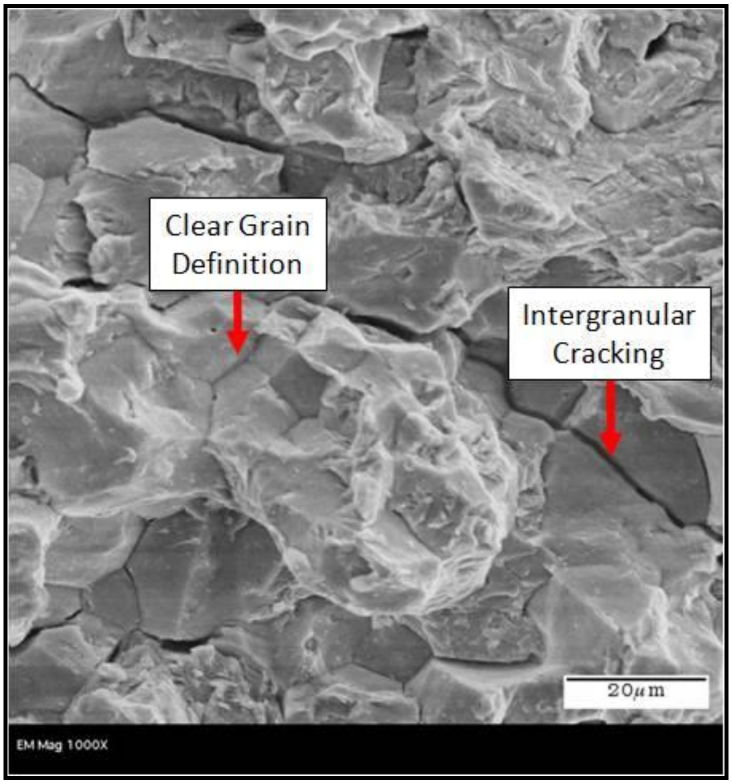

Figure 4.5-13: SEM Photograph of Intergranular Fracture Mode

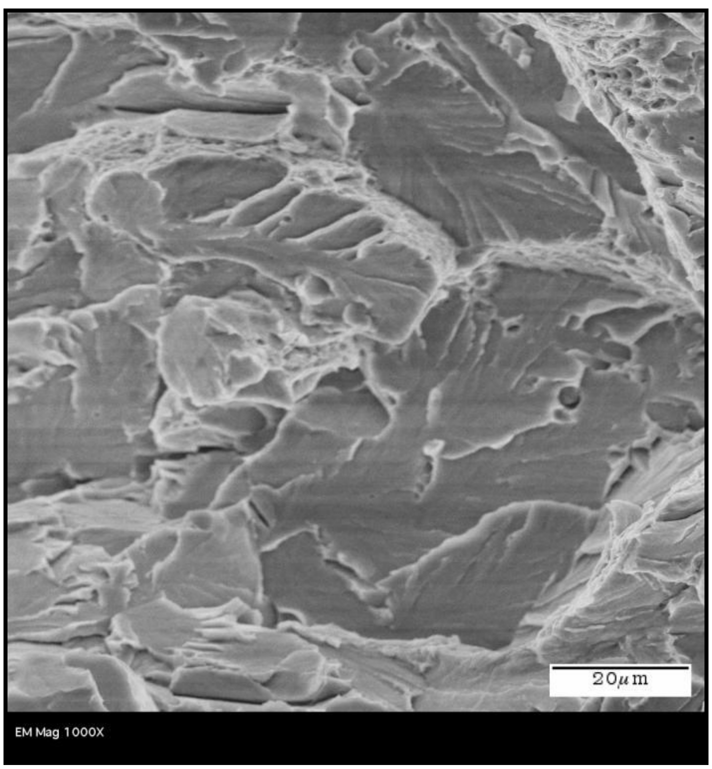

Figure 4.5-14: SEM Photograph of Cleavage Fracture Mode

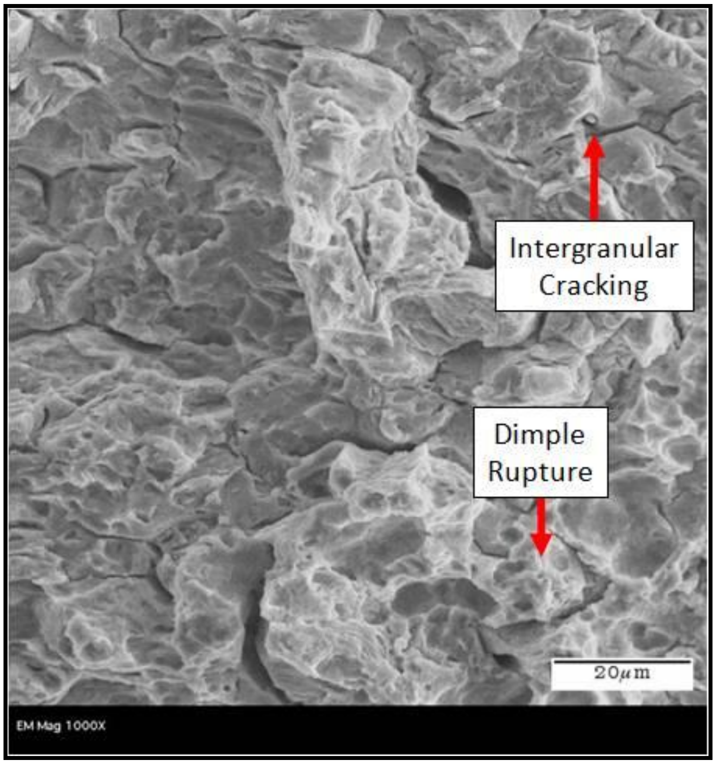

Figure 4.5-15: SEM Photograph of mixed IG and Dimpled Fracture Modes

Conclusion:
From the analysis under the SEM, the fracture modes of the specimens tested in Test V can be characterized by the test performed on them. The first failure mode of dimple rupture occurs during FFS(B) and impact tests. The second failure mode of hydrogen embrittlement occurs during environmental Rising Step Load tests with imposed potentials. The third failure mode of cleavage occurs during impact testing. The fourth and final failure mode of mixed fracture occurs during environmental Rising Step Load tests with imposed potentials.

4.5.6 Crack Initiation Analysis in 2008 Rod Dead-End

LRA received rod samples of one of the 2008 shear key anchor bolts that fractured after installation on the bridge. The section of most interest was the dead end of the bolt that was located near the fracture (Rod 1-V-S2-A2-D). Upon receiving machined samples of Rod 1-V-S2-A2-D, the specimens were examined before testing. It was found that there was a circumferential Pre-existing crack in the section of the rod that LRA received that extended one-third of the circumference of the bolt in the thread root.

One of the machined threaded specimens contained a portion of this Pre-existing crack. The crack was located in the machined square bar portion of the threaded specimen approximately one-quarter of an inch from the end of the specimen. **Figure 4.5-16** shows the specimen after removing the cracked portion.

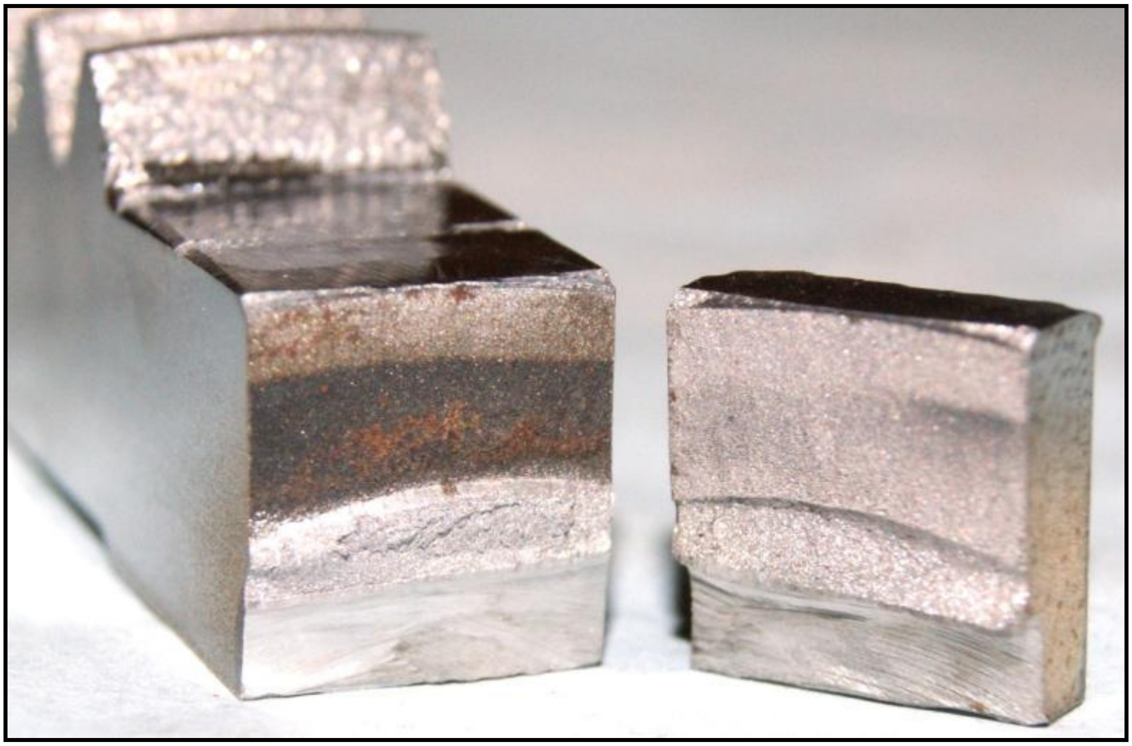

Figure 4.5-16: Pre-existing Crack in Threaded Specimen cut from Rod 1-V-S2-A2-D

To compare the fracture mode of the Pre-existing crack to the fracture mode of an EHE tested Rod 1-V-S2-A2-D threaded specimen, fractographic analysis by SEM was conducted on the fracture surface of both specimens.

Fractographic Analysis of Pre-existing Crack:
After cleaning the fracture face of the Pre-existing crack in an ultrasonic cleaner with Alconox first and then Acetone, a photograph was taken (**Figure 4.5-17**) for reference during SEM analysis. The fracture locations indicated in **Figure 4.5-17** are indicative of the following fracture modes:

1. Region of crack Initiation (Damaged Zone)
2. IG Hydrogen Crack growth
3. Mixed IG and dimpled
4. Overload

After cleaning and the initial photograph, SEM photos were taken of the four locations indicated in **Figure 4.5-17** at 1,000X and 500X magnification. See **Figure 4.5-18** for photos of each of the regions.

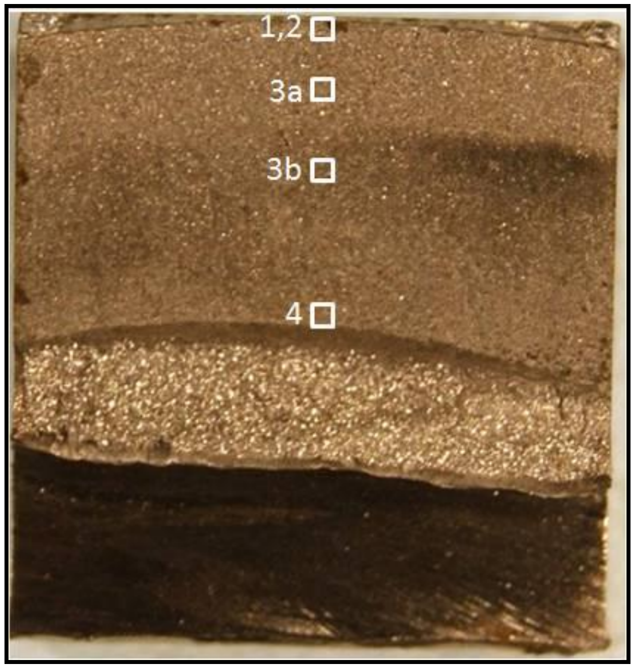

Figure 4.5-17: Fracture Face of Pre-existing Crack in 2008 Dead End

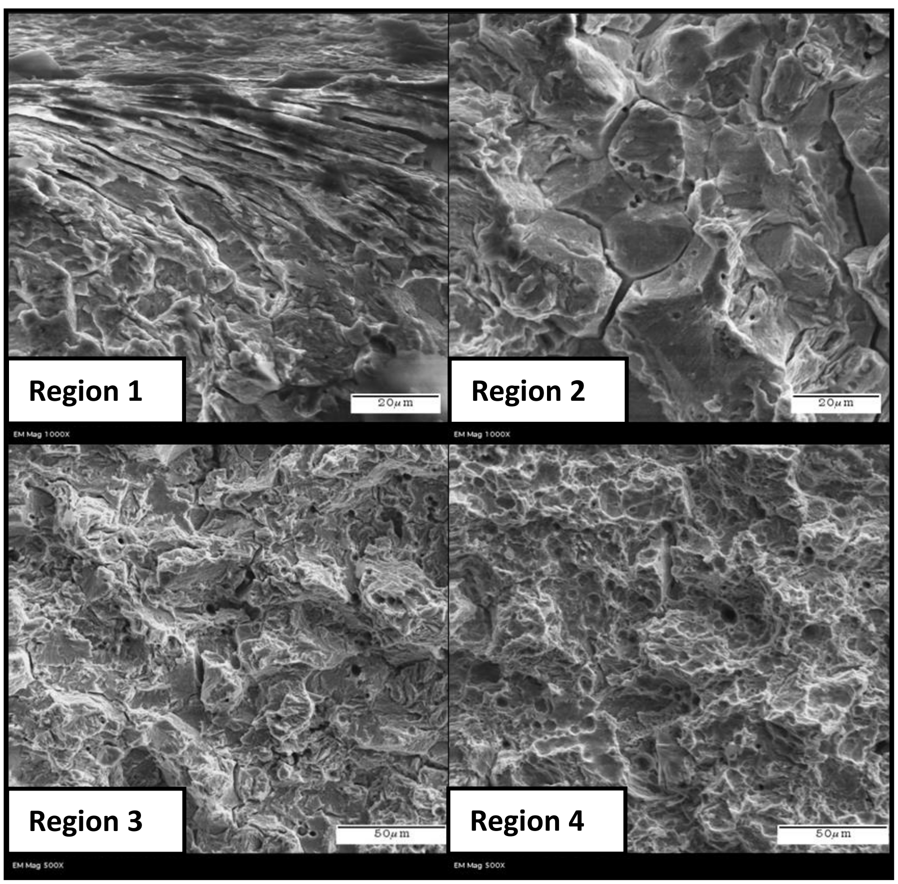

Figure 4.5-18: SEM of Fracture Mode Regions in pre-existing crack

The first region, crack initiation, is evidenced by the thread root at the top of the image showing signs of cold work that occurred during the machining of the threads. In addition, IG can be seen in this region.

The second region, where the fracture mode is IG cracking, is evidenced by the faceted nature of the fracture face or IG in this region. In addition, the small population of dimples and the pronounced grain separation are indicative of IG cracking as well, indicative of an increase in the stress intensity.

The third region has some grain separation along with a larger population of dimples. This indicates a mixed fracture region where a combination of dimple rupture and IG are occurring.

The fourth and final region of the fracture face has a vast majority of dimpled rupture and little to no grain separation or faceting. This region is characteristic of the dimpled rupture fracture mode.

Fractographic Analysis of Test V EHE Crack:
After the 1-V-S2-A2-D Thd 5 fractured during its environmental Test V RSL test, the specimen was baked and impact tested with a Charpy V-Notched (**CVN**) impact machine after cooling in LN_2. Before performing SEM analysis on this specimen, the fracture face was photographed to illustrate the cracked region. The fracture locations indicated in **Figure 4.5-19** are indicative of the following fracture modes:

1. Region of crack Initiation (Damaged Zone)
2. IG Hydrogen Crack growth
3. Mixed IG and dimpled
4. Overload

Figure 4.5-19: Fracture Face of Rod 1-V-S2-A2-D Thd 5

After cleaning and after the photograph of the fracture face was taken, SEM photos were taken of the four locations indicated in **Figure 4.5-19** at 500X and 1000X magnification. See **Figure 4.5-20** for photos of each of the regions.

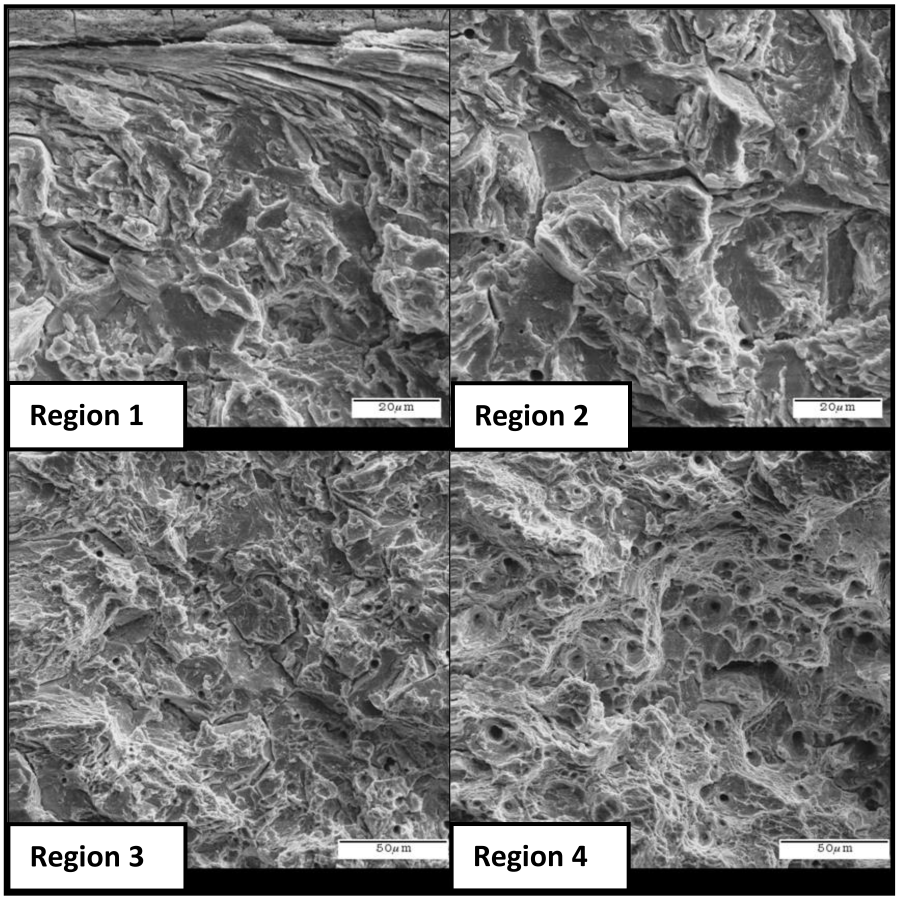

Figure 4.5-20: SEM of Failure Mode Regions of Sample 1-V-S2-A2-D Thd 5

The first region, crack initiation, is evidenced by the thread root at the top of the image showing signs of cold work that occurred during the machining of the threads. In addition, IG can be seen in this region.

The second region, where the fracture mode is hydrogen cracking, is evidenced by the faceted nature of the fracture face in this region. In addition, the small population of dimples and the pronounced grain separation are indicative of IG cracking as well, indicative of an increase in the stress intensity.

The third region has some grain separation along with a larger population of dimples. This indicates a mixed fracture region where a combination of dimple rupture and IG cracking are occurring.

The fourth and final region of the fracture face has a vast majority of dimpled rupture and little to no grain separation or faceting occurring. This region is characteristic of the overload fracture mode. This fractographic pattern is consistent with crack growth under a constant load or increasing stress intensity.

Conclusion:
Upon comparison of the two sets of SEM photos of the specimen with the in-situ crack and the EHE tested threaded specimen, it was determined that the fracture modes of the two samples are nearly identical. Thus, the pre-existing crack in the 1-V-S2-A2-D rod that was installed on the bridge was induced by environmental hydrogen embrittlement. This implies that the rod must have been immersed in water under stress and hydrogen embrittlement occurred from hydrogen charging due to the galvanic reaction between the galvanized zinc and steel substrate.

5 Test V Conclusions

1. There was no IHE found in the SAS Rods obtained at LRA.

2. The $KI_{\rho\text{-EHE}}$ results for the 2010 rods are higher than $KI_{\rho\text{-EHE}}$ results for the 2008 rods due to a combination of cleanliness and toughness of the steel and the manufacturing quality of the threads.

3. HE/SCC cracking in bars with rolled threads:

    a. For rods rolled threads with an M-shaped hardness profile, the initial cracking arrests by a blunting mechanism due to elongated grains in a lower hardness material

    b. Crack arrest is often maintained until load is increased

    c. Because of the crack blunting (smiley faces), cracking in the core occurs at a higher stress intensity factor than corresponding cracking in cut threads. Often the magnitude of this stress intensity factor is as much as 20% greater than any cut thread threshold.

    d. The group of rods with rolled threads that have an “M” shaped profile from the hardness testing done in Test II and Test III, all lie above the trend line for cut threads.

6 Abbreviations, Acronyms, and Symbols

6.1 Abbreviations and Acronyms

BATA	Bay Area Toll Authority
C	Specimen cut from the center cross section of a rod (fpc)
CTOD	Crack tip opening displacement
DTI	Damage Tolerance Index
EAC	Environmentally assisted cracking
EDM	Electric discharge machine
EHE	Environmental Hydrogen Embrittlement
FDI	Fracture Diagnostics International
FEM	Finite Element Models
FFS	Fast Fracture Strength
fpc	Fatigue pre-cracked specimen
HDG-Zn	Hot dipped galvanized zinc
HE	Hydrogen embrittlement
HRC	Rockwell C Hardness
HSC	Hydrogen stress cracking
IG	Intergranular cracking
IHE	Internal hydrogen embrittlement
ISL	Incremental Step Loading
LRA	L.Raymond & Associates, *A Professional Consulting Corporation*
MR	Specimen cut from the cross section of a rod at the mid-radius (fpc)
OBG	Orthotropic box girders
OCP	Open Circuit Corrosion Potential of the coating
OD	Specimen cut from the cross section of a rod at the outside diameter (Refers to fpc but can also be Thd)

ODfpc	See OD
ODthd	See Thd
PFA	Post failure analysis
RSL™	Rising step load
SCC	Stress Corrosion Cracking
SCE	Saturated Calomel Electrode
SED	Strain Energy Density
SEM	Scanning Electron Microscope
SEN(B)	Single edge notched specimen tested in bending
SFOBB	San Francisco-Oakland Bay Bridge
SLT	Sustained load test
TBPOC	Toll Bridge Program Oversight Committee
Thd	Threaded specimen

6.2 Symbols

%FFS	% Fast Fracture Strength, 100% refers to the Kmax per rod found during FFS Testing
CVN	Charpy V-Notched
DTI_{-EHE}	EHE threshold DTI found during EHE
DTI_{-IHE}	IHE threshold DTI found during IHE
DTI_{max}	Maximum DTI found during FFS
Fu	Force ultimate or minimum ultimate tensile strength
$Fu_{-applied}$	The applied force for the remaining rods on the bridge
Fu_{-EHE}	EHE Force ultimate or EHE minimum ultimate tensile strength
Hsr	Hydrogen Susceptibility ratio, ration of the threshold for the onset of hydrogen assisted cracking to the tensile strength of the material (Environmental threshold/UTS)
k	Stiffness, compliance, or spring rate of the specimen being tested (lbs/in)
KIc	Fracture Toughness (E399 Loading Rates)
KIctod	Stress intensity at the crack tip initiation (crack tip opening displacement)

KI_{-IHE}	IHE stress intensity threshold (not geometry dependent/material property, fpc specimen)
KIscc	SCC threshold stress intensity factor (T)
KIρ	Stress intensity thresholds for Thd specimens with root radius, ρ
$KI\rho_{-EHE}$	EHE stress intensity threshold (geometry dependent on root radius ρ, Thd specimen)
$KI\rho_{-IHE}$	IHE stress intensity threshold (geometry dependent on root radius ρ, Thd specimen)
Kmax	Maximum stress intensity factor obtained during a FFS Test (fpc and Thd specimen)
P*	Seen as equivalent load applied to a specimen with idealized geometry derived from the load applied to actual specimen
P_{FFS}	Maximum Load obtained during an FFS rate consistent with ASTM E8, baseline load
P_{i-1}	The first load drop or fracture load recorded from the first EHE or IHE test ran with the FFS as its target
Pmax	If during FFS, see P_{FFS}, other testing (IHE, EHE) the maximum load the specimen held before fracture
P_{target}	For 1^{st} EHE or IHE test set P_{target} to FFS, for n^{th} EHE or IHE test P_{target} is 1.1 times $P_{th-(n-1)}$; Ex: P_{th-2} = 100 lbs, P_{target} for test 3 will be 110 lbs
P_{th}	Threshold load obtained during an RSL test per ASTM F1624
P_{th-1}	The step before the first fracture load, P_{i-1}, is the threshold load for the first EHE or IHE test ran with the FFS as its target
P_{th-2}	The second EHE or IHE threshold, performed with steps of 5% of P_{target}
Rsb	Ratio of specimen crack strength to yield strength in bending,
T_d	Dynamic tear modulus
UTS	Ultimate Tensile Strength
Vsce	Corrosion potential of the specimen controlled with reference to an SCE
W_E	strain energy density under the elastic portion of the curve typical stress-strain curve
W_F	strain energy density under the under the necking or damage portion of the curve typical stress-strain curve
W_U	strain energy density under the uniform plastic portion of the curve typical stress-strain curve

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Appendices

Appendix A: Test Protocol

A.1 Specimen Preparation

Rod samples were received at LRA and visually examined for general condition and major defects. Samples varied in length from 6 to 24 inches.

A 2.5-inch long segment was cut from the sample and specimens were machined from this segment by electrical discharge machining, EDM. Two types of specimens were prepared. One type of specimen was cut from the outer edge of the segment and included the thread and the hot dipped galvanized zinc, HDG-Zn, coating. The nominal dimensions of the threaded specimens were 0.61 inch wide (0.61W) by 0.4 inch thick (0.4B) by 2.5 inches long. A section was removed from the backside of the specimen to reduce the specimen width at the thread root to 0.55 inch (0.55W).

A second type of specimen was cut from the interior of the segment. Interior specimens were cut to dimensions of 0.4 in. wide by 0.4 in. thick by 2.25 in. long. A slot, 0.1 inch deep, was cut in the center of each fpc specimen as a starter slot for fatigue pre-cracking. The location from which an interior specimen was removed was noted and specimens were tested as outer diameter, mid-radius, or center specimens (OD, MR, and C). The two types of specimens are shown in **Figure A.1-1**. The distribution of specimens in a rod is illustrated in **Figure A.1-2**.

Figure A.1-1: Threaded Specimen and fpc Specimen

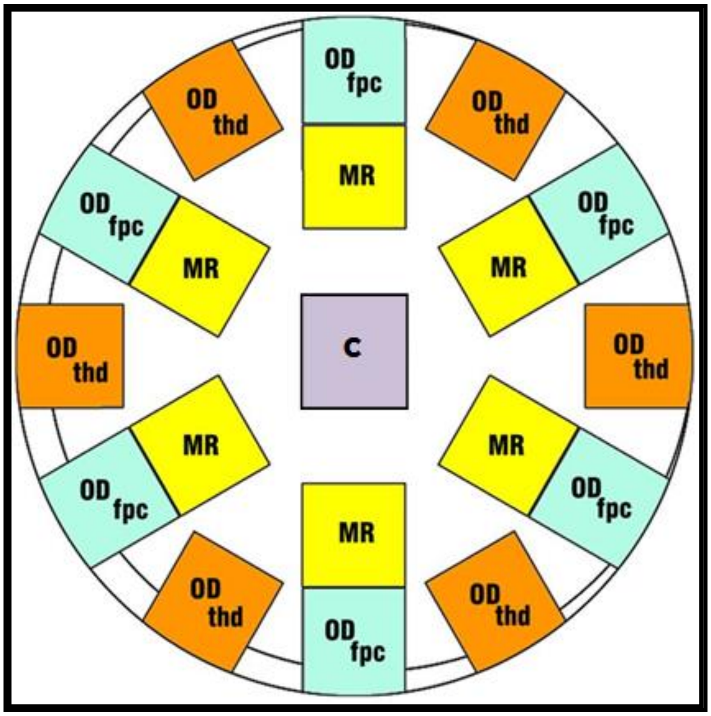


Figure A.1-2: Machining Plan for 3-inch Diameter Rod

A.2 Open Circuit Potential Testing of Rod Samples

The Open Circuit Potential, OCP, of each rod sample provided was measured per the procedure outlined in Special Projects Section 4.5.2 on OCP. Typically, the measured value for OCP would drop rapidly, to a minimum value, within a few hours. The OCP of the galvanizing varied from rod to rod from a low of -1.100 Vsce to a high of -0.850 Vsce.

A.3 Hardness Testing of Specimens

The hardness of each specimen was measured using a Rockwell Hardness Tester (Wilson Instrument Division, American Chain and Cable Co.) per ASTM E8. The Rockwell C Hardness (HRC) scale was used for each measurement taken and the hardness was measured at six points on the side of the specimen, spanning its length. The measured hardness was then correlated to the Ultimate Tensile Strength of the material per ASTM E140.

A.4 Fatigue Pre-crack Specimen Testing

Prior to testing, SEN(B) specimens were fatigue pre-cracked within the limits defined by ASTM E399 and E1820. The EDM slot was extended by fatigue approximately 0.08 to 0.100 inches. The precise depth of the pre-crack is measured following testing. The final stress intensity used during fatigue pre-cracking, typically 15 ksi√in, was less than 60% of the measured stress intensity for crack initiation, typically 25 ksi√in to 35 ksi√in. For the SEN(B) specimens that required a fatigue pre-crack, a Physmet FCM-300B was used to pre-crack the specimens. This unique piece of equipment uses constant displacement rings to produce cracks ranging from 0.005" to 0.250" in less than 10 minutes.

To provide baseline reference data for each rod and specimen type, a specimen of each rod and type (MR, OD or Center) is tested to rupture using a rate consistent with ASTM E8. This establishes a fast fracture strength load, P_{FFS}, for a given specimen geometry. Data recorded during this test was also used to calculate KIctod per ASTM F1290-99 which is an estimate for the material's fracture toughness, KIc. Subsequently, the impact energy was measured and used to calculate the Dynamic Tear Modulus, T_d. T_d is an estimate of the energy absorbed per unit crack extension to resist crack propagation under moderate strain rates typical for tensile testing.

To measure the effect of residual, or internal hydrogen in the steel due to processing, IHE testing was performed. The K_{I-IHE}, threshold in air, is determined per ASTM F1624, for MR and OD specimens.

To measure the EHE susceptibility of the material, fpc specimens were tested in a salt-water environment (3.5% NaCl in distilled water) using the step load procedure defined in ASTM F1624 Section 8 as modified in Annex A1. For the majority of testing, an external potential of -1.106 Vsce was applied to simulate the most negative potential that would be applied by a galvanized coating recorded in Test IV. The K_{I-EHE}, threshold in salt water, is determined per ASTM F1624.

A.5 Threaded Specimen Testing

To provide baseline reference data for each rod, a threaded specimen was tested to rupture using a rate consistent with ASTM E8. This established a fast fracture strength load, P_{FFS}, for a given specimen geometry. The specimens are not fatigue pre-cracked and thus are "irregular geometry-type" specimens. However, a value for an effective stress intensity can be calculated assuming the specimen is a notched specimen where the geometry of the thread takes the place of the notch. This value of the stress intensity indicates the uncracked response of the threaded rod and thus is designated as KIρ indicating a significant notch root radius of ρ.

To measure the effect of residual, or internal hydrogen in the steel due to processing, IHE testing was performed. The $K_{I\rho-IHE}$, threshold in air, is determined per ASTM F1624 using threaded specimens.

To measure the EHE susceptibility of the material, threaded specimens were tested in a salt-water environment (3.5% NaCl in distilled water) using the step load procedure defined in ASTM F1624 Section 8 as modified in Annex A1. Prior to the test being started, a scribe mark was applied to the coating at the root of a thread to simulate damaged coating or a "holiday" in the coating. For the majority of testing, an external potential of -1.106 Vsce was applied to simulate the most negative potential that would be applied by a galvanized coating. The $K_{I\rho-EHE}$, threshold in salt water, is determined per ASTM F1624 with Holiday.

To determine the $K_{I\rho-EHE}$ threshold, two analysis methods were used depending on whether the specimen threads were rolled or machined. For rolled threads, the visual threshold determination method was used. For machined threads, the stiffness threshold determination method was used unless the visual threshold was very well defined. More information on the fracture mechanisms can be found in Section 2.5.

A.5.1 Post EHE Test Thread Root Photos

Photographs were taken of the thread roots of threaded specimens post EHE testing and dynamic impact loading. Due to the clarity of some post EHE thread root photos, photos were taken again but post impact loading and on adjacent threads to the fracture face instead of the most susceptible thread root with the original EHE crack. A longer crack represents a test that initiated cracking over a weekend or holiday and could not stop cracking until a technician unloaded the specimen from the RSL test machine. These longer cracks are most often from the most susceptible thread root with the original EHE crack. Other photos of thread roots with little cracks to none were taken post impact testing. These thread roots were adjacent to the thread root that was split open during dynamic impact loading (original EHE crack) creating the fracture face. These two types of photographs show the spectrum of an EHE crack at the thread root of the most susceptible thread root to the adjacent threads.

A.6 Nomenclature for Test V Test Result Parameters

Figure A.6-1 shows the nomenclature for Test V test result parameters used throughout the Test V Summary Tables in the following Appendices.

Hardness (HRC)	=> Hardness Rockwell 'C' Scale per ASTM E23
UTS (ksi)	=> Ultimate Tensile Strength per ASTM E140
Ptarget (lbs)	=> Target load for RSL loading profile = % Pmax
Pmax (lbs)	=> Maximun load defined in ASTM F1624
Pth (lbs)	=> Threshold load defined in ASTM F1624
%FS (Pth/Pmax)	=> Percentage Fracture Strength; i.e., Pth/Pmax
Kmax (ksi√in)	=> Stress Intensity Factor calculated from maximum load in fracture toughness test per ASTM E399/E1290/E1820
KIscc (ksi√in)	=> Threshold stress intensity for onset of stress corrosion crack growth of a fatigue pre-cracked specimen
$KI_{p\text{-}EHE}$ (ksi√in)	=> Threshold stress intensity for onset of stress corrosion crack growth of a threaded specimen
DTI (√in)	=> Damage Tolerance Index; i.e., Kthreshold/UTS
σnet (ksi)	=> Net stress
Rsb	=> Specimen strength ratio in bending per ASTM E812/E2078, (max local net stress/UTS)
Hsrb	=> Hydrogen Susceptibility ratio in bending per ASTM E2078, (max local net SCC stress/UTS)
$\delta\varepsilon/\delta t$ ($10^{-8}s^{-1}$)	=> Strain Rate
a (in)	=> Measured crack depth of fatigue precrack for SEN(B)
KIctod (ksi√in)	=> The measured stress intensity factor from crack-tip opening displacement per ASTM E1290 ≈ KIc
Step Load Profile	=> The loading profile used on RSL™ software
P* (lbs)	=> Normalized Load (load that a standard-sized specimen would experience to effect the same Stress Intensity)
Fu	=> The minimum ultimate strength as a fuction of stress intensity

Figure A.6-1 Nomenclature for Test V Test Result Parameters

Appendix B: Rod 4-V-1

B.1 Description of Sample

Rod 4-V-1 was a Pier E2 Bearing Bolt (Top Housing: B1, B2, B3, B4) from the same heat of material that was tested in Test Rig 5 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 2 inches in diameter with rolled threads. The segment from this section of the rod provided to LRA is shown in **Figure B.1-1**.

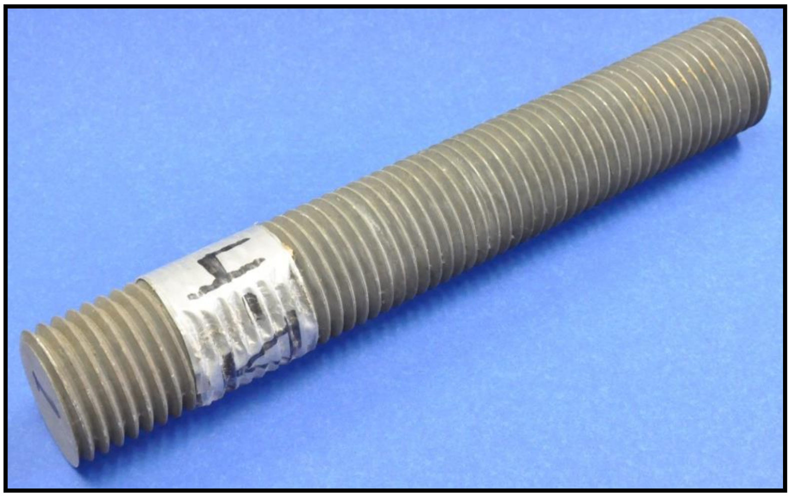


Figure B.1-1: Pier E2 Bearing Bolt (Top Housing), Rod 4-V-1

B.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 4-V-1 and can be seen versus time in **Figure B.2-1**. The final OCP recorded for Rod 4-V-1 was Vsce=-0.867 V.

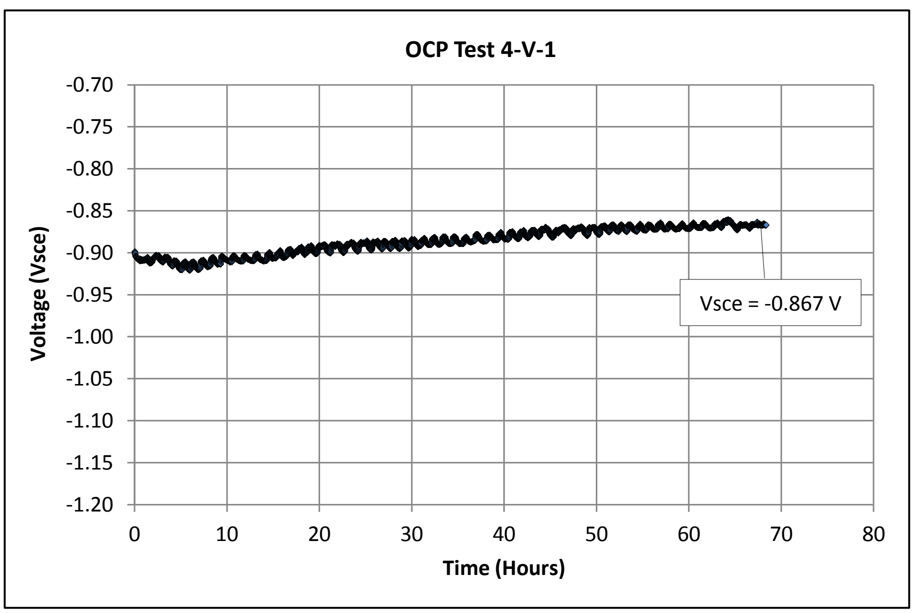


Figure B.2-1: Open Circuit Potential for Rod 4-V-1

B.3 Hardness

The hardness data and profile for sample 4-V-1 are shown in **Table B.3-1** and **Figure B.3-1**.

Table B.3-1: Hardness Data of Rod 4-V-1 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	33.5	33.5
MR 1, FFS	36.0	35.1
MR 2, IHE	35.0	
MR 3, EHE	35.5	
MR 4, EHE	34.0	
Thd 7, FFS	36.0	35.9
Thd 2, IHE	36.0	
Thd 4, EHE	36.5	
Thd 6, EHE	36.0	
Thd 8, EHE	35.0	

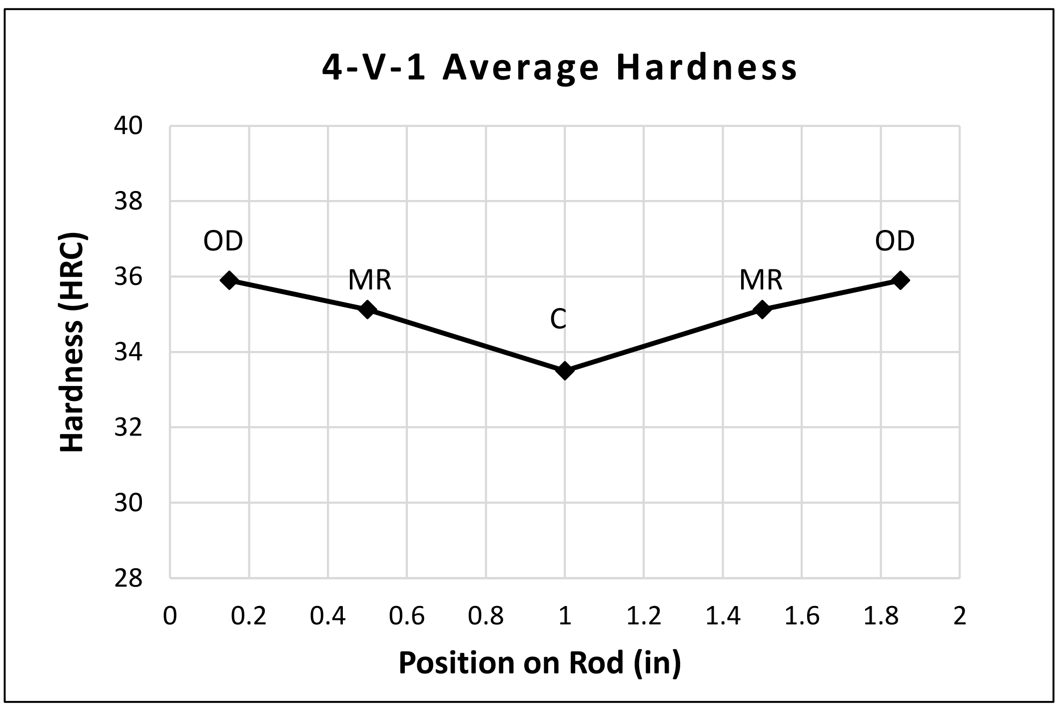


Figure B.3-1: Hardness Profile of Rod 4-V-1

B.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables. The specimens are listed first with the FFS test specimen, followed by the IHE test specimen, and last with the EHE test specimen in consecutive sample order.

B.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 4-V-1

LRA Job No.:	**TYL130901**	**Structural Components**: Pier E2 Bearing Bolts-Top Housing (B1, B2, B3, B4)
Rod#:	**4-V-1**	
Product Form:	**1e**	**Comments**: Rolled Threads; Same Heat as Test Rig #5 in Test IV
Rod OD:	**2"**	

	Sample #/ID	HRC		K-FFS	K-IHE	K-EHE
Fatigue Pre-cracked	**MR 1, FFS**	**36.0**	K_{max}	85.4		
			DTI_{th}	0.53		
			Fu	1.00		
			Strain Rate ($x10^{-8}$ in/in/sec)	7900		
	MR 2, IHE	**35.0**	$K_{threshold}$		92.7	
			DTI_{th}		0.59	
			Fu		1.09	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.3	
	MR 3, EHE	**35.5**	$K_{threshold}$			23.3
			DTI_{th}			0.15
			Fu			0.27
			Strain Rate ($x10^{-8}$ in/in/sec)			4.5
	MR 4, EHE	**34.0**	$K_{threshold}$			26.9
			DTI_{th}			0.18
			Fu			0.31
			Strain Rate ($x10^{-8}$ in/in/sec)			1.5
	Center 1, FFS	**33.5**	K_{max}	86.1		
			DTI_{th}	0.57		
			Fu	1.01		
			Strain Rate ($x10^{-8}$ in/in/sec)	9500		

B.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 4-V-1						
LRA Job No.:	**TYL130901**	**Structural Components**: Pier E2 Bearing Bolts-Top Housing (B1, B2, B3, B4) **Comments**: Rolled Threads; Same Heat as Test Rig #5 in Test IV				
Rod#:	**4-V-1**					
Product Form:	**1e**					
Rod OD:	**2"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 7, FFS**	**36.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	331.3 1.13 1.5 2000		
	Thd 2, IHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		323.8 1.11 1.4 1.7	
	Thd 4, EHE	**36.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			291.5 1.00 1.3 1.3
	Thd 6, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			311.1 1.06 1.4 2.0
	Thd 8, EHE	**35.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			292.9 1.00 1.3 1.6

B.4.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 4-V-1
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**4-V-1**
Product Form:	**1e**
Rod OD:	**2"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	MR 1, FFS	Air	36.0	162	99.1	99.1	99.1	100.0%	85.4	0.53	286.8	1.8	7900	0.2072	145.7	50 lbs/min		1.00	
	MR 2, IHE	Air	35.0	157	2147.0	3331.2	3331.2	108.5%	92.7	0.59	314.7	2.0	2.3	0.2119		10/5/2,4		1.09	
	MR 3, EHE	3.5% NaCl @ -1.106V	35.5	159	67.0	40.2	26.7	27.3%	23.3	0.15	78.5	0.5	4.5	0.2089		10/5/2,4		0.27	
	MR 4, EHE	3.5% NaCl @ -1.106V	34.0	153	44.0	39.6	30.8	31.5%	26.9	0.18	90.8	0.6	1.5	0.2095		10/5/2,4		0.31	
	Center 1, FFS	Air	33.5	151	86.5	86.5	86.5	100.0%	86.1	0.57	302.2	2.0	9500	0.2246	158.9	50 lbs/min		1.01	
Threaded	Thd 7, FFS	Air	36.0	162	374.0	374.0	374.0	100.0%	96.6	0.60	237.3	1.5	2000			0.4 in/min	331.3	1.13	
	Thd 2, IHE	Air	36.0	162	264.0	373.4	373.4	97.7%	94.4	0.58	231.5	1.4	1.7			10/5/2,4	323.8	1.11	
	Thd 4, EHE	3.5% NaCl @ -1.106V	36.5	164	160.0	317.9	298.8	88.0%	85.0	0.52	214.4	1.3	1.3			10/5/2,4	291.5	1.00	No Holiday
	Thd 6, EHE	3.5% NaCl @ -1.106V	36.0	162	285.0	362.1	355.4	93.9%	90.7	0.56	222.3	1.4	2.0			10/5/2,4	311.1	1.06	Did Not Crack in Holiday
	Thd 8, EHE	3.5% NaCl @ -1.106V	35.0	157	220.0	340.9	330.4	88.4%	85.4	0.54	209.4	1.3	1.6			10/5/2,4	292.9	1.00	Did Not Crack in Holiday

B.5 Fatigue Pre-cracked Specimen Test Results

B.5.1 MR 1, FFS:

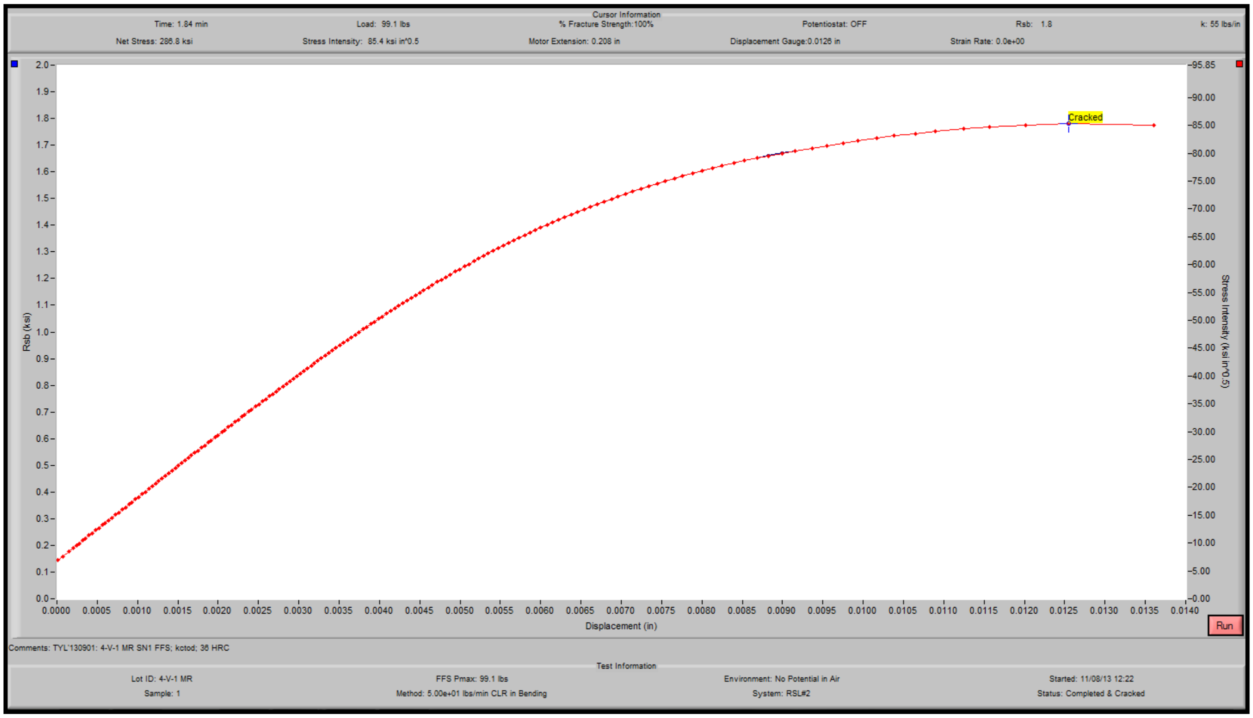


Figure B.5-1: Rod 4-V-1 MR 1, Graphical FFS Results

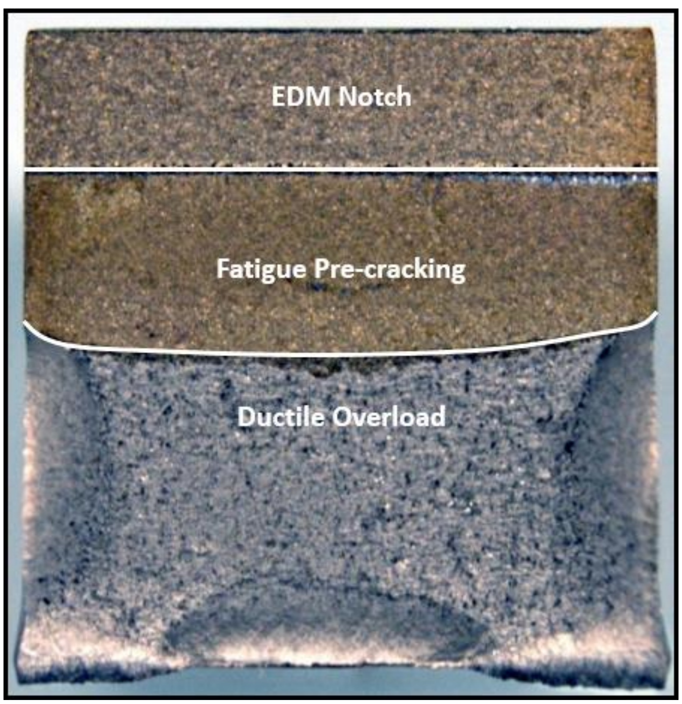
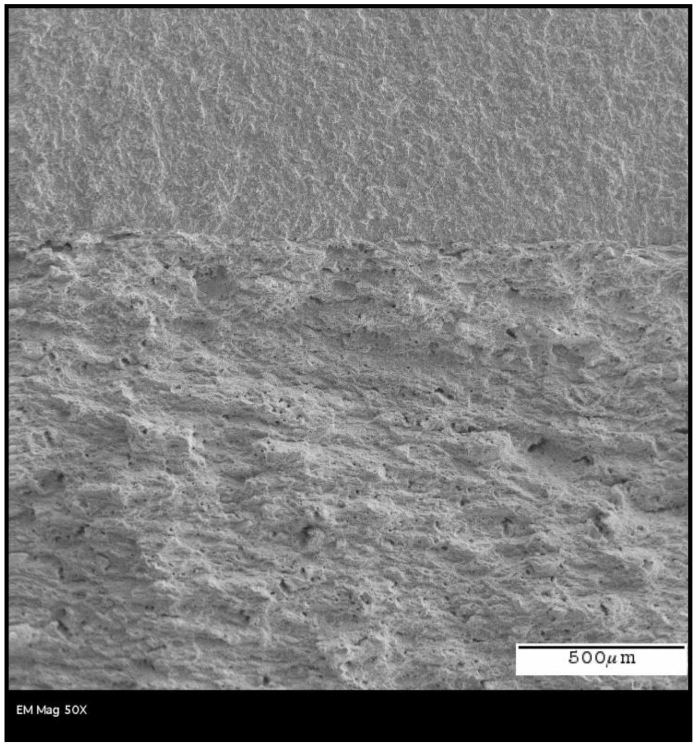
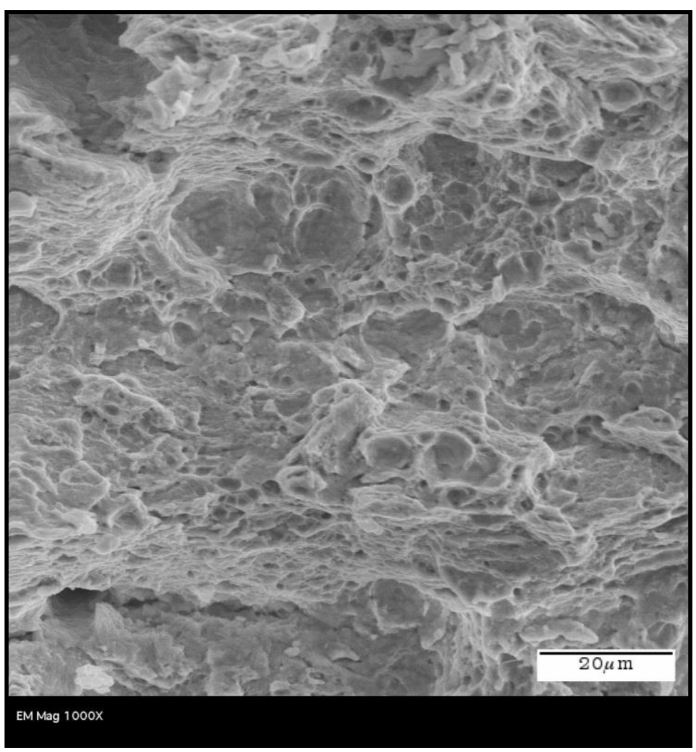


Figure B.5-2: Fracture Face of Rod 4-V-1 MR 1, FFS

Figure B.5-3: SEM of Rod 4-V-1 MR 1, FFS



fpc – OL Transition 50X



Overload 1000X

B.5.2 MR 2, IHE:

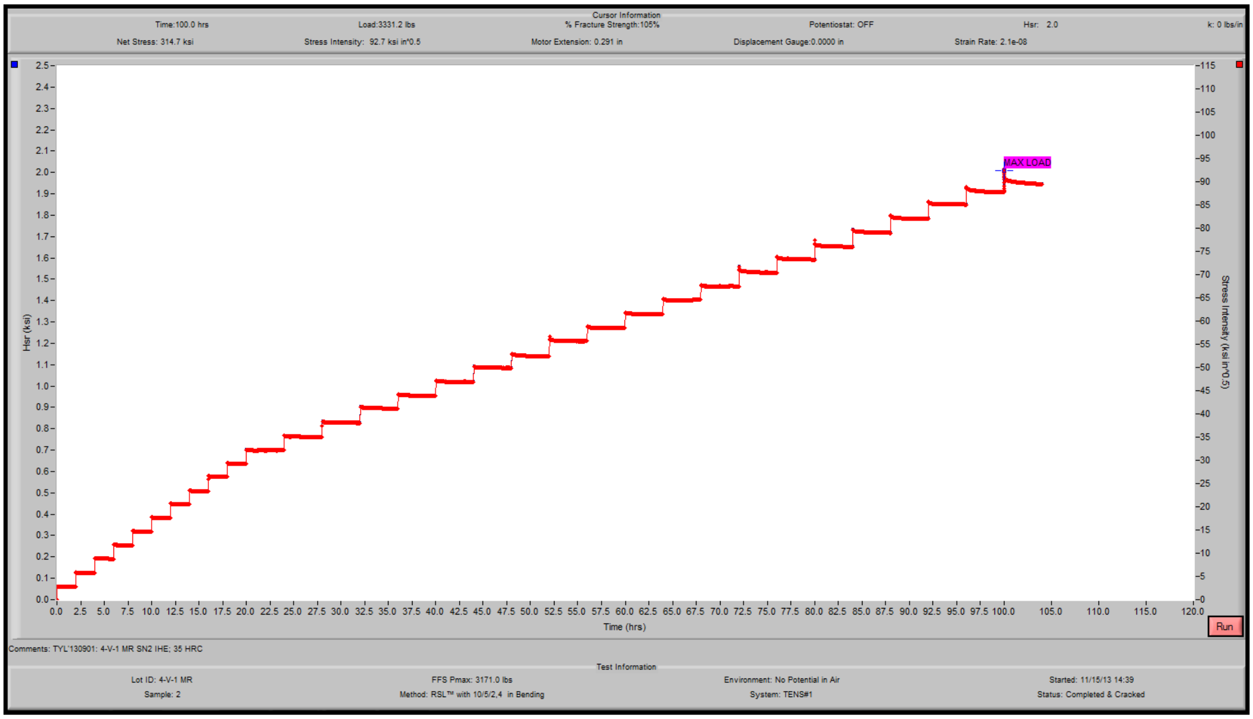


Figure B.5-4: Rod 4-V-1 MR 2, Graphical IHE Results

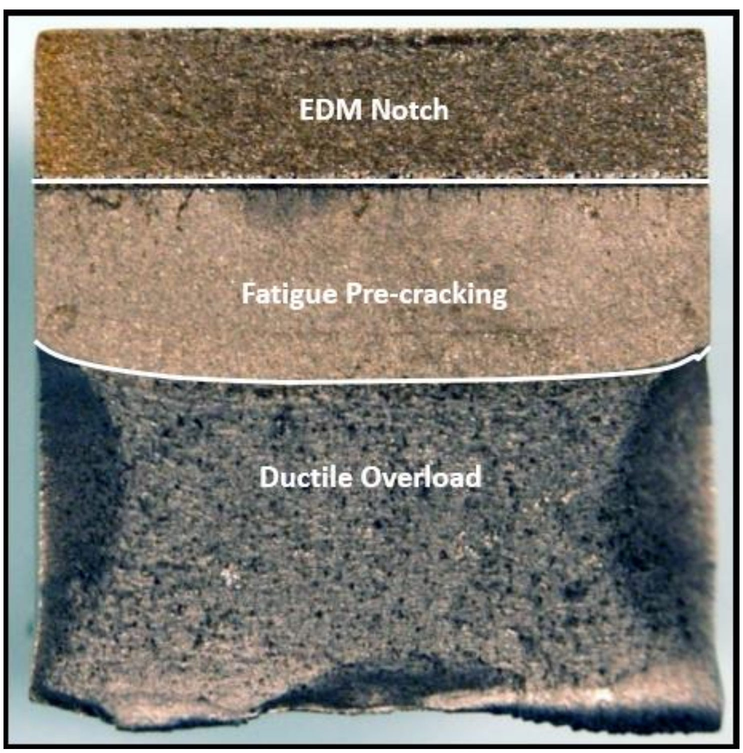


Figure B.5-5: Fracture Face of Rod 4-V-1 MR 2, IHE

B.5.3 MR 3, EHE:

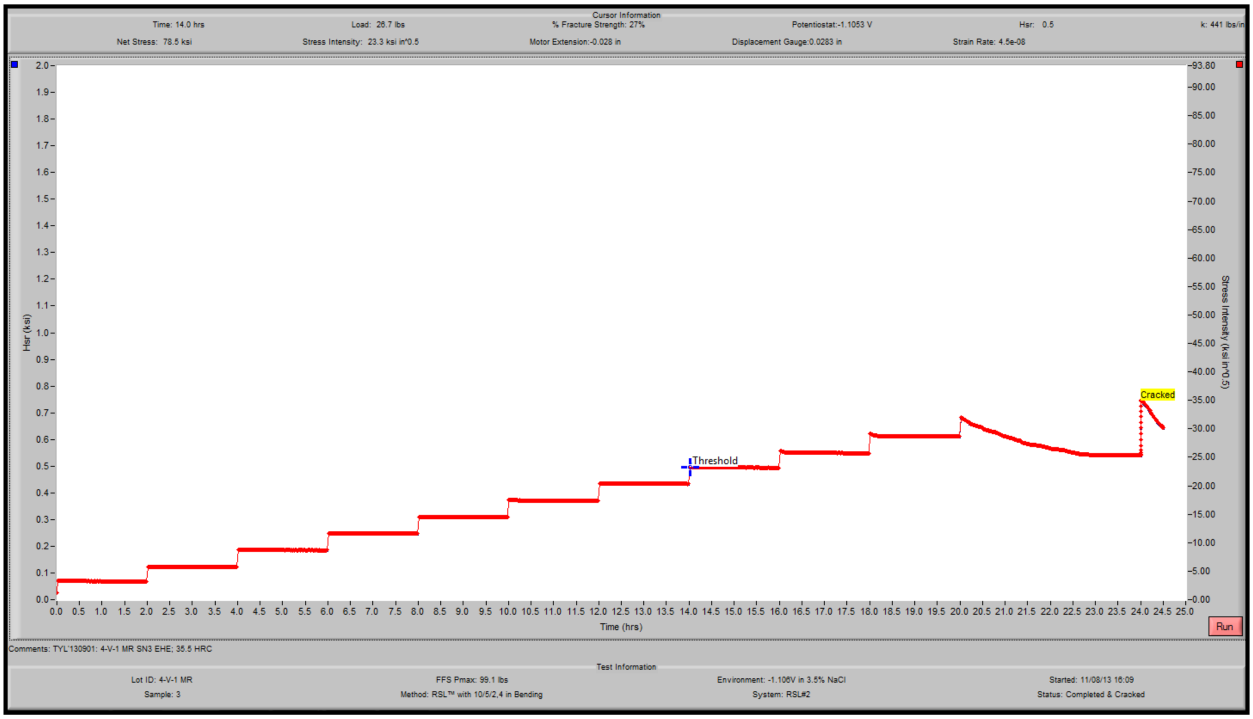


Figure B.5-6: Rod 4-V-1 MR 3, Graphical EHE Results

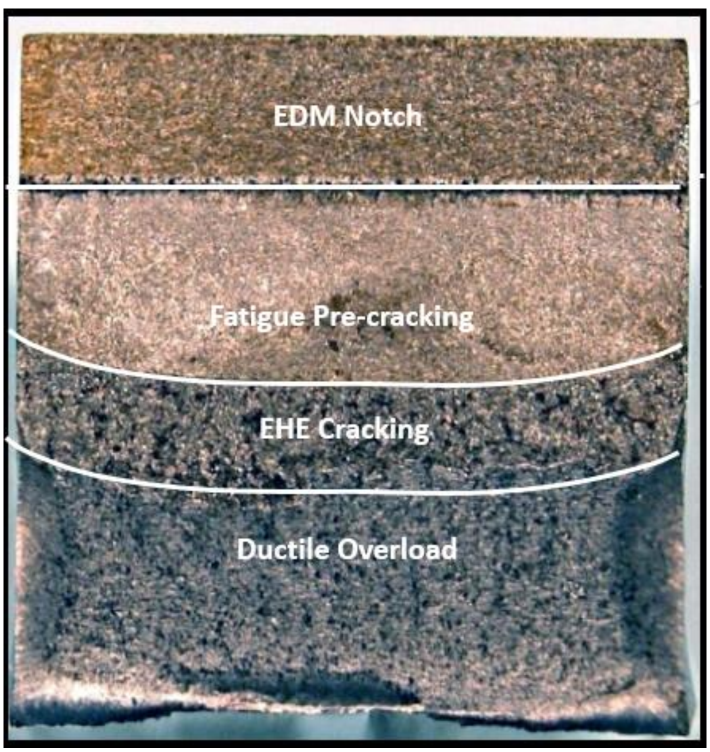
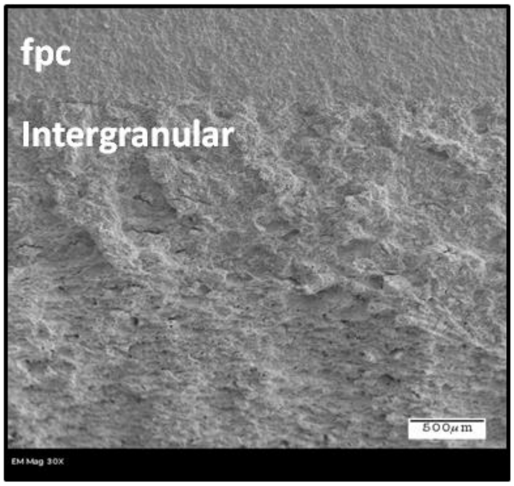
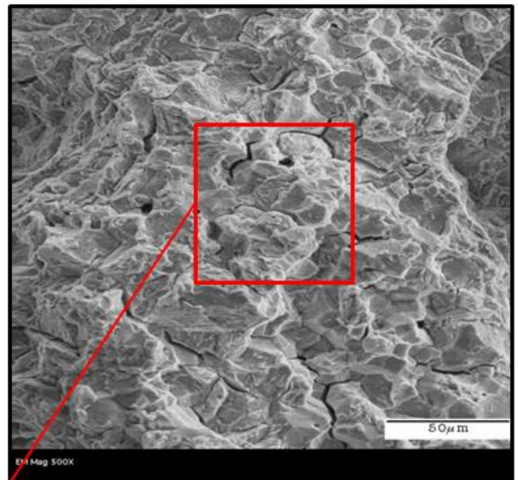


Figure B.5-7: Fracture Face of Rod 4-V-1 MR 3, EHE

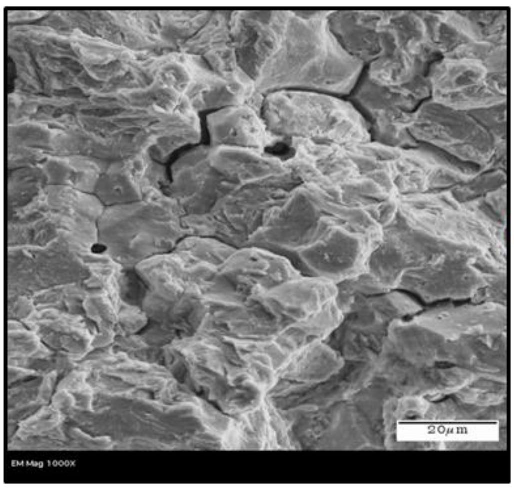
Figure B.5-8: SEM of Rod 4-V-1 MR 3, EHE



Macro 30X



Intergranular 500X



Intergranular 1000X

B.5.4 MR 4, EHE:

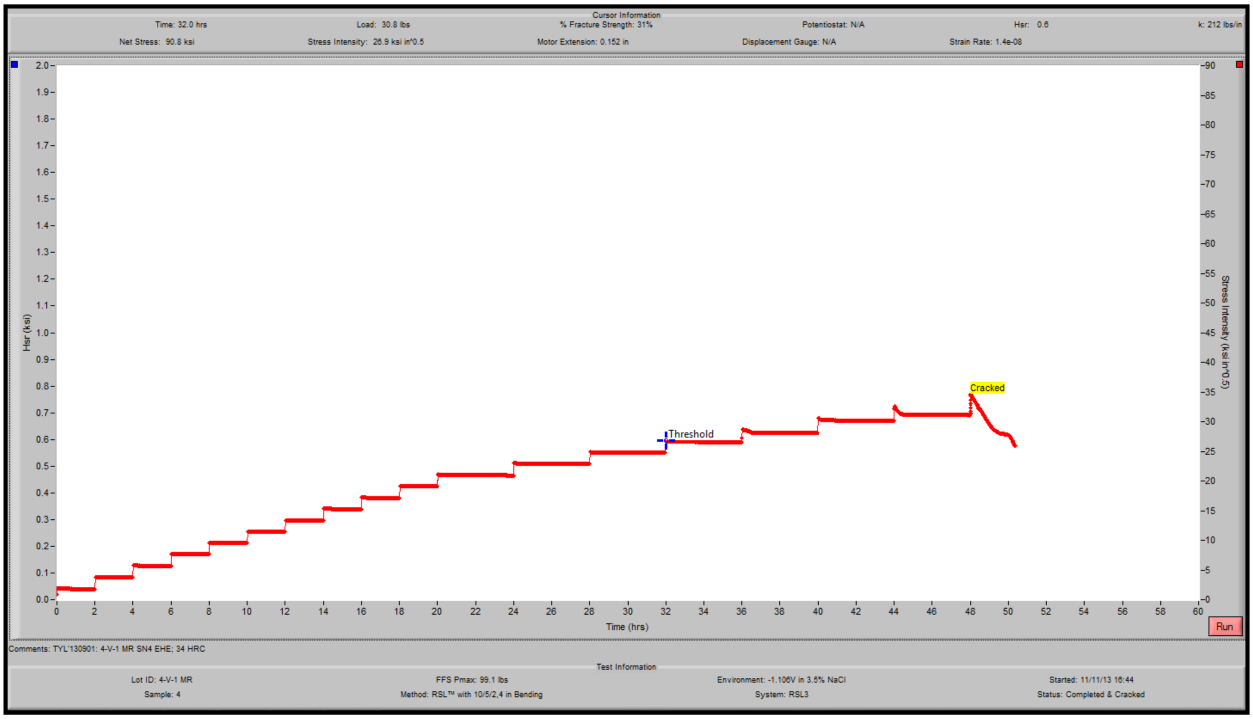


Figure B.5-9: Rod 4-V-1 MR 4, Graphical EHE Results

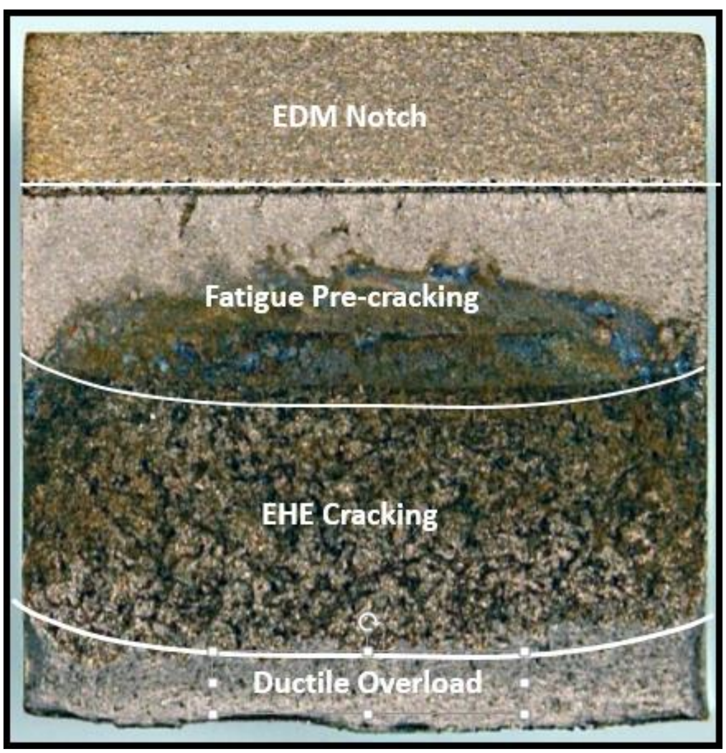
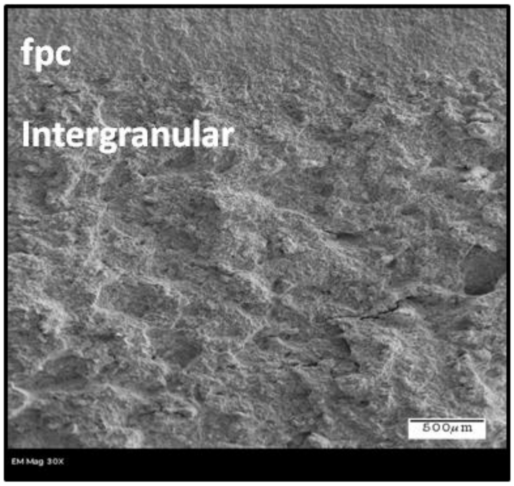
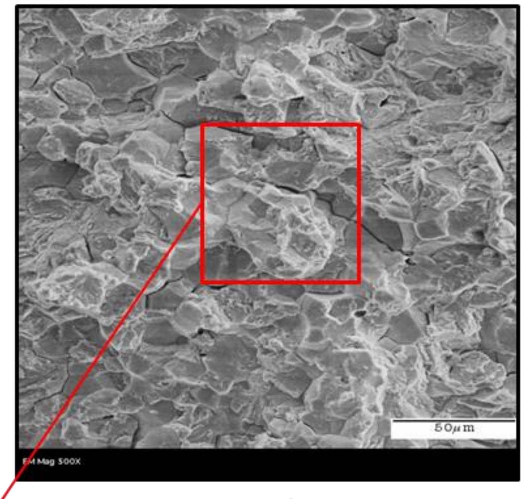


Figure B.5-10: Fracture Face of Rod 4-V-1 MR 4, EHE

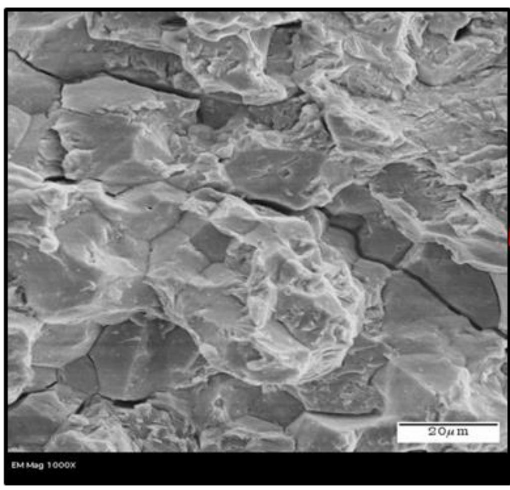
Figure B.5-11: SEM of Rod 4-V-1 MR 4, EHE



Macro 30X



Intergranular 500X



Intergranular 1000X

B.5.5 Center 1, FFS:

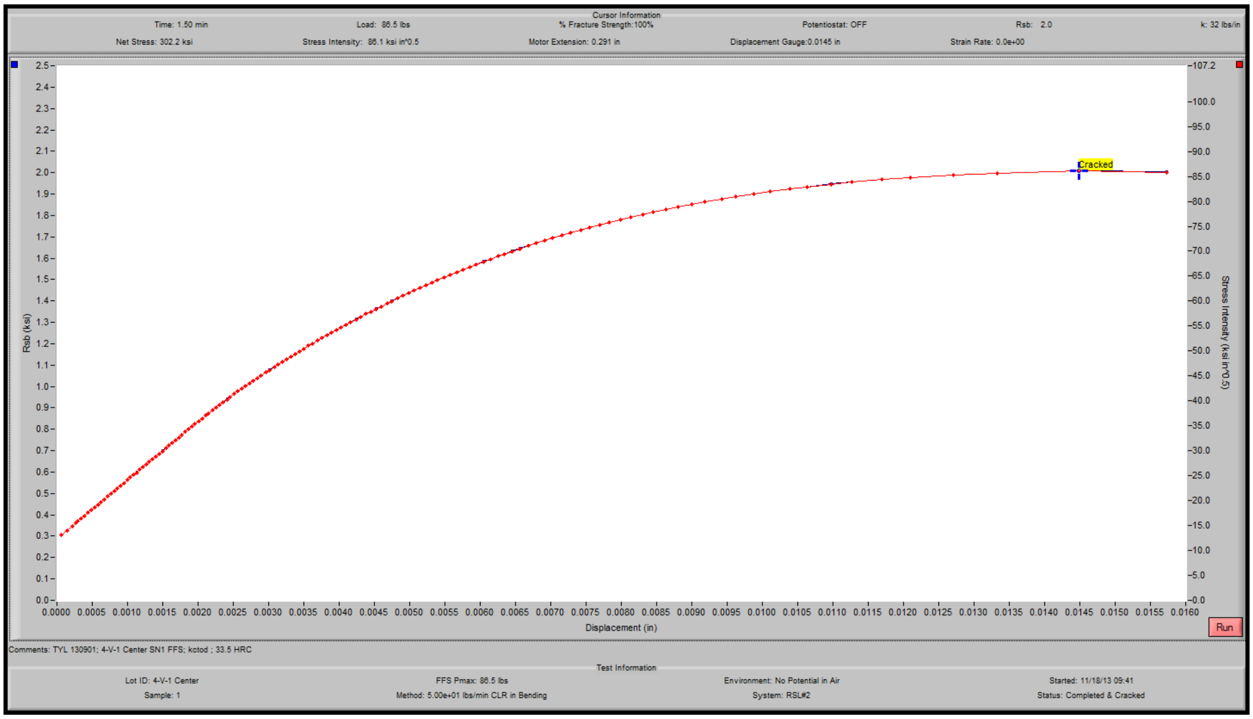


Figure B.5-12: Rod 4-V-1 Center 1, Graphical FFS Results

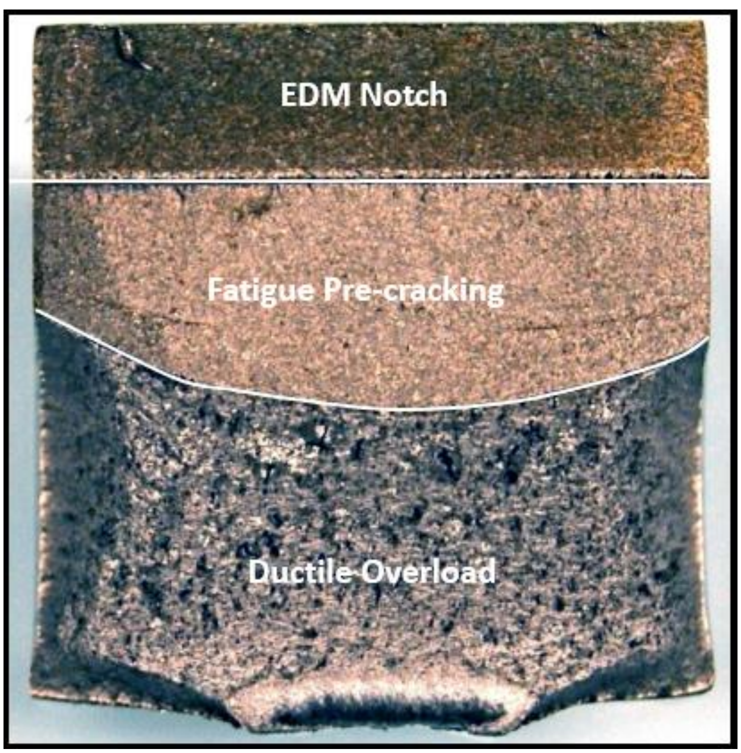


Figure B.5-13: Fracture Face of Rod 4-V-1 Center 1, FFS

B.6 Threaded Specimen Test Results

B.6.1 Thd 7, FFS:

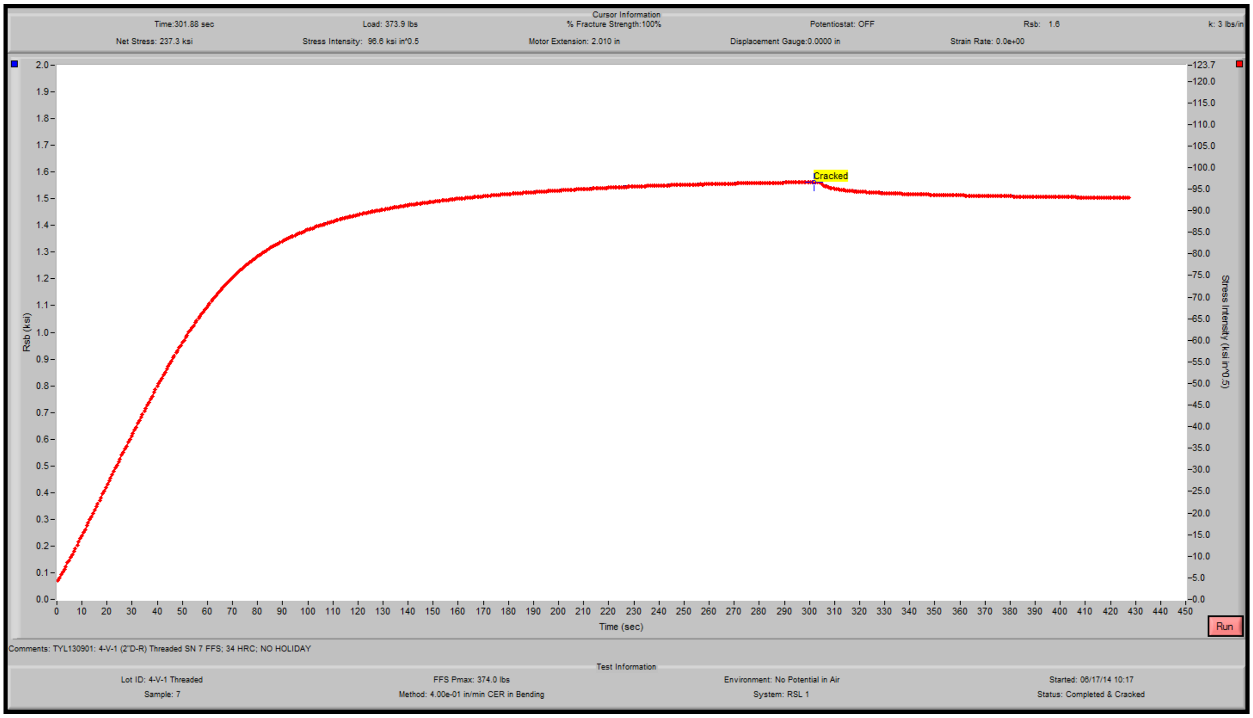


Figure B.6-1: Rod 4-V-1 Thd 7, Graphical FFS Results

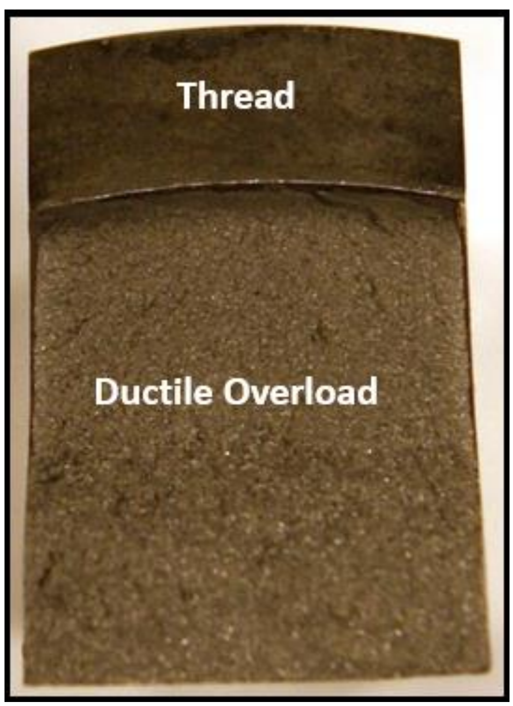


Figure B.6-2: Rod 4-V-1 Thd 7, FFS Fracture Face

B.6.2 Thd 2, IHE:

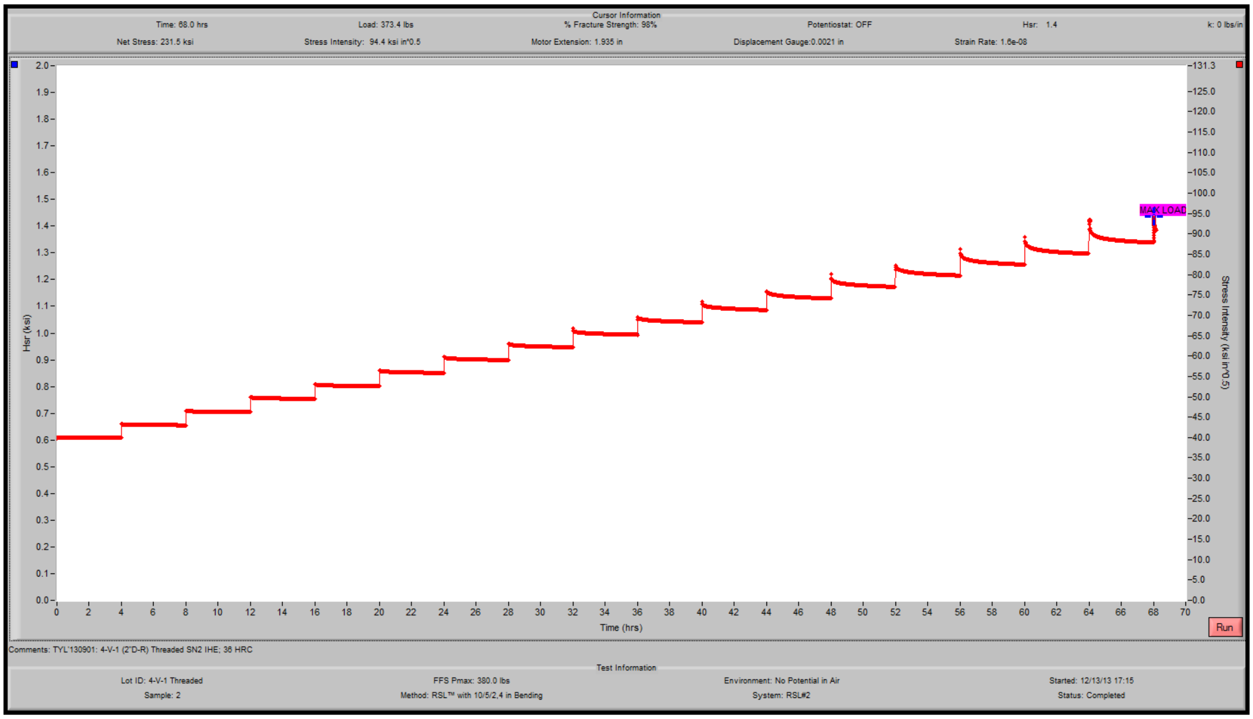


Figure B.6-3: Rod 4-V-1 Thd 2, Graphical IHE Results

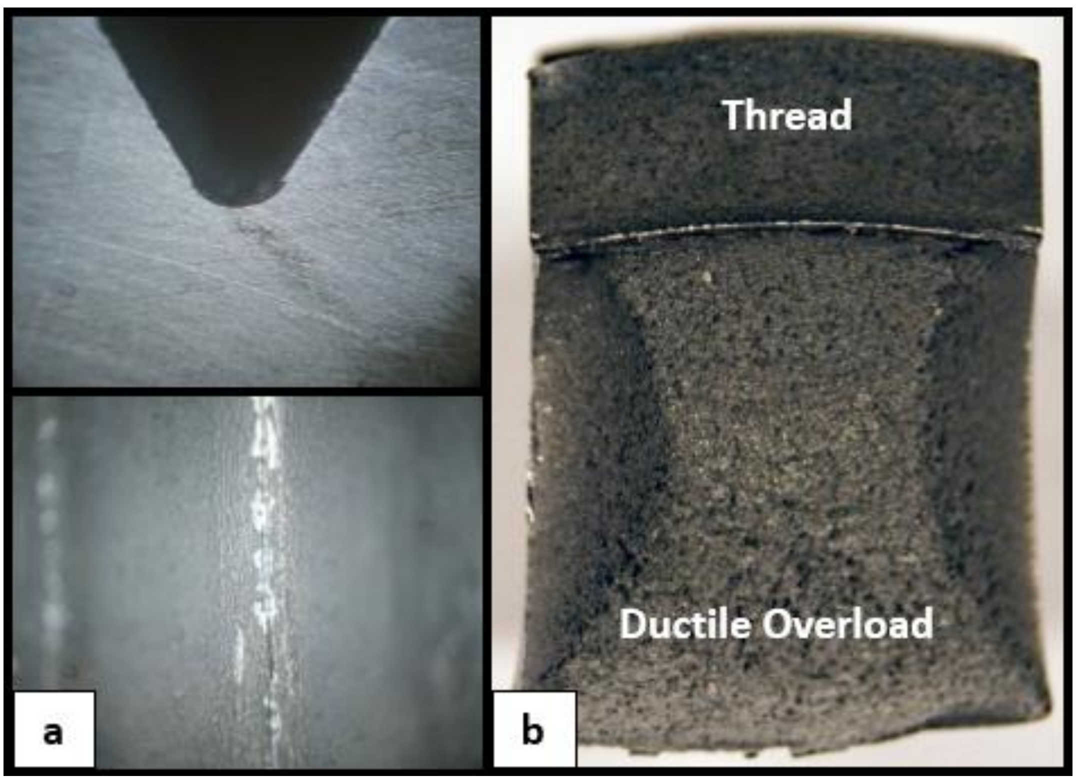


Figure B.6-4: Rod 4-V-1 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

B.6.3 Thd 4, EHE:

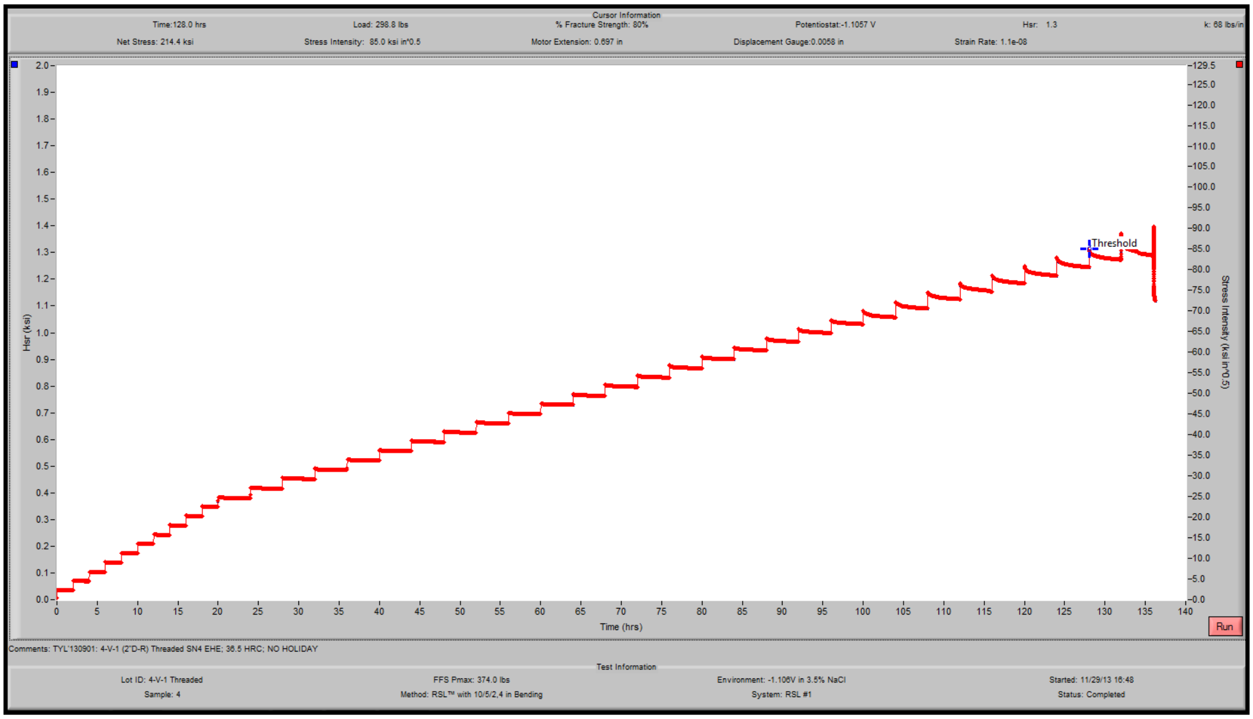


Figure B.6-5: Rod 4-V-1 Thd 4, Graphical EHE Results

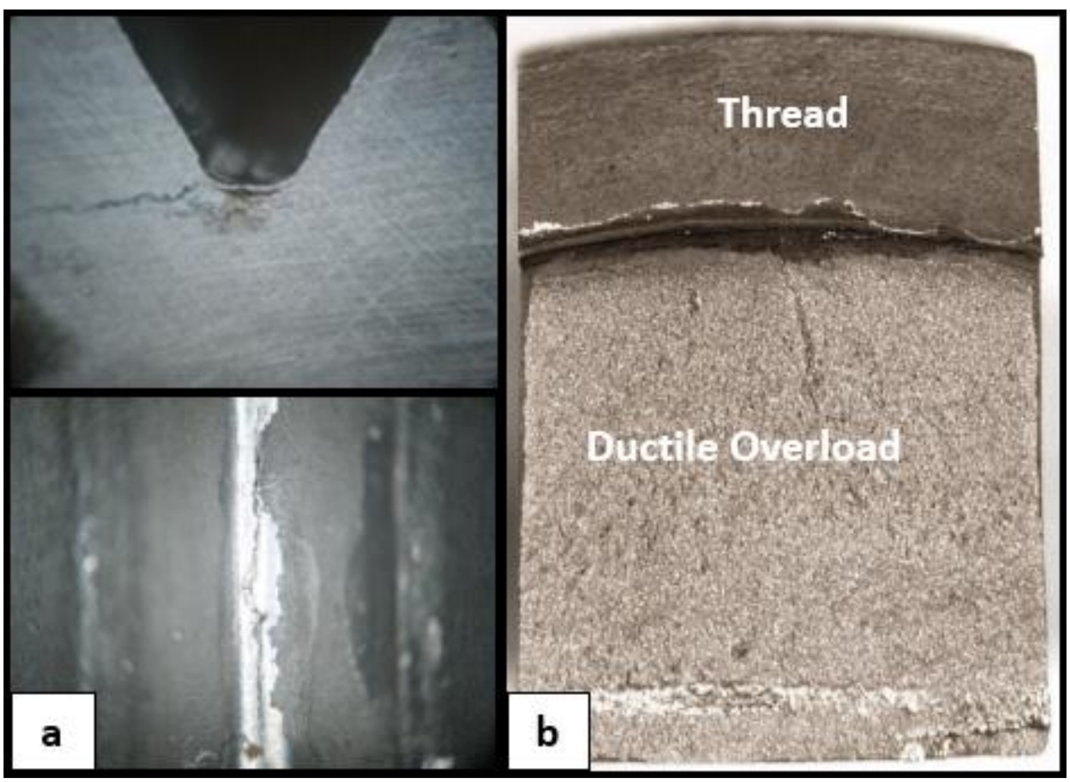
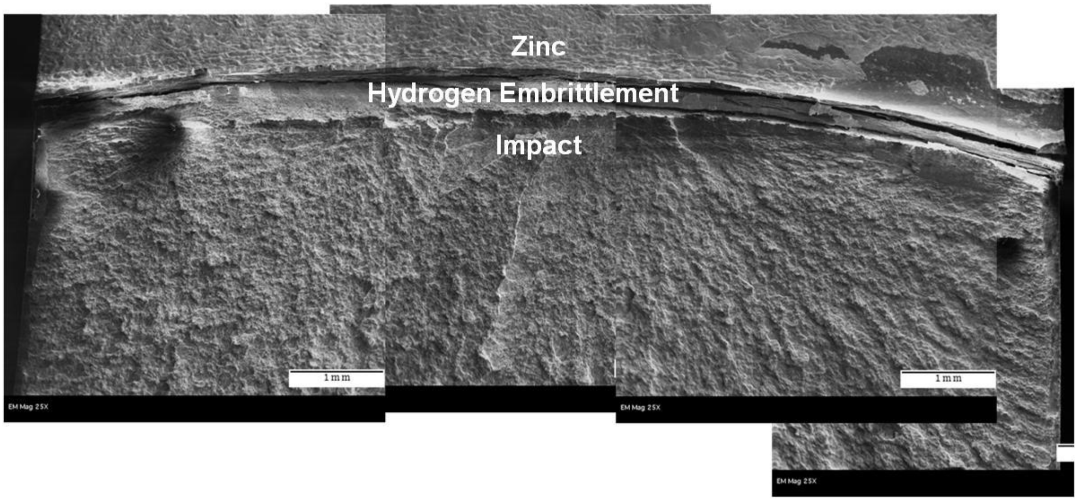
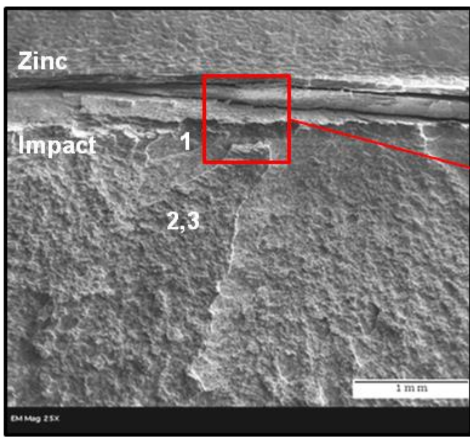


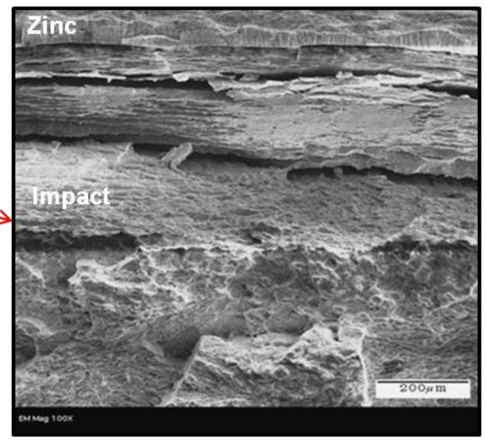
Figure B.6-6: Rod 4-V-1 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure B.6-7: SEM of Rod 4-V-1 Thd 4, EHE

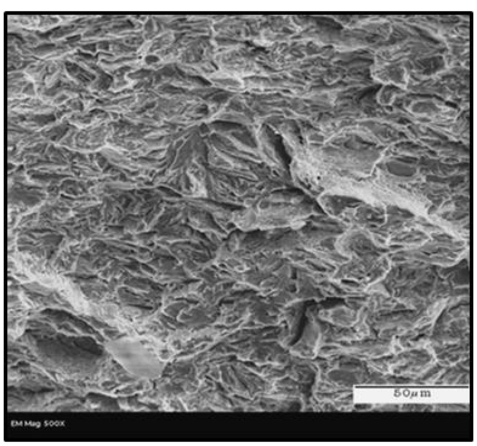




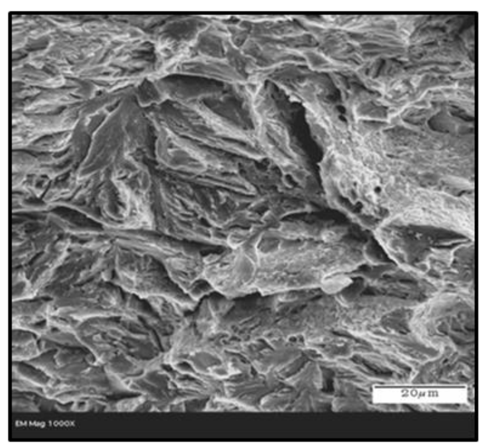
Thread Root 25X



1) Ductile Overload 100X



2) Impact, Brittle Cleavage
500X



3) Impact, Brittle Cleavage
1000X

B.6.4 Thd 6, EHE:

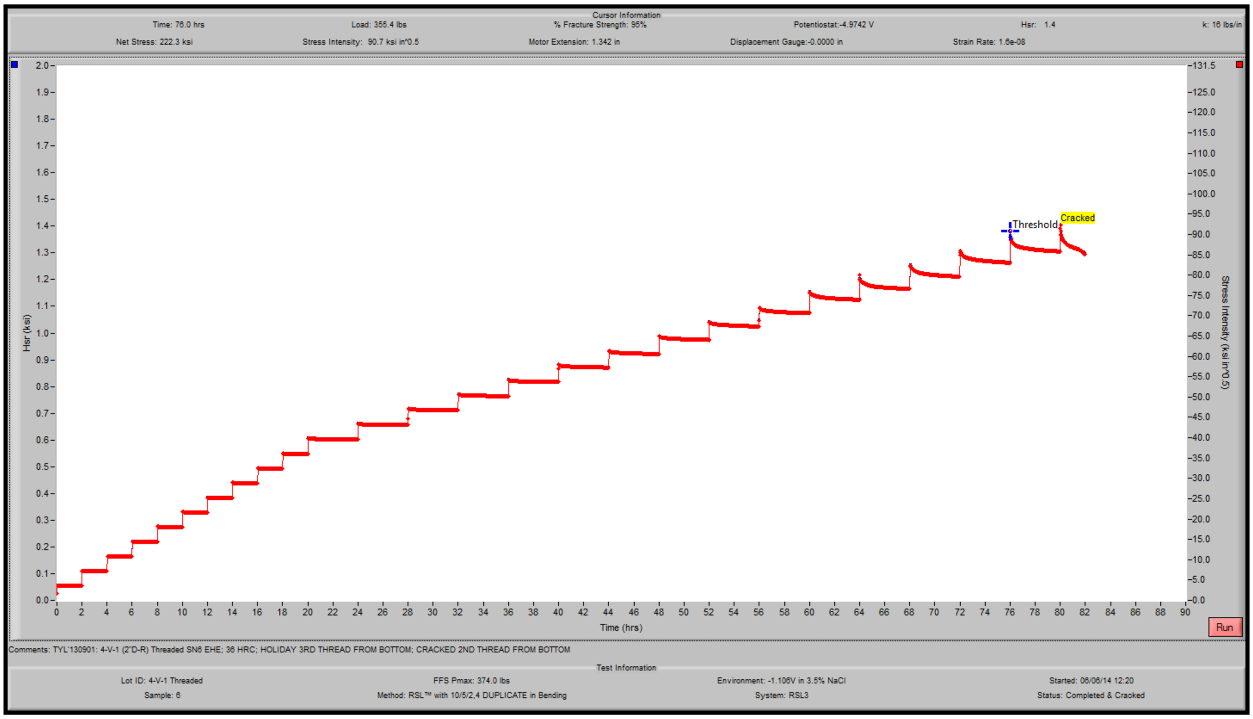


Figure B.6-8: Rod 4-V-1 Thd 6, Graphical EHE Results

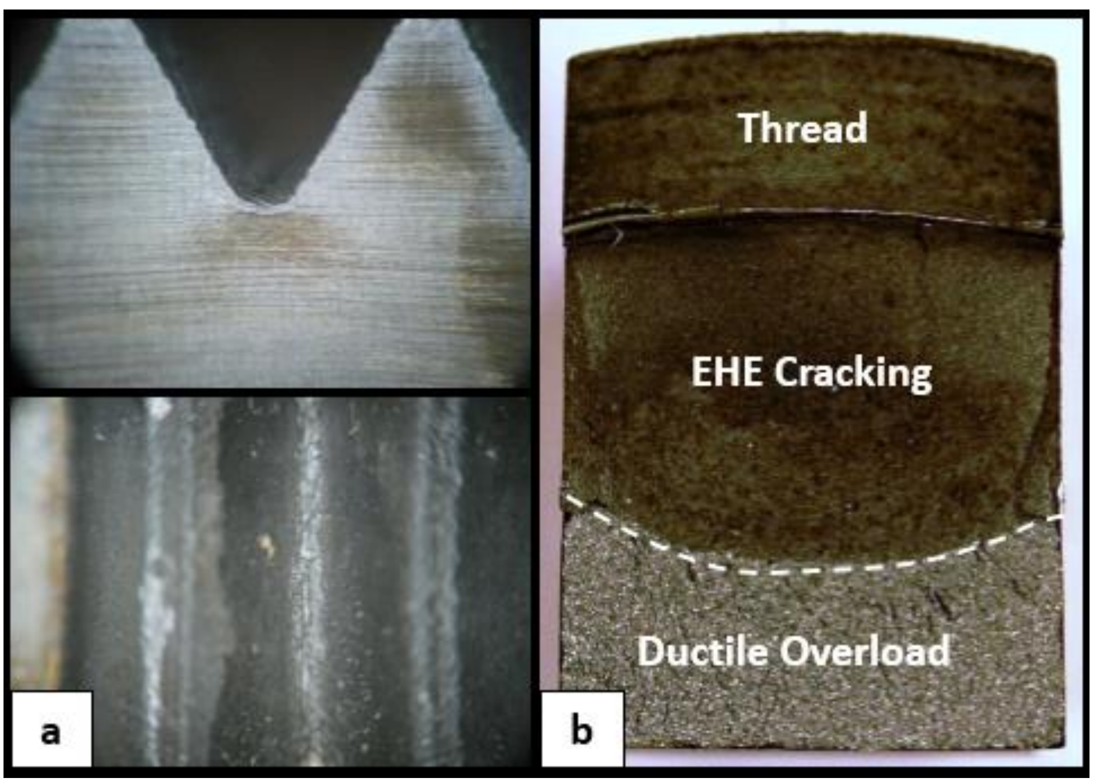


Figure B.6-9: Rod 4-V-1 Thd 6 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

B.6.5 Thd 8, EHE:

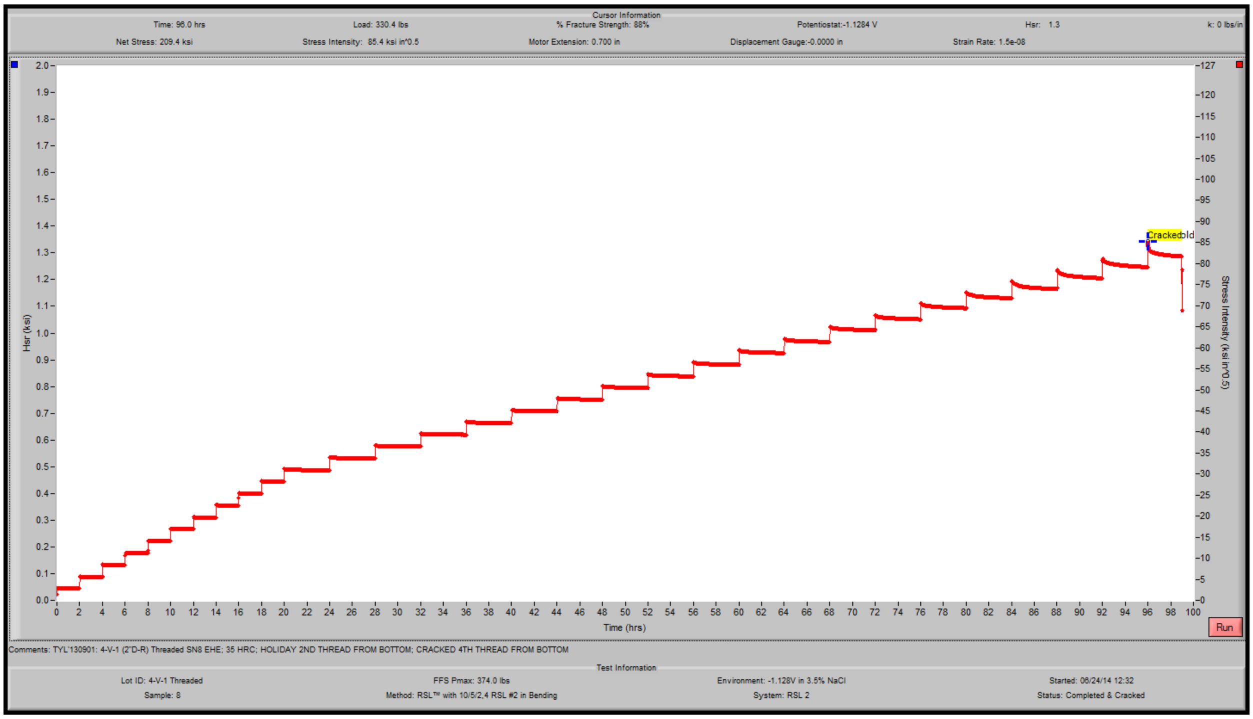


Figure B.6-10: Rod 4-V-1 Thd 8, Graphical EHE Results

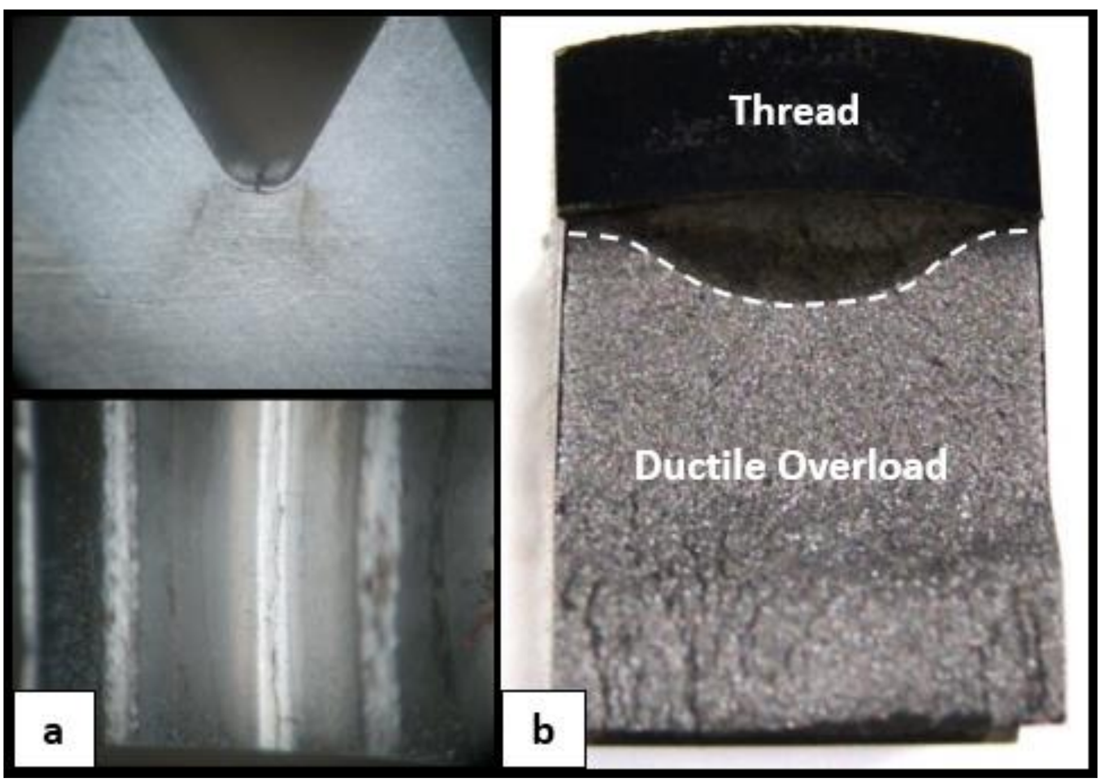


Figure B.6-11**: Rod 4-V-1 Thd 8 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face**

Appendix C: Rod 4-V-2

C.1 Description of Sample

Rod 4-V-2 was a Pier E2 Bearing Bolt (Top Housing: B1, B2, B3, B4) from the same heat of material that was tested in Test Rig 5 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 2 inches in diameter with rolled threads. The segment from this section of the rod provided to LRA is shown in **Figure C.1-1**.

Figure C.1-1: Pier E2 Bearing Bolt (Top Housing), Rod 4-V-2

C.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 4-V-2 can be seen in **Figure C.2-1** where the black portion of the Shadowgraph represents the rod material. As can be seen from **Figure C.2-1**, these rolled thread roots show uniformity around the root radius.

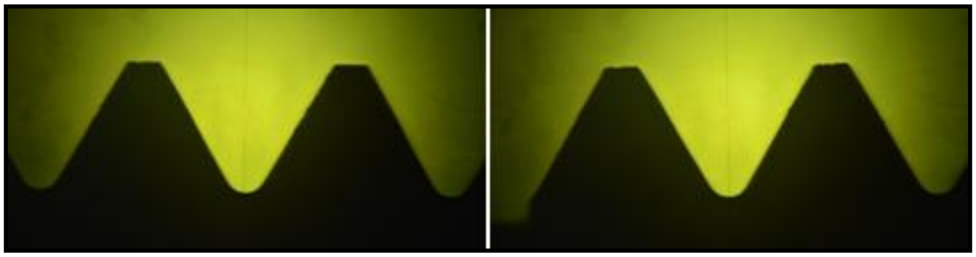


Figure C.2-1: Thread Comparison of Two Threads of Rod 4-V-2

C.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 4-V-1 and can be seen versus time in **Figure C.3-1**. The final OCP recorded for Rod 4-V-2 was Vsce=-0.827 V.

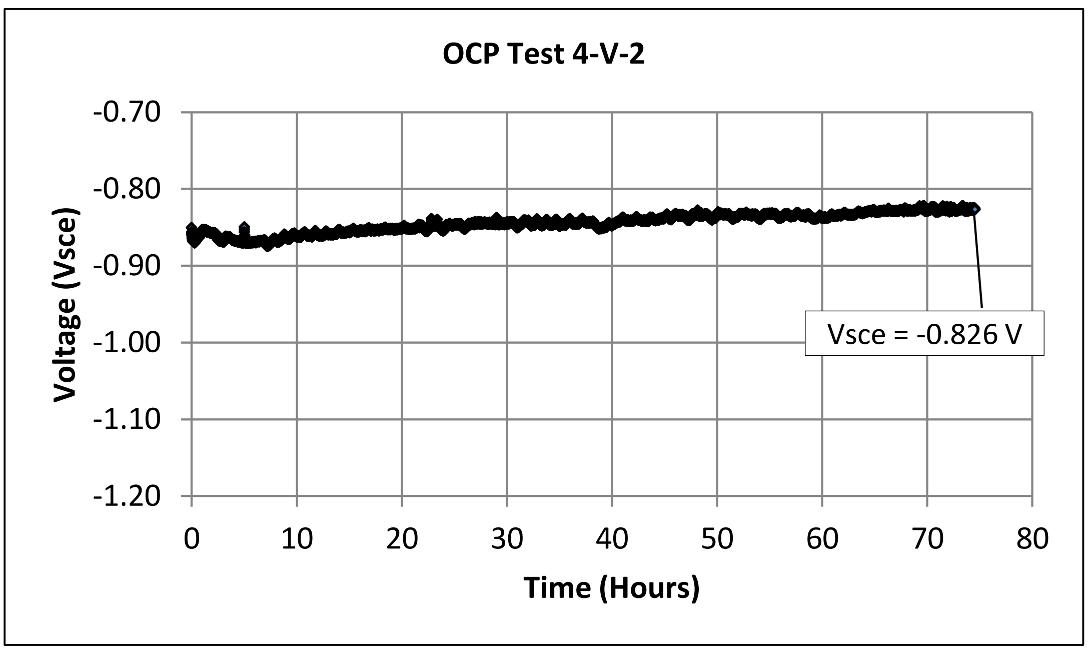


Figure C.3-1: Open Circuit Potential for Rod 4-V-2

C.4 Hardness

The hardness data and profile for sample 4-V-2 are shown in **Table C.4-1** and **Figure C.4-1**.

Table C.4-1: Hardness Data of Rod 4-V-2 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	33.5	33.5
MR 1, FFS	36.0	35.1
MR 2, IHE	35.0	
MR 3, EHE	35.5	
MR 4, EHE	34.0	
Thd 7, FFS	36.0	35.9
Thd 2, IHE	36.0	
Thd 4, EHE	36.5	
Thd 6, EHE	36.0	
Thd 8, EHE	35.0	

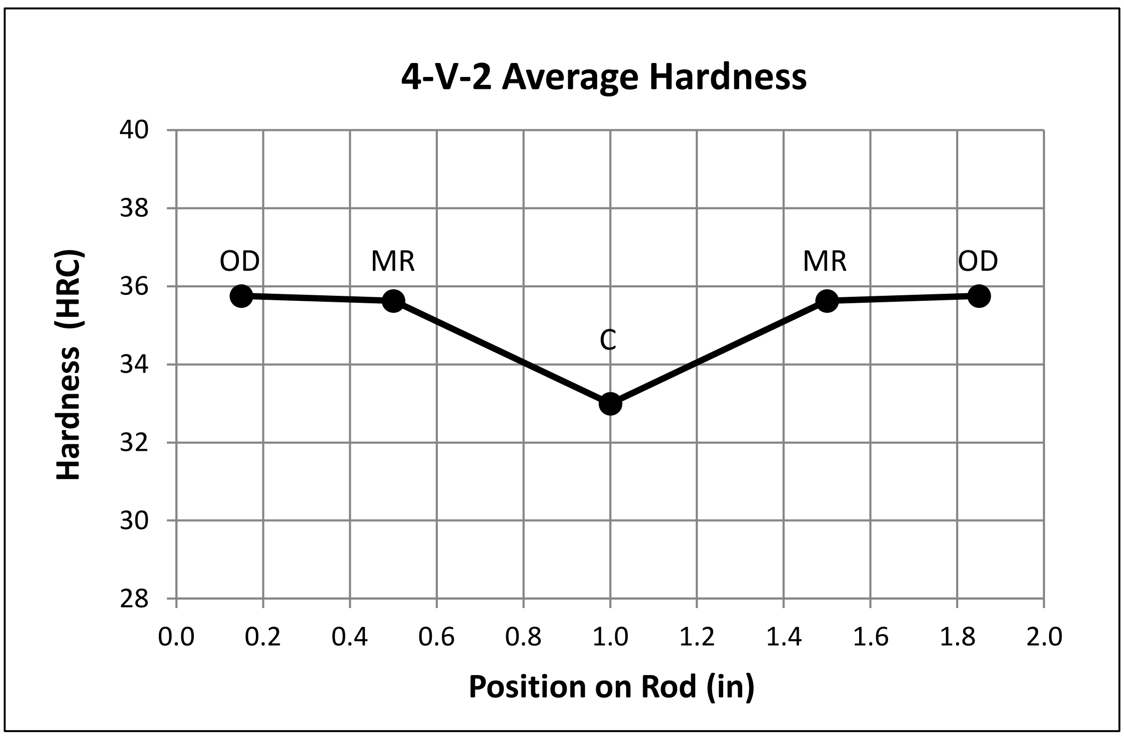


Figure C.4-1: Hardness Profile of Rod 4-V-2

C.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

C.5.1 Fatigue Pre-crack Results:

<table>
<tr><td colspan="7">Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 4-V-2</td></tr>
<tr><td>LRA Job No.:</td><td>TYL130523</td><td colspan="5" rowspan="2">Structural Components: Pier E2 Bearing Bolts-Top Housing (B1, B2, B3, B4)</td></tr>
<tr><td>Rod#:</td><td>4-V-2</td></tr>
<tr><td>Product Form:</td><td>1e</td><td colspan="5" rowspan="2">Comments: Rolled Threads; Same Heat as Test Rig #5 in Test IV</td></tr>
<tr><td>Rod OD:</td><td>2"</td></tr>
<tr><td></td><td>Sample #/ID</td><td>HRC</td><td></td><td>K-FFS</td><td>K-IHE</td><td>K-EHE</td></tr>
<tr><td rowspan="5">Fatigue Pre-cracked</td><td>MR 1, FFS</td><td>35.5</td><td>K_{max}
DTI_{th}
Fu
Strain Rate (x10^{-8} in/in/sec)</td><td>84.3
0.53
0.99
8700</td><td></td><td></td></tr>
<tr><td>MR 3, IHE</td><td>35.5</td><td>$K_{threshold}$
DTI_{th}
Fu
Strain Rate (x10^{-8} in/in/sec)</td><td></td><td>95.9
0.60
1.12
3.0</td><td></td></tr>
<tr><td>MR 2, EHE</td><td>35.5</td><td>$K_{threshold}$
DTI_{th}
Fu
Strain Rate (x10^{-8} in/in/sec)</td><td></td><td></td><td>30.7
0.19
0.36
1.5</td></tr>
<tr><td>MR 4, EHE</td><td>36.0</td><td>$K_{threshold}$
DTI_{th}
Fu
Strain Rate (x10^{-8} in/in/sec)</td><td></td><td></td><td>27.5
0.17
0.32
1.4</td></tr>
<tr><td>Center 1, FFS</td><td>33.0</td><td>K_{max}
DTI_{th}
Fu
Strain Rate (x10^{-8} in/in/sec)</td><td>83.2
0.56
0.97
9700</td><td></td><td></td></tr>
</table>

C.5.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 4-V-2						
LRA Job No.:	**TYL130523**	**Structural Components**: Pier E2 Bearing Bolts-Top Housing (B1, B2, B3, B4)				
Rod#:	**4-V-2**					
Product Form:	**1e**	**Comments**: Rolled Threads; Same Heat as Test Rig #5 in Test IV				
Rod OD:	**2"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**36.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	336.4 1.15 1.5 4000		
	Thd 2, IHE	**35.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		334.0 1.14 1.5 1.7	
	Thd 4, EHE	**35.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			299.4 1.02 1.3 1.9
	Thd 5, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			290.1 0.99 1.3 0.9

C.5.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 4-V-2
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130523**
Rod #:	**4-V-2**
Product Form:	**1e**
Rod OD:	**2"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	MR 1, FFS	Air	35.5	159	90.6	90.6	90.6	100.0%	84.3	0.53	289.7	1.8	8700	0.2160	149.3	50 lbs/min		0.99	
	MR 2, EHE	3.5% NaCl @ -1.106V	35.5	159	59.7	41.9	32.8	36.4%	30.7	0.19	105.9	0.7	1.5	0.2177		10/5/2,4		0.36	
	MR 3, IHE	Air	35.5	159	2457.6	3196.4	3196.4	113.8%	95.9	0.60	333.2	2.1	3.0	0.2223		10/5/2,4		1.12	
	MR 4, EHE	3.5% NaCl @ -1.106V	36.0	162	36.0	34.2	28.8	32.6%	27.5	0.17	95.4	0.6	1.4	0.2188		10/5/2,4		0.32	
	Center 1, FFS	Air	33.0	149	80.6	80.6	80.6	100.0%	83.2	0.56	295.3	2.0	9700	0.2278	152.0	50 lbs/min		0.97	
Threaded	Thd 1, FFS	Air	36.0	162	373.5	373.5	373.5	100.0%	98.1	0.61	239.6	1.5	4000	N/A		150 lbs/min	336.4	1.15	
	Thd 2, IHE	Air	35.5	159	301.5	374.5	374.5	99.3%	97.4	0.61	239.4	1.5	1.7	N/A		10/5/2,4	334.0	1.14	
	Thd 4, EHE	3.5% NaCl @ -1.106V	35.5	159	280.0	351.4	341.9	89.0%	87.3	0.55	214.1	1.3	1.9	N/A		10/5/2,4	299.4	1.02	Did Not Crack In Holiday
	Thd 5, EHE	3.5% NaCl @ -1.106V	36.0	162	280.0	336.2	318.3	86.2%	84.6	0.52	208.9	1.3	0.9	N/A		10/5/1,8	290.1	0.99	Did Not Crack In Holiday

C.6 Fatigue Pre-cracked Specimen Test Results

C.6.1 NMR 1, FFS:

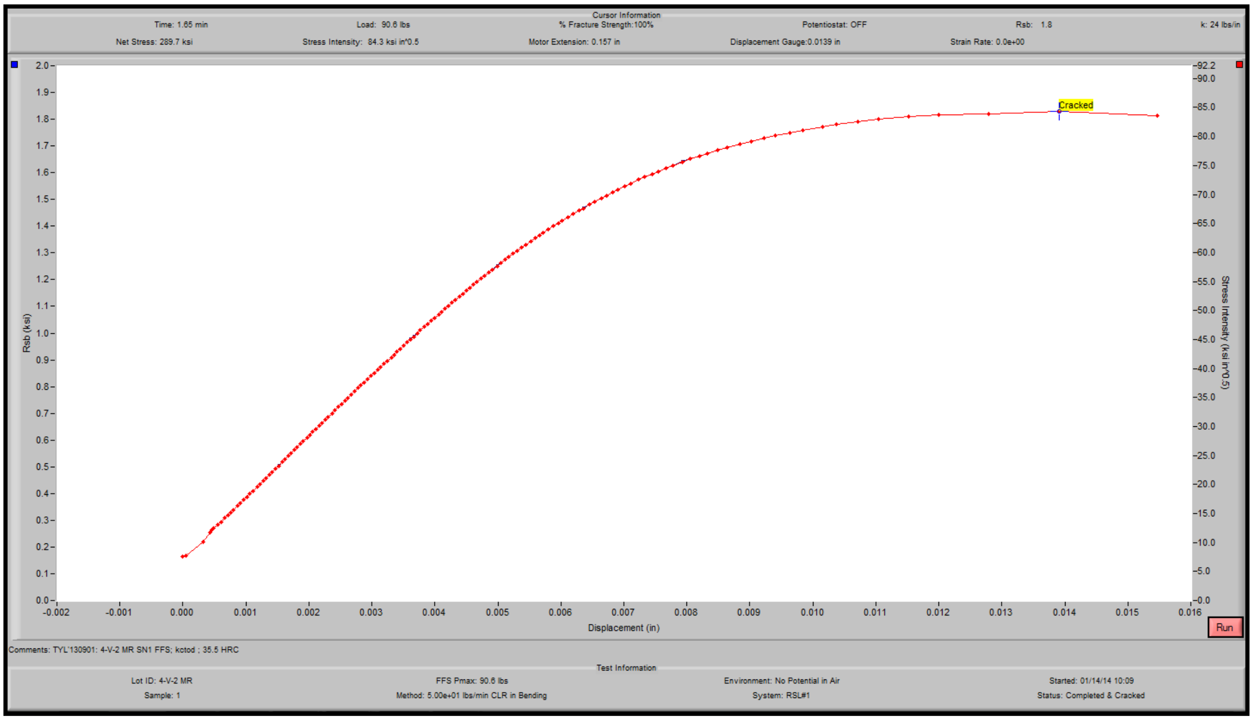


Figure C.6-1: Rod 4-V-2 MR 1, Graphical FFS Results

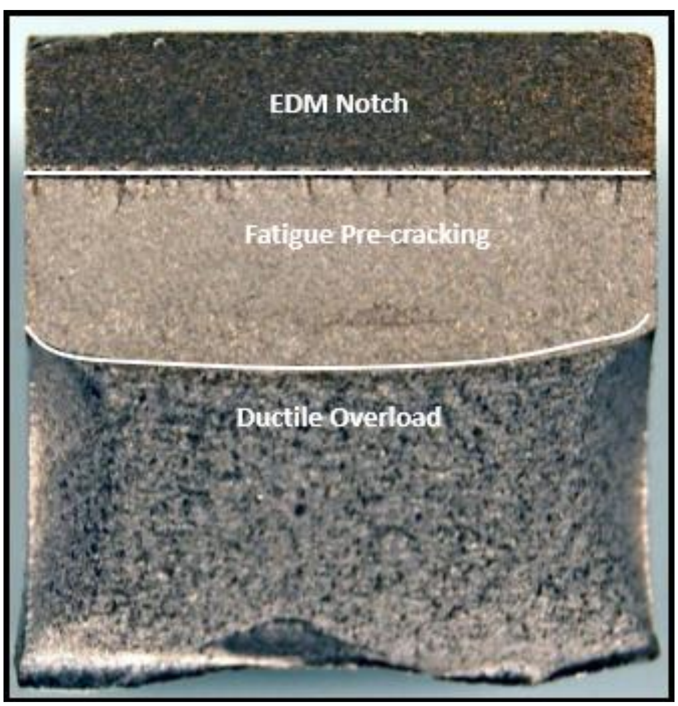


Figure C.6-2: Fracture Face of Rod 4-V-2 MR 1, FFS

C.6.2 MR 2, EHE:

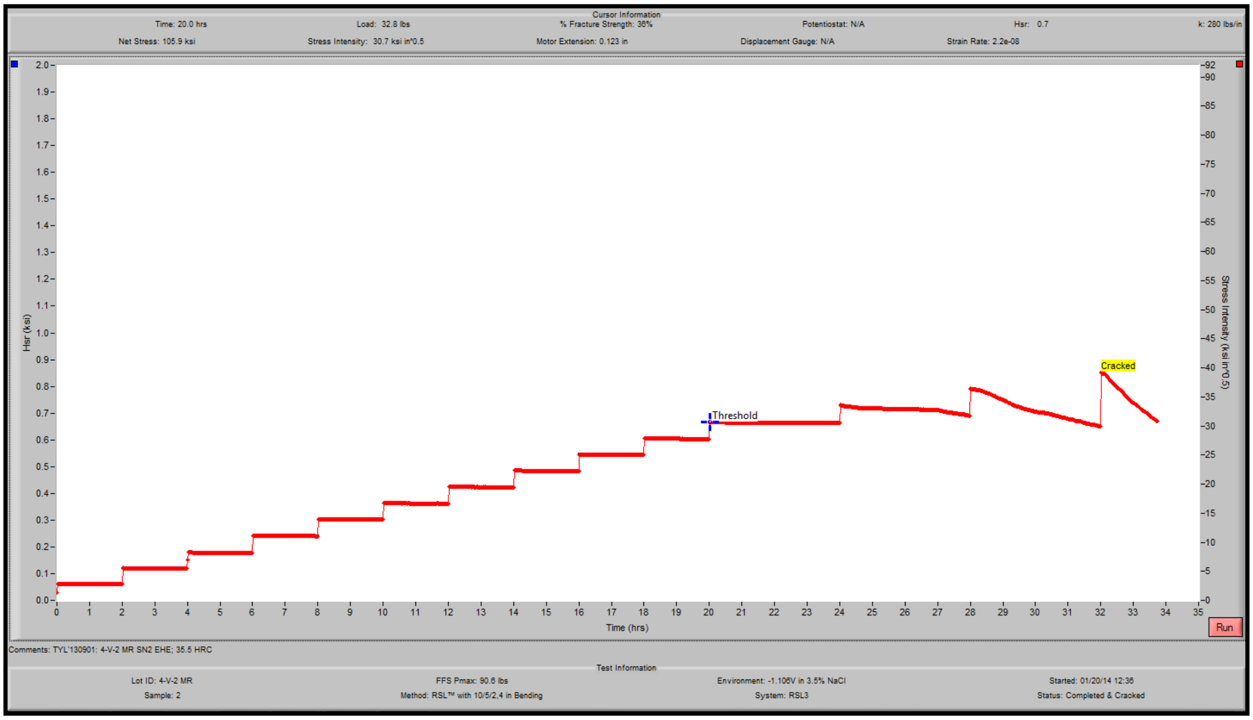
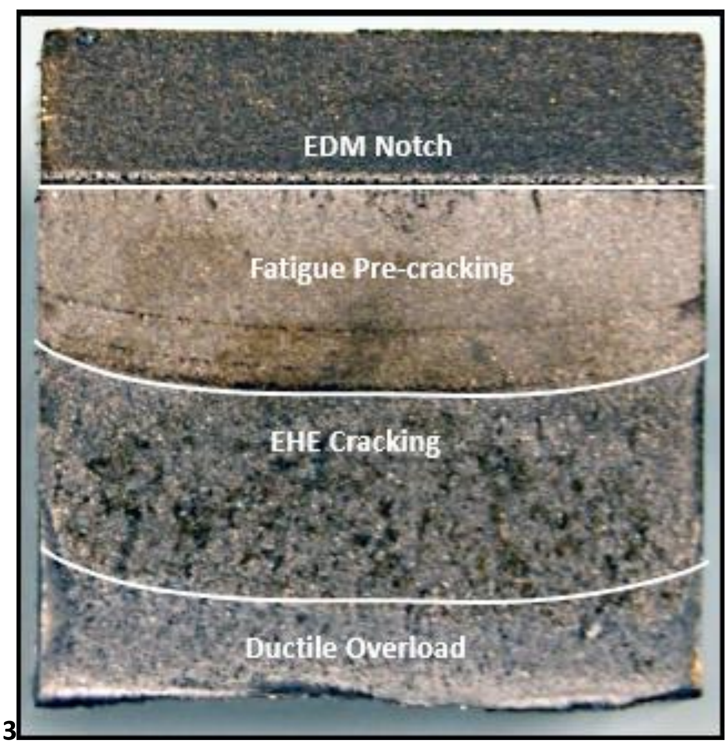


Figure C.6-3: Rod 4-V-2 MR 2, Graphical EHE Results



3

Figure C.6-4: Fracture Face of Rod 4-V-2 MR 2, EHE

C.6.3 MR 3, IHE:

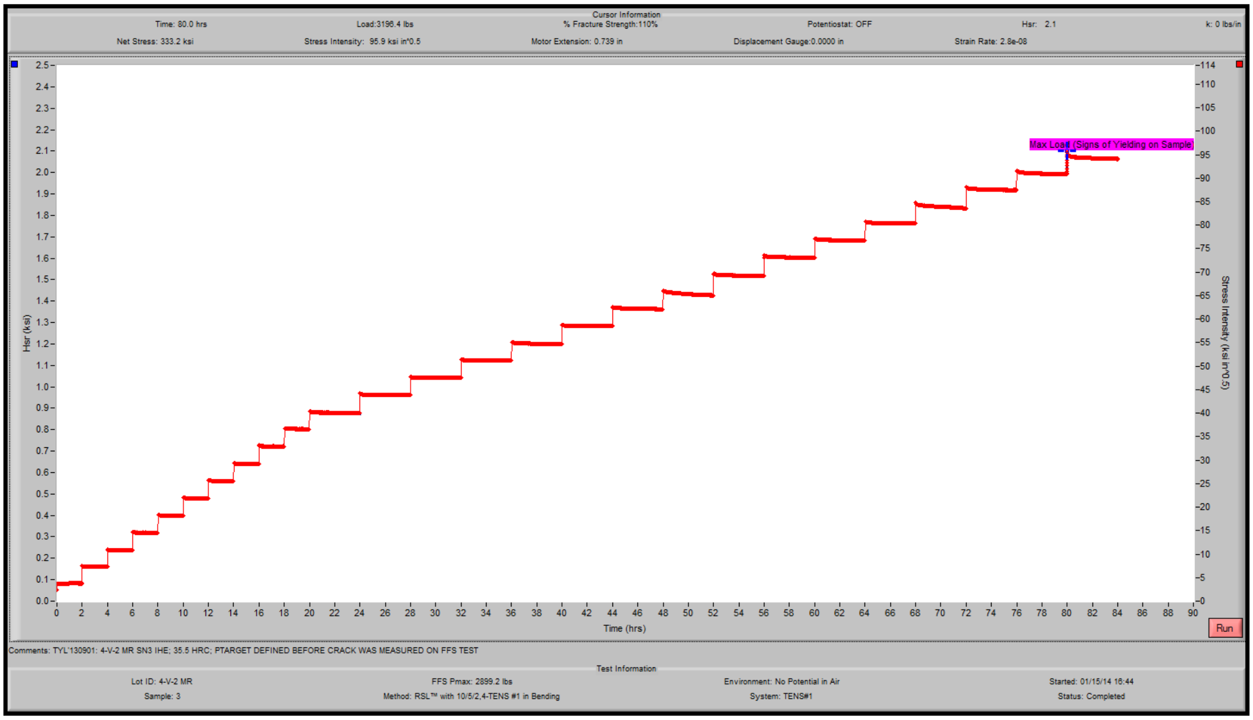


Figure C.6-5: Rod 4-V-2 MR 3, Graphical IHE Results

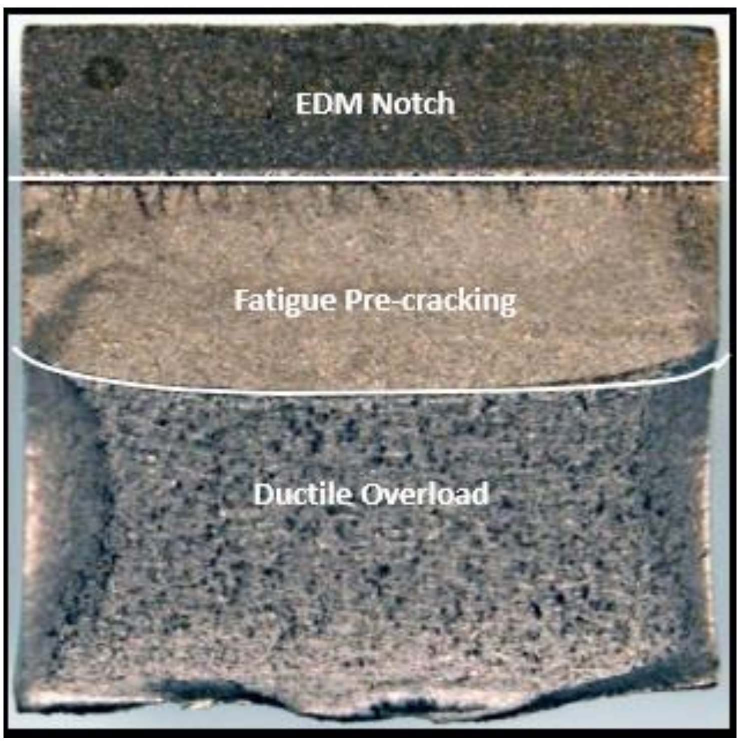


Figure C.6-6: Fracture Face of Rod 4-V-2 MR 3, IHE

C.6.4 MR 4, EHE:

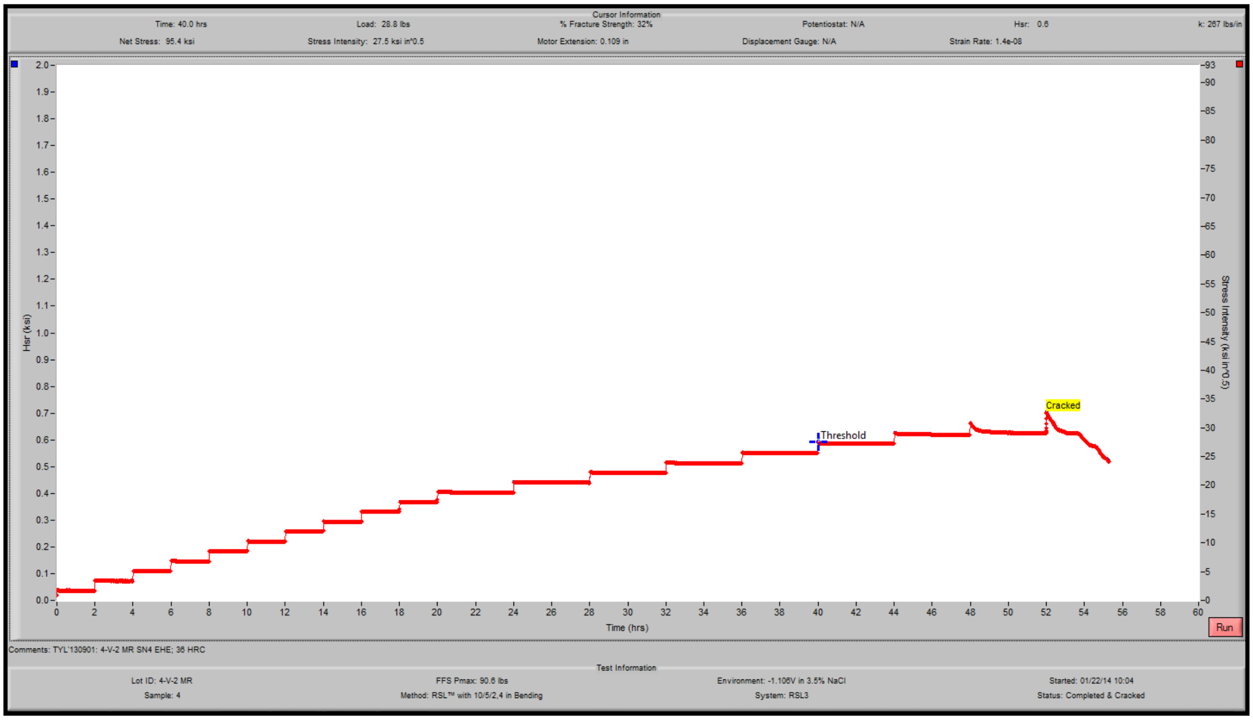


Figure C.6-7: Rod 4-V-2 MR 4, Graphical EHE Results

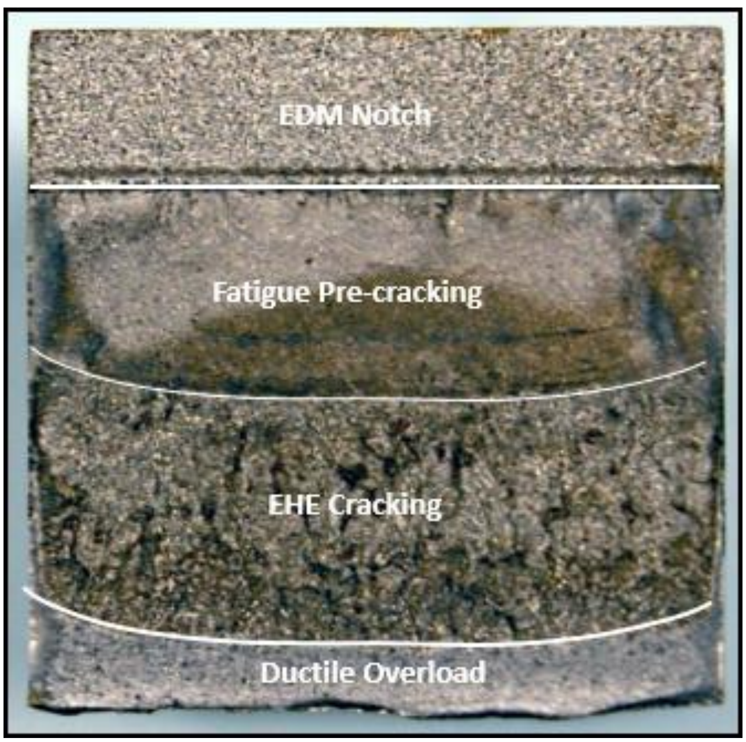


Figure C.6-8: Fracture Face of Rod 4-V-2 MR 4, EHE

C.6.5 Center 1, FFS:

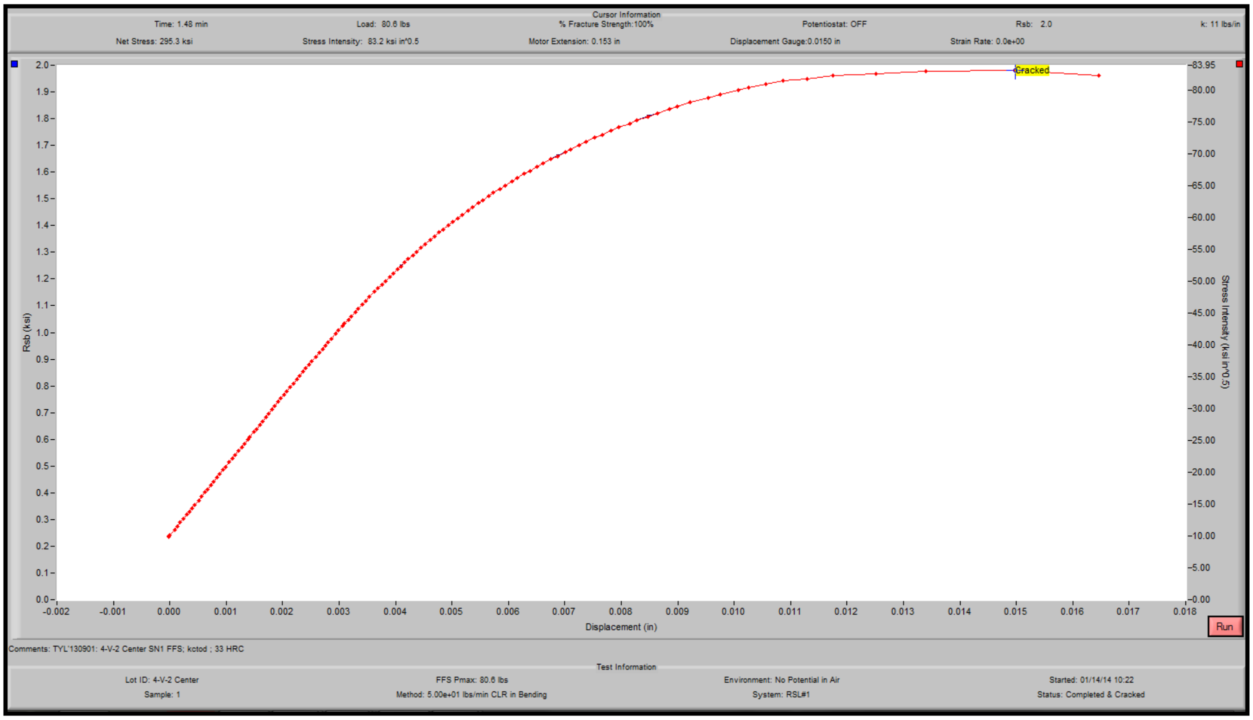


Figure C.6-9: Rod 4-V-2 Center 1, Graphical FFS Results

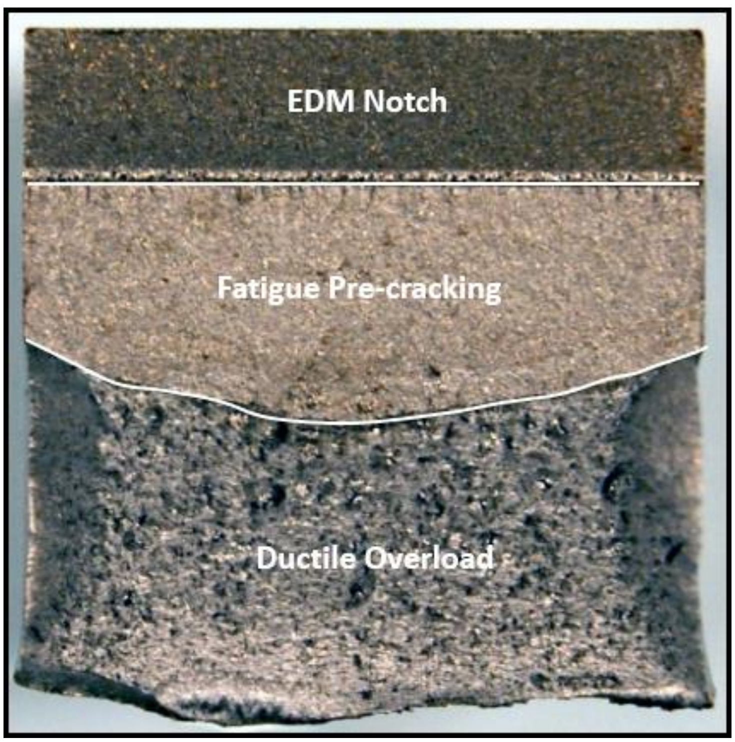


Figure C.6-10: Fracture Face of Rod 4-V-2 Center 1, FFS

C.7 Threaded Specimen Test Results

C.7.1 Thd 1, FFS:

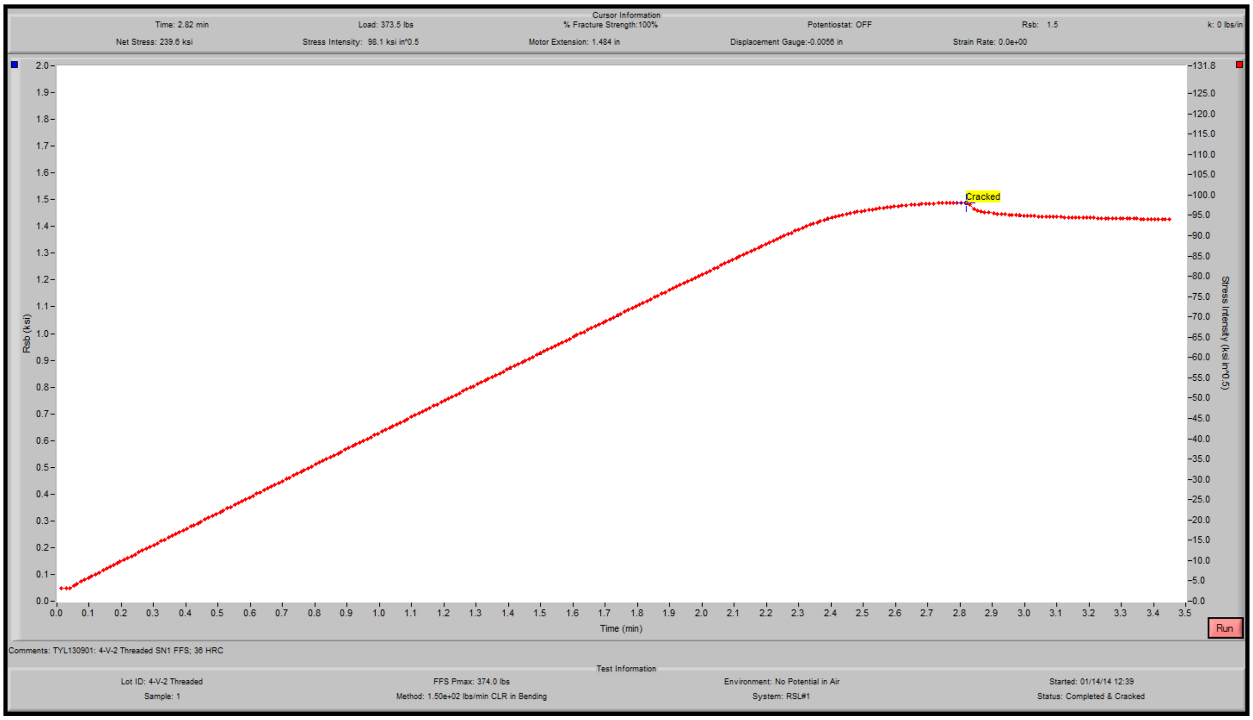
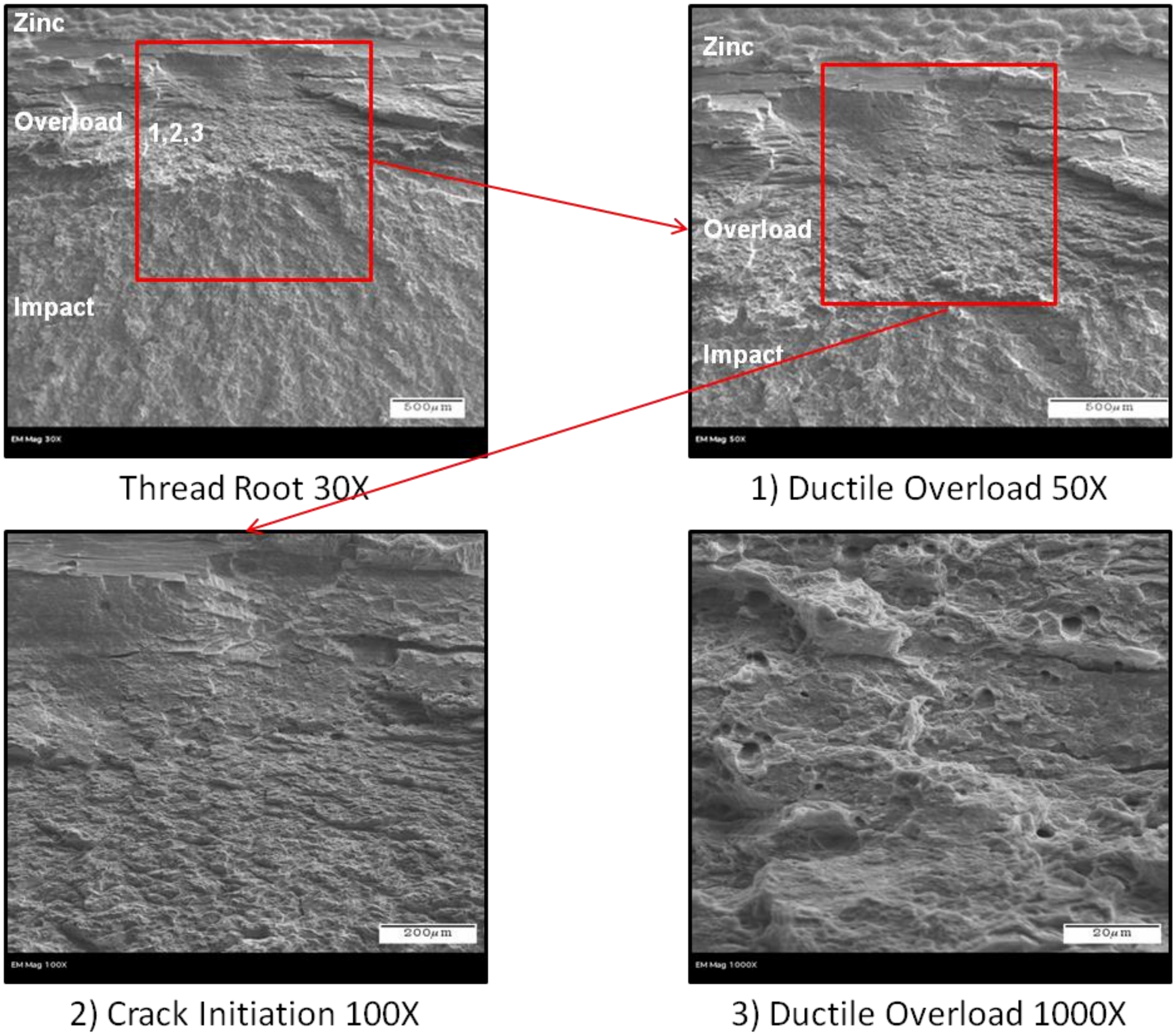


Figure C.7-1: Rod 4-V-2 Thd 1, Graphical FFS Results

Figure C.7-2: Rod 4-V-2 Thd 1 FFS Fracture Face

Figure C.7-3: SEM of Rod 4-V-2 Thd 1, FFS



C.7.2 Thd 2, IHE:

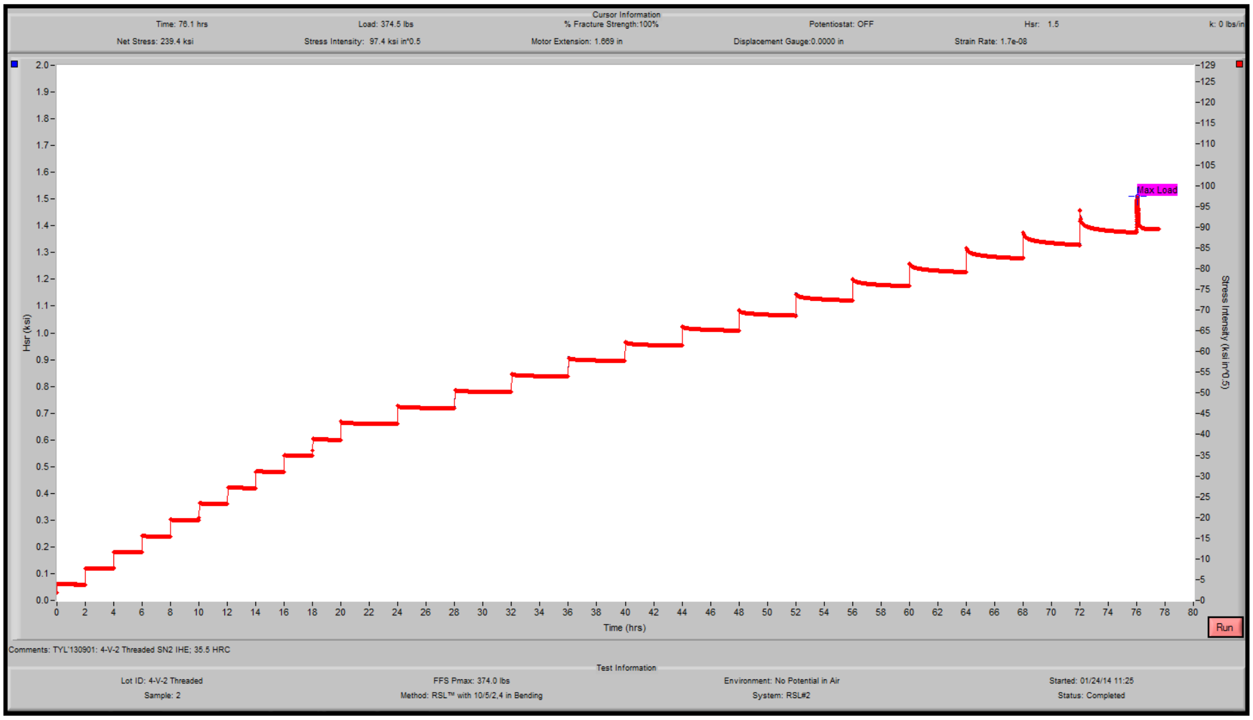


Figure C.7-4: Rod 4-V-2 Thd 2, Graphical IHE Results

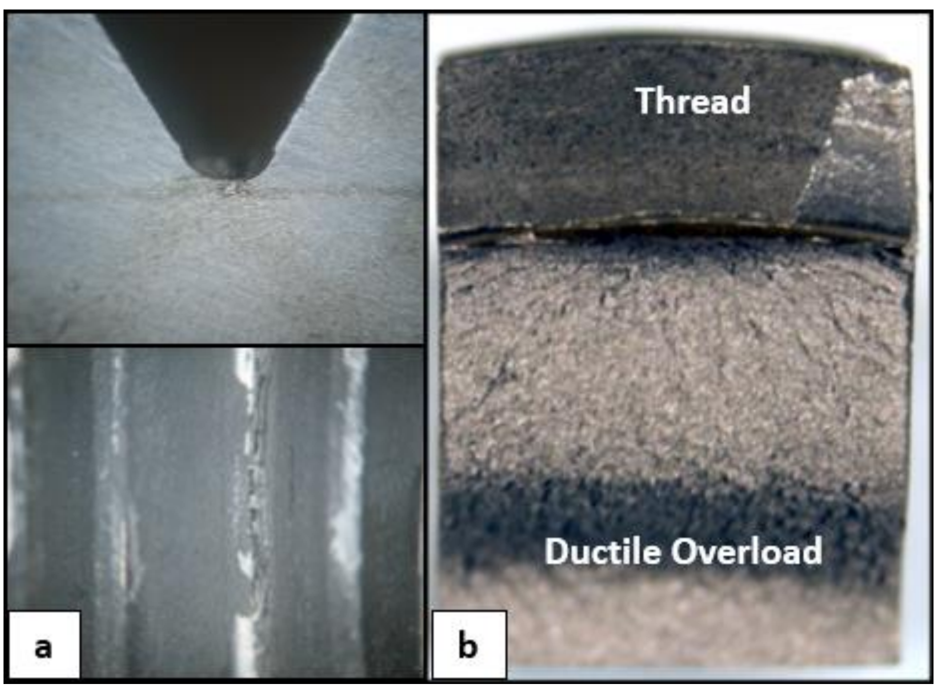


Figure C.7-5: Rod 4-V-2 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

C.7.3 Thd 4, EHE:

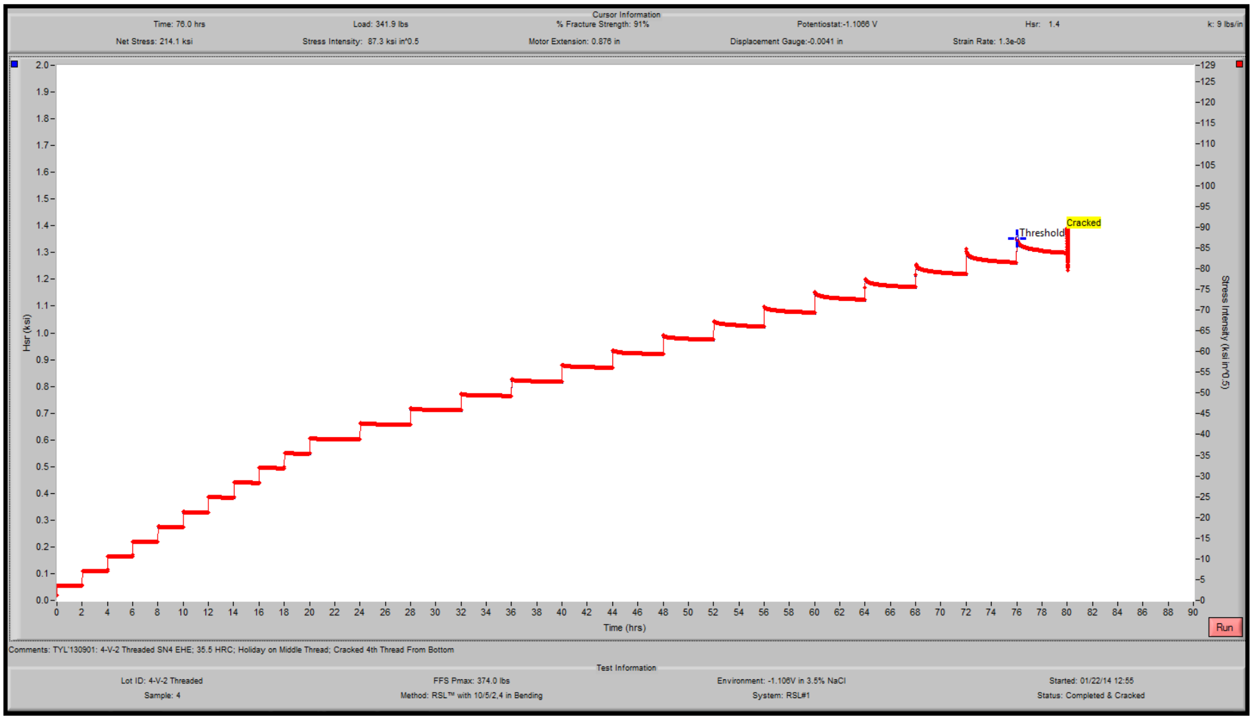


Figure C.7-6: Rod 4-V-2 Thd 4, Graphical EHE Results

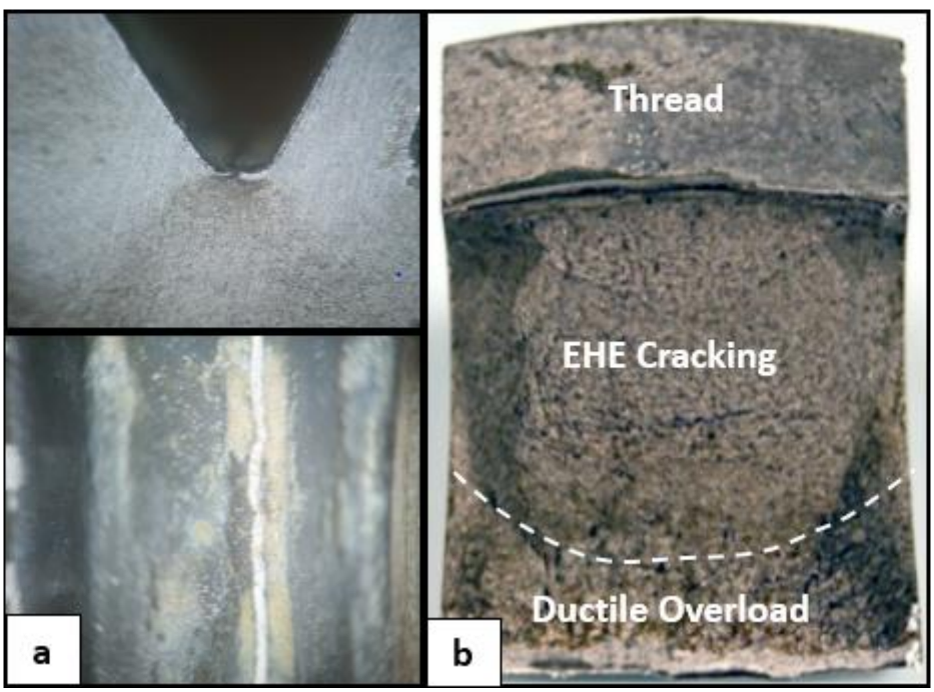
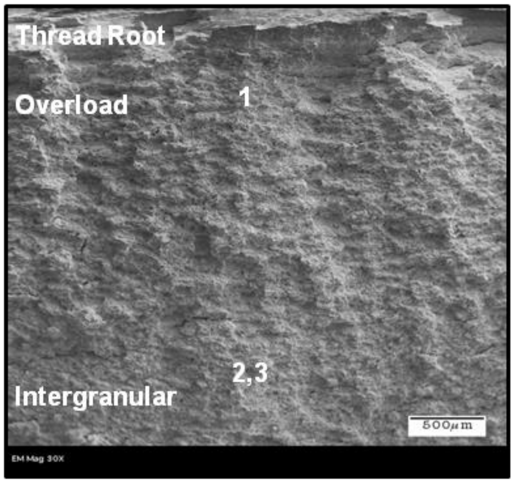
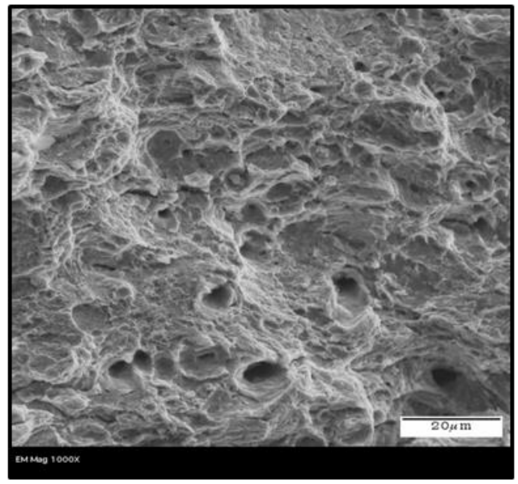


Figure C.7-7: Rod 4-V-2 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

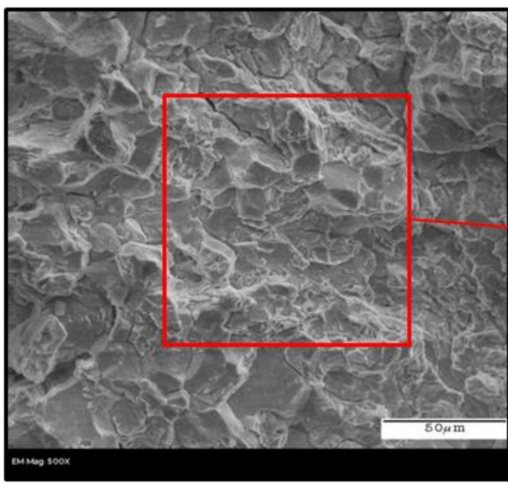
Figure C.7-8: SEM of Rod 4-V-2 Thd 4, EHE



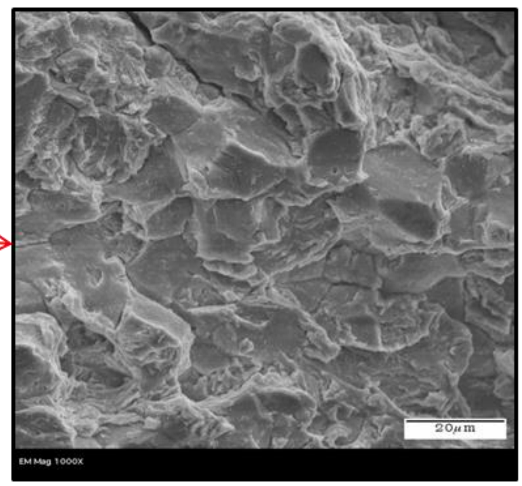
Thread Root 30X



1) Ductile Overload 1000X



2) Intergranular 500X



3) Intergranular 1000X

C.7.4 Thd 5, EHE:

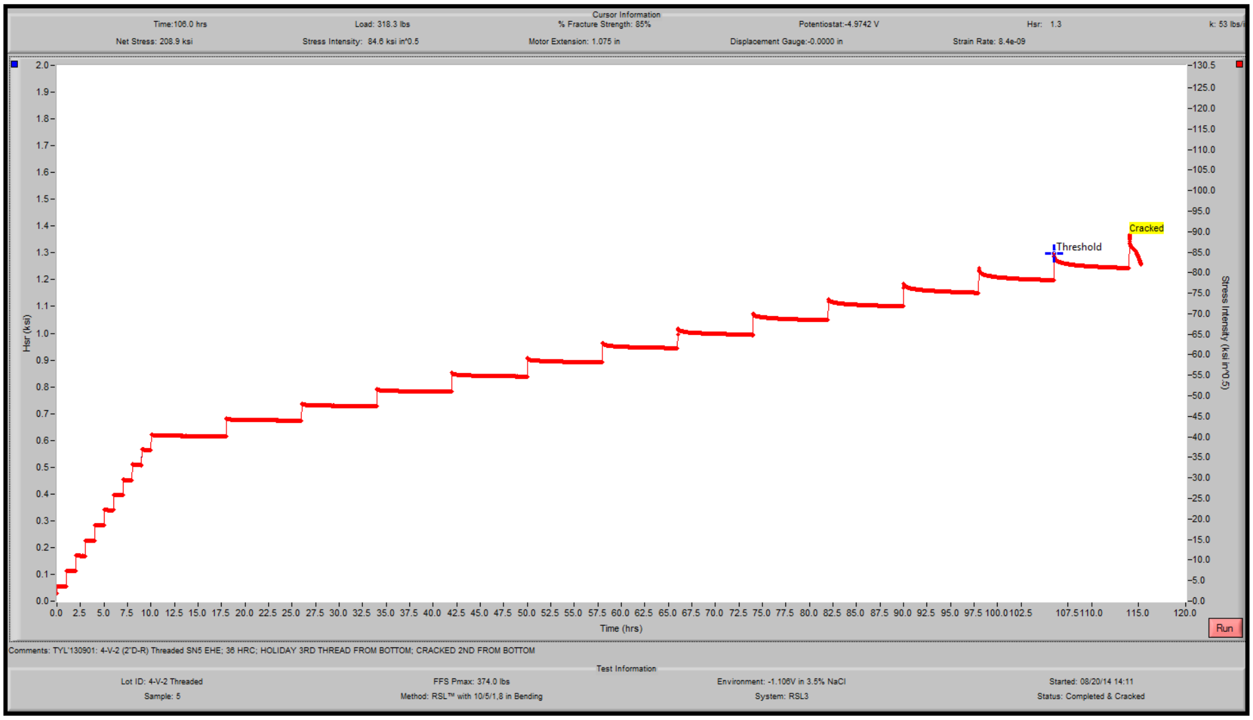


Figure C.7-9: Rod 4-V-2 Thd 5, Graphical EHE Results

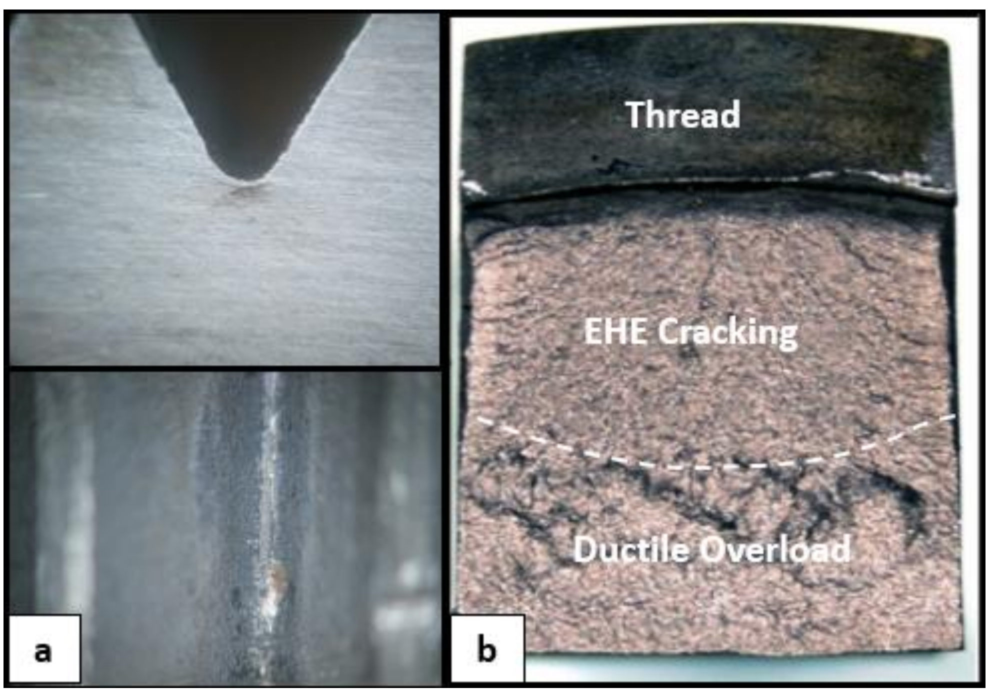


Figure C.7-10: Rod 4-V-2 Thd 5 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix D: Rod 1-V-S2-A2-A

D.1 Description of Sample

Rod 1-V-S2-A2-A was located at the top of the Shear Key Anchor Bolts on Pier E2 (S1/S2) and was from the same group of material that was tested in Test Rigs 12 and 13 in Test IV. The letter A at the end of the serial number identifies that this section of the 2008 Rod 1-V-S2-A2 was located opposite the fracture end (live end). It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 3 inches in diameter with machined threads. The segment from this section of the rod provided to LRA is shown in **Figure D.1-1**.

Figure D.1-1: Pier E2 Shear Key Anchor Bolt (Bottom, Live End, S1/S2), Rod 1-V-S2-A2-A

D.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 1-V-S2-A2-A can be seen in **Figure D.2-1** where the black portion of the Shadowgraph represents the rod material. As can be seen from **Figure D.2-1**, these machined thread roots are not uniform about the root radius.

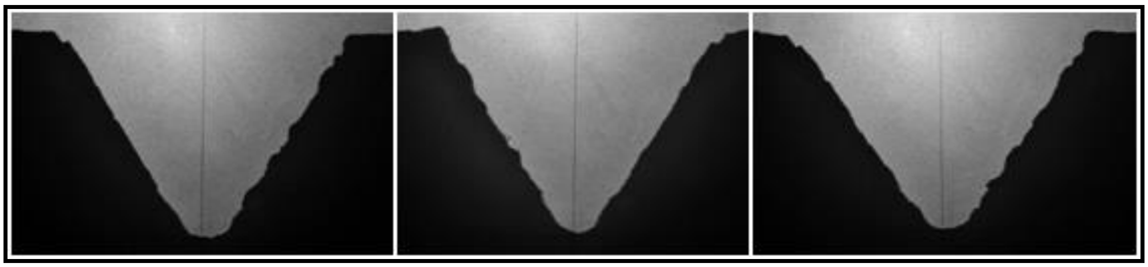


Figure D.2-1: Thread Comparison of Three Threads of Rod 1-V-S2-A2-A

D.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 1-V-S2-A2-A and can be seen versus time in **Figure D.3-1**. The final OCP recorded for Rod 1-V-S2-A2-A was Vsce=-0.893 V.

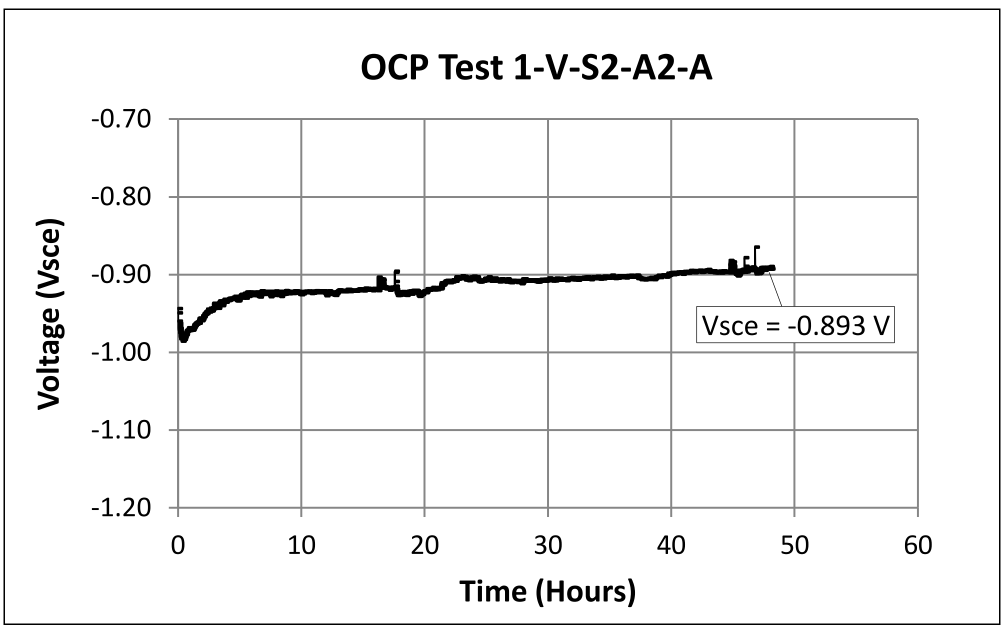


Figure D.3-1: Open Circuit Potential for Rod 1-V-S2-A2-A

D.4 Hardness

The hardness data and profile for sample 1-V-S2-A2-A are shown in **Table D.4-1** and **Figure D.4-1**.

Table D.4-1: Hardness Data of Rod 1-V-S2-A2-A Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	31.5	31.5
MR 2, IHE	32.0	34.5
MR 3, EHE	35.5	
MR 4, EHE	35.0	
MR 5, EHE	33.5	
MR 6, FFS	35.5	
MR 8, EHE	35.5	
OD 1, FFS	37.0	36.7
OD 2, IHE	36.5	
OD 3, EHE	37.5	
OD 4, EHE	35.5	
OD 5, IHE	37.5	
OD 6, EHE	37.5	
OD 7, EHE	37.5	
Thd 1, FFS	36.5	
Thd 2, IHE	36.0	
Thd 3, EHE	36.0	
Thd 4, EHE	36.0	
Thd 5, EHE	36.5	
Thd 6, EHE	36.5	

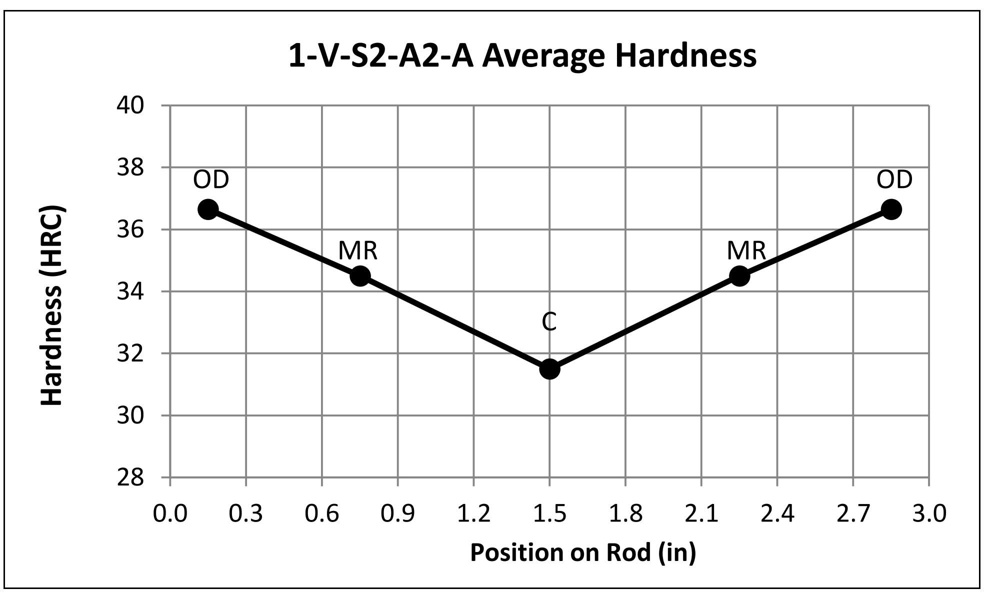


Figure D.4-1: Hardness Profile of Rod 1-V-S2-A2-A

D.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following “checker board” tables.

D.5.1 Fatigue Pre-cracked Results:

Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 1-V-S2-A2-A

LRA Job No.:	**TYL130901**	**Structural Component**: Shear Key Anchor Bolts-Bottom (S1/S2)
Rod#:	**1-V-S2-A2-A**	
Product Form:	**1e**	**Comments:** Machined Threads; 2008 at Top (Live End)
Rod OD:	**3"**	Same Group of Material as Test Rig #12 and #13 in Test IV

	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**37.0**	Kmax	84.9		
			DTI_{th}	0.51		
			Fu	0.96		
			Strain Rate ($x10^{-8}$ in/in/sec)	8500		
	OD 2, IHE	**36.5**	$K_{threshold}$		77.7	
			DTI_{th}		0.47	
			Fu		0.88	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.2	
	OD 3, EHE	**37.5**	$K_{threshold}$			49.9
			DTI_{th}			0.30
			Fu			0.56
			Strain Rate ($x10^{-8}$ in/in/sec)			2.3
	OD 4, EHE	**35.5**	$K_{threshold}$			40.4
			DTI_{th}			0.25
			Fu			0.46
			Strain Rate ($x10^{-8}$ in/in/sec)			1.5
	OD 5, IHE	**37.5**	$K_{threshold}$		79.1	
			DTI_{th}		0.47	
			Fu		0.89	
			Strain Rate ($x10^{-8}$ in/in/sec)		1.8	
	OD 6, EHE	**37.5**	$K_{threshold}$			19.2
			DTI_{th}			0.11
			Fu			0.22
			Strain Rate ($x10^{-8}$ in/in/sec)			1.3
	OD 7, EHE	**37.5**	$K_{threshold}$			23.6
			DTI_{th}			0.14
			Fu			0.27
			Strain Rate ($x10^{-8}$ in/in/sec)			1.0

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 1-V-S2-A2-A						
LRA Job No.:	**TYL130901**	**Structural Component**: Shear Key Anchor Bolts-Bottom (S1/S2)				
Rod#:	**1-V-S2-A2-A**					
Product Form:	**1e**	**Comments:** Machined Threads; 2008 at Top (Live End) Same Group of Material as Test Rig #12 and #13 in Test IV				
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 6, FFS**	**35.5**	Kmax DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	78.9 0.49 0.89 8500		
	MR 2, IHE	**32.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		80.9 0.56 0.91 2.2	
	MR 3, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			30.2 0.19 0.34 2.0
	MR 4, EHE	**35.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			24.1 0.15 0.27 1.2
	MR 5, EHE	**33.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			31.0 0.21 0.35 1.1
	MR 8, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			27.3 0.17 0.31 0.9
	Center 1, FFS	**31.5**	Kmax DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	74.1 0.52 0.84 8400		

D.5.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 1-V-S2-A2-A

LRA Job No.:	TYL130901	**Structural Component**: Shear Key Anchor Bolts-Bottom (S1/S2)
Rod#:	1-V-S2-A2-A	
Product Form:	1e	**Comments:** Machined Threads; 2008 at Top (Live End)
Rod OD:	3"	Same Group of Material as Test Rig #12 and #13 in Test IV

	Sample #/ID	HRC		P-FFS	P-IHE	P-EHE
Threaded	Thd 1, FFS	36.5	Pmax* (lbs)	337.8		
			Fu	1.11		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	9000		
	Thd 2, IHE	36.0	$P_{threshold}$* (lbs)		332.3	
			Fu		1.09	
			Hsr		1.5	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.2	
	Thd 3, EHE	36.0	$P_{threshold}$* (lbs)			240.4
			Fu			0.79
			Hsr			1.1
			Strain Rate ($x10^{-8}$ in/in/sec)			2.2
	Thd 4, EHE	36.0	$P_{threshold}$* (lbs)			221.6
			Fu			0.73
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			2.0
	Thd 5, EHE	36.5	$P_{threshold}$* (lbs)			188.6
			Fu			0.62
			Hsr			0.8
			Strain Rate ($x10^{-8}$ in/in/sec)			2.0
	Thd 6, EHE	36.5	$P_{threshold}$* (lbs)			195.1
			Fu			0.64
			Hsr			0.9
			Strain Rate ($x10^{-8}$ in/in/sec)			1.7

D.5.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 1-V-S2-A2-A
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**1-V-S2-A2-A**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	37.0	167	94.2	94.2	94.2	100.0%	84.9	0.51	289.7	1.7	8500	0.2135	132.7	50 lbs/min		0.96	
	OD 2, IHE	Air	36.5	164	65.0	89.0	87.8	91.5%	77.7	0.47	263.3	1.6	2.2	0.211		10/5/2,4		0.88	
	OD 3, EHE	3.5% NaCl @ -1.106V	37.5	169	64.0	71.2	54.4	58.8%	49.9	0.30	171.0	1.0	2.3	0.2157		10/5/2,4		0.56	
	OD 4, EHE	3.5% NaCl @ -1.106V	35.5	159	41.0	59.5	45.0	47.6%	40.4	0.25	137.6	0.9	1.5	0.2127		10/5/2,4		0.46	
	OD 5, IHE	Air	37.5	169	50.0	89.5	87.3	93.2%	79.1	0.47	270.4	1.6	1.8	0.2150		10/5/2,4		0.89	
	OD 6, EHE	3.5% NaCl @ -1.106V	37.5	169	35.0	28.0	20.9	22.6%	19.2	0.11	65.7	0.4	1.3	0.2132		10/5/2,4		0.22	
	OD 7, EHE	3.5% NaCl @ -1.106V	37.5	169	30.0	30.0	26.9	27.8%	23.6	0.14	80.0	0.5	1.0	0.2084		10/5/2,4		0.27	
	MR 6, FFS	Air	35.5	159	87.1	87.1	87.1	100.0%	78.9	0.49	269.1	1.7	8500	0.2110	122.2	50 lbs/min		0.89	
	MR 2, IHE	Air	32.0	145	1984.0	2977.2	2862.0	102.5%	80.9	0.56	276.2	1.9	2.2	0.2148		10/5/2,4		0.91	
	MR 3, EHE	3.5% NaCl @ -1.106V	35.5	159	62.0	40.3	33.9	38.3%	30.2	0.19	102.5	0.6	2.0	0.2119		10/5/2,4		0.34	
	MR 4, EHE	3.5% NaCl @ -1.106V	35.0	157	37.0	35.2	27.7	30.5%	24.1	0.15	81.5	0.5	1.2	0.2105		10/5/2,4		0.27	
	MR 5, EHE	3.5% NaCl @ -1.106V	33.5	151	30.0	39.1	32.9	39.3%	31.0	0.21	107.0	0.7	1.1	0.2153		10/5/2,4		0.35	
	MR 8, EHE	3.5% NaCl @ -1.106V	35.5	159	25.0	33.8	29.9	34.6%	27.3	0.17	93.2	0.6	0.9	0.2115		10/5/2,4		0.31	
	Center 1, FFS	Air	31.5	143	82.2	82.2	82.2	100.0%	74.1	0.52	252.3	1.8	8400	0.2116	141.5	50 lbs/min		0.84	
Threaded	Thd 1, FFS	Air	36.5	164	357.0	357.0	357.0	100.0%	98.5	0.60	242.7	1.5	9000			300 lbs/min	337.8	1.11	
	Thd 2, IHE	Air	36.0	162	283.1	360.7	354.0	98.4%	96.9	0.60	238.8	1.5	2.2			10/5/2,4	332.3	1.09	
	Thd 3, EHE	3.5% NaCl @ -1.106V	36.0	162	283.1	283.6	253.3	71.2%	70.1	0.43	173.1	1.1	2.2			10/5/2,4	240.4	0.79	Did Not Crack In Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	36.0	162	260.0	260.3	233.0	65.6%	64.6	0.40	159.2	1.0	2.0			10/5/2,4	221.6	0.73	Did Crack In Holiday
	Thd 5, EHE	3.5% NaCl @ -1.106V	36.5	164	240.0	204.2	191.2	55.8%	55.0	0.34	136.9	0.8	2.0			10/5/2,4	188.6	0.62	Did Not Crack In Holiday
	Thd 6, EHE	3.5% NaCl @ -1.106V	36.5	164	210.0	220.6	198.8	57.8%	56.9	0.35	141.5	0.9	1.7			10/5/2,4	195.1	0.64	Did Crack In Holiday

D.6 Fatigue Pre-cracked Specimen Test Results

D.6.1 OD 1, FFS:

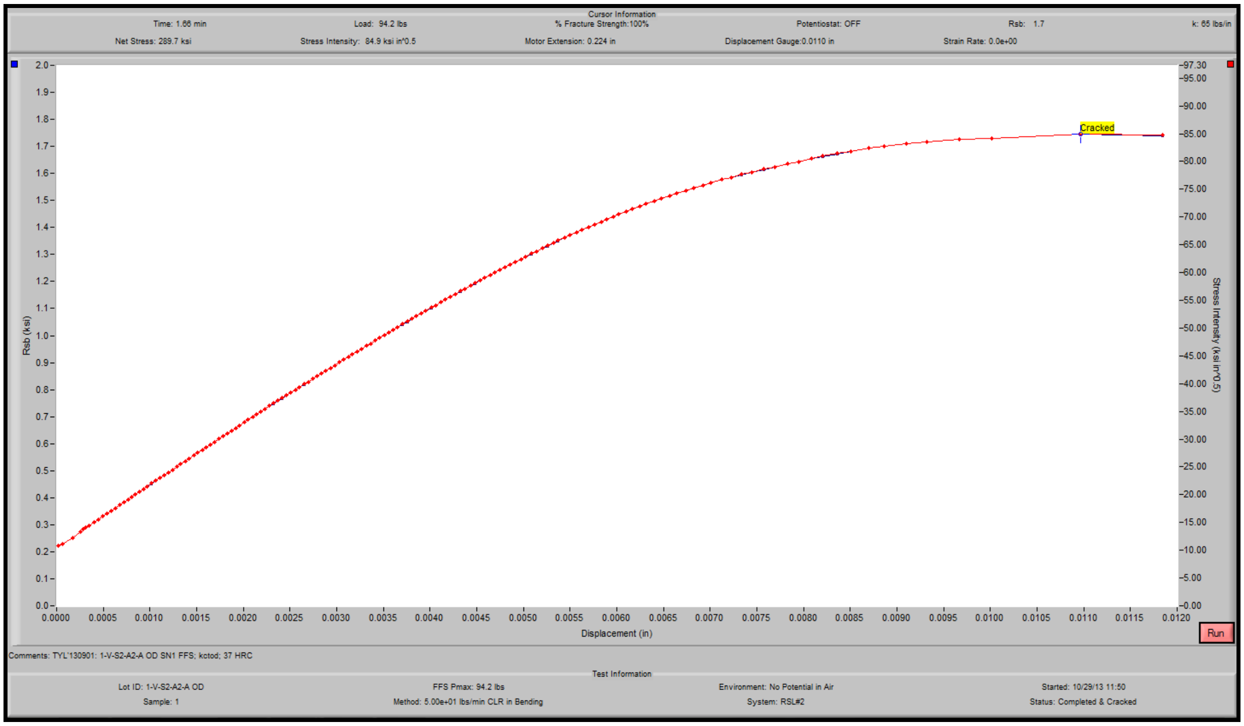
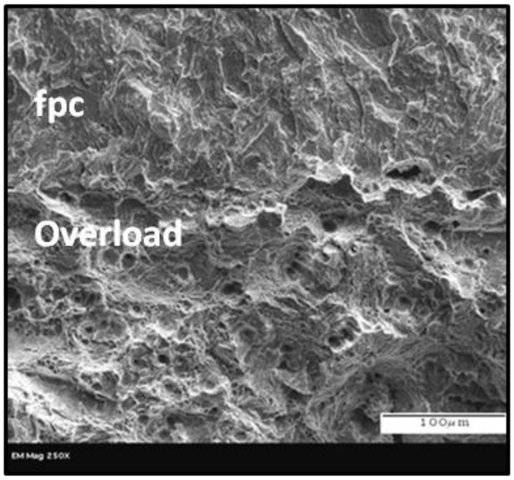


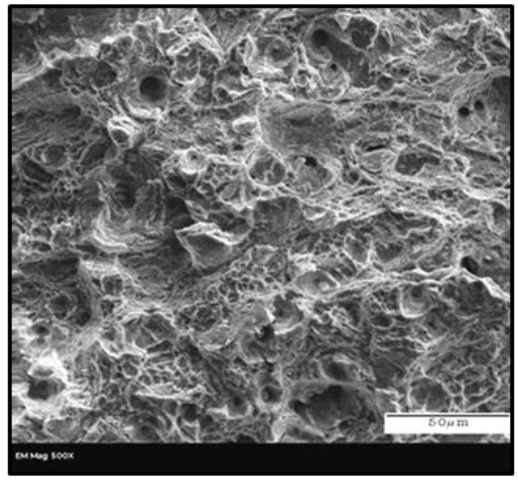
Figure D.6-1: Rod 1-V-S2-A2-A OD 1, Graphical FFS Results

Figure D.6-2: Fracture Face of Rod 1-V-S2-A2-A OD 1, FFS

Figure D.6-3: SEM of Rod 1-V-S2-A2-A OD 1, FFS



fpc – OL transition 250X



Overload 500X

D.6.2 OD 2, IHE:

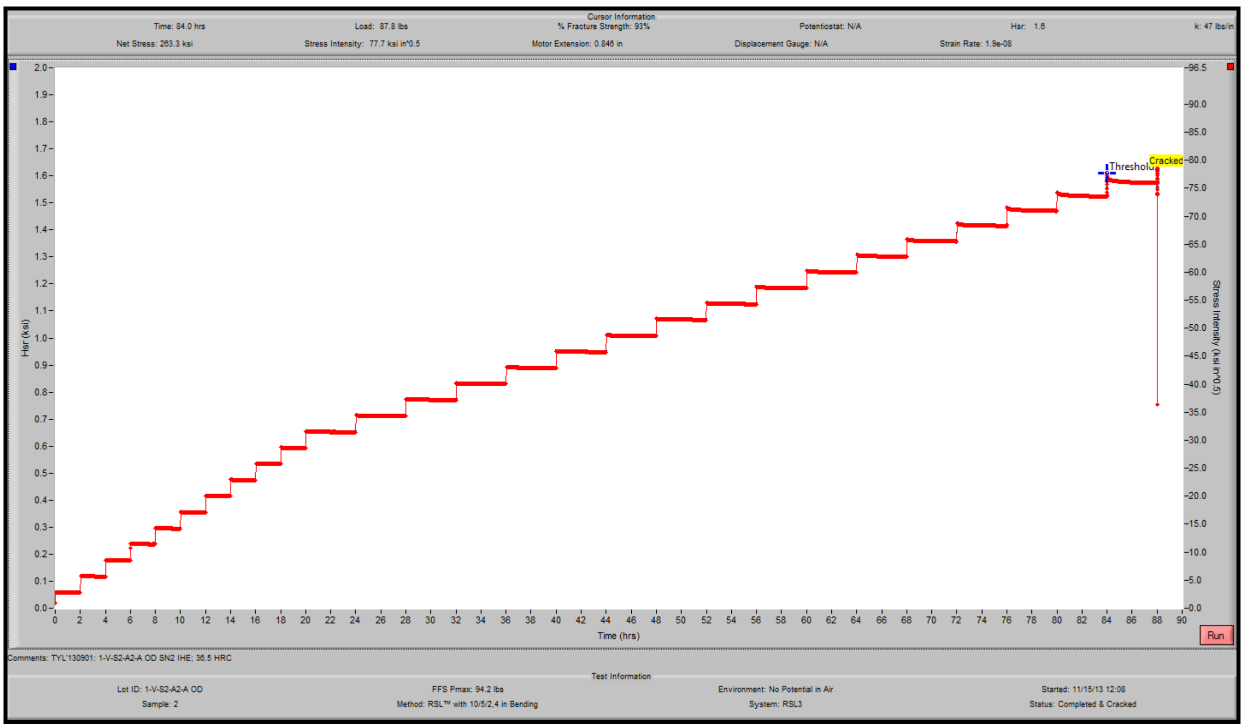


Figure D.6-4: Rod 1-V-S2-A2-A OD 2, Graphical IHE Results

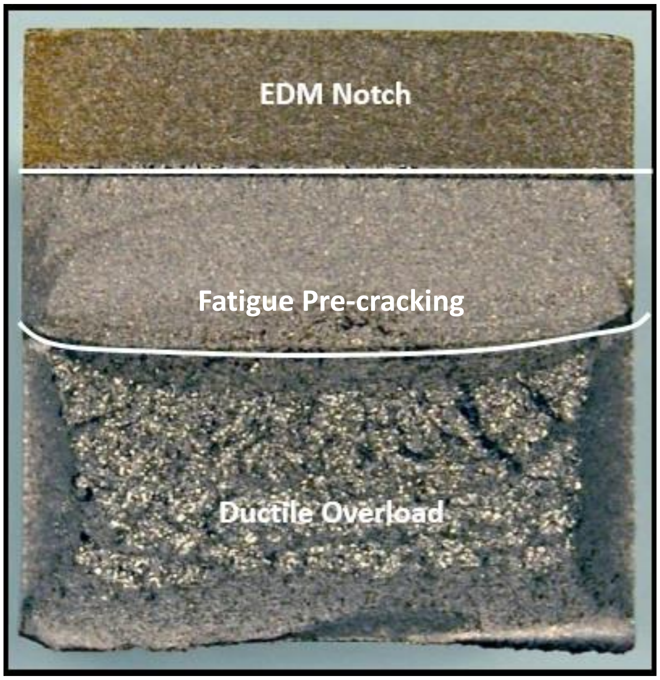
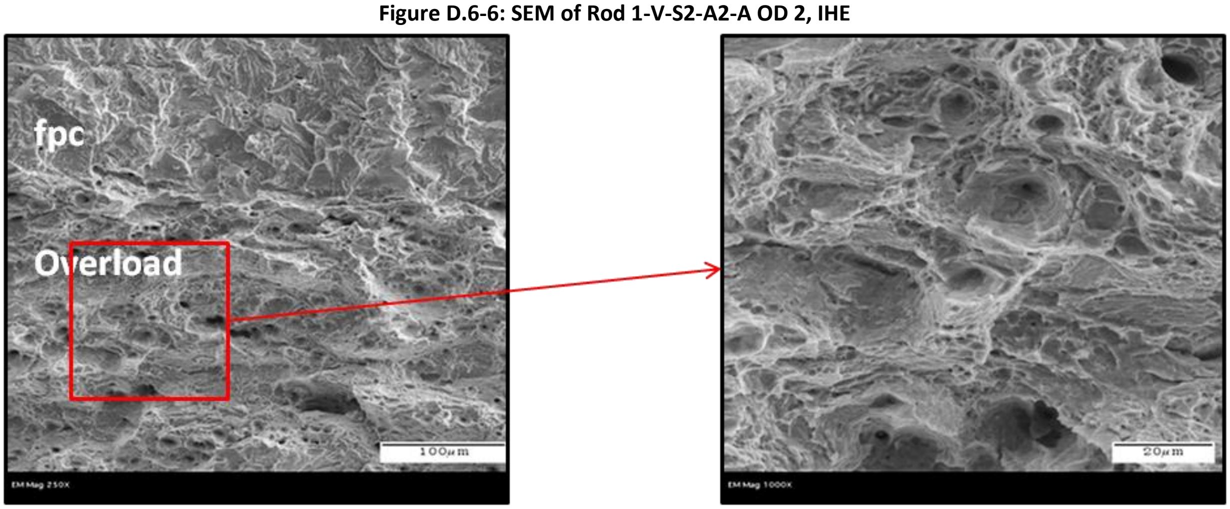


Figure D.6-5: Fracture Face of Rod 1-V-S2-A2-A OD 2, IHE

Figure D.6-6: SEM of Rod 1-V-S2-A2-A OD 2, IHE



fpc – OL transition 250X

Overload 1000X

D.6.3 OD 3, EHE:

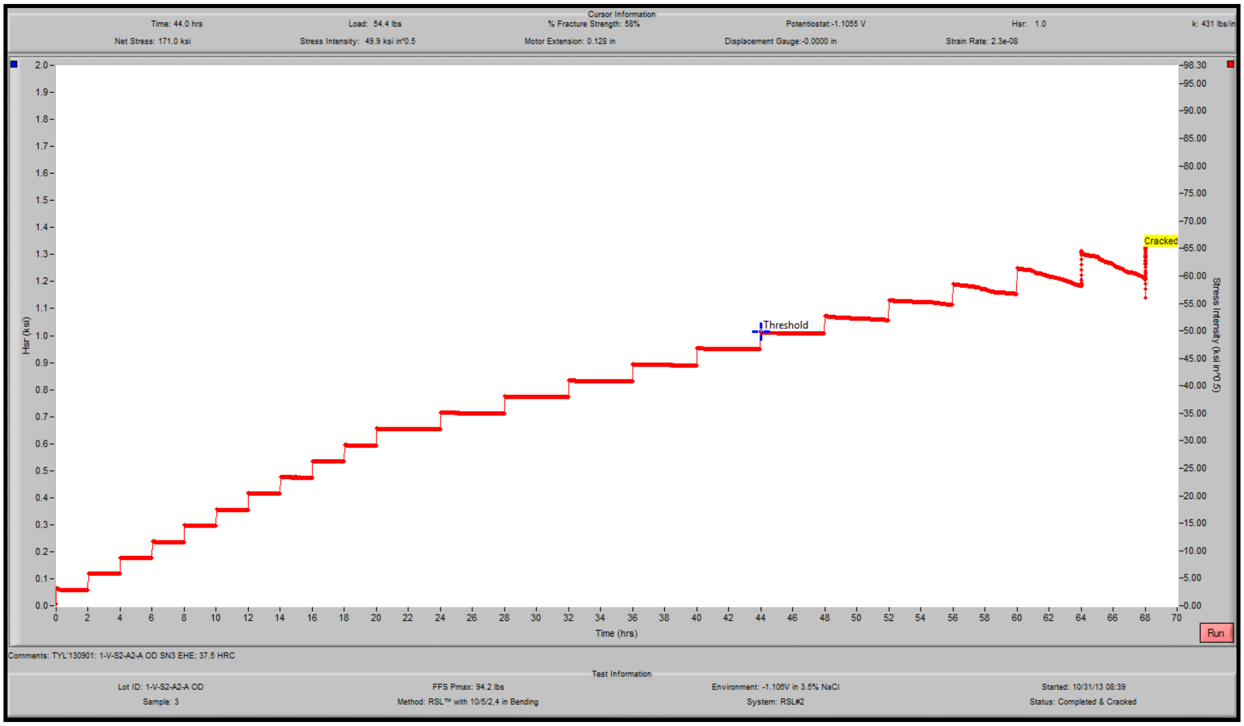


Figure D.6-7: Rod 1-V-S2-A2-A OD 3, Graphical EHE Results

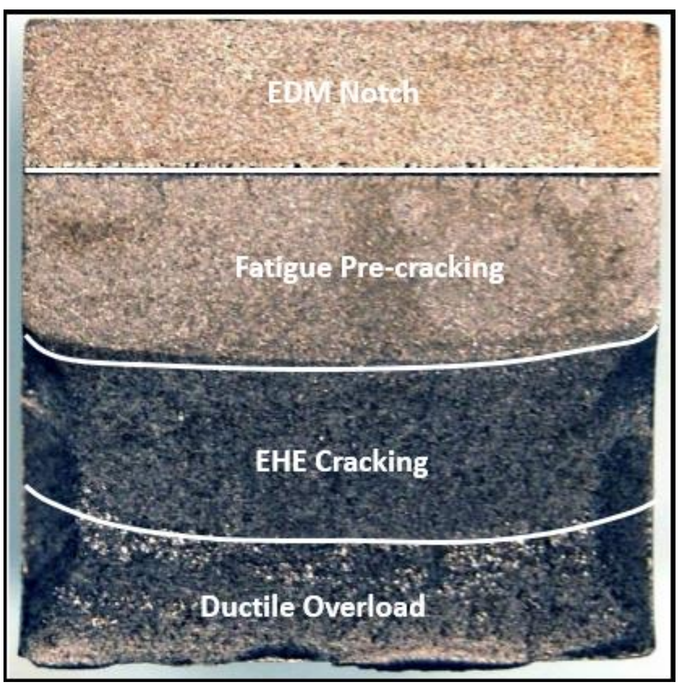
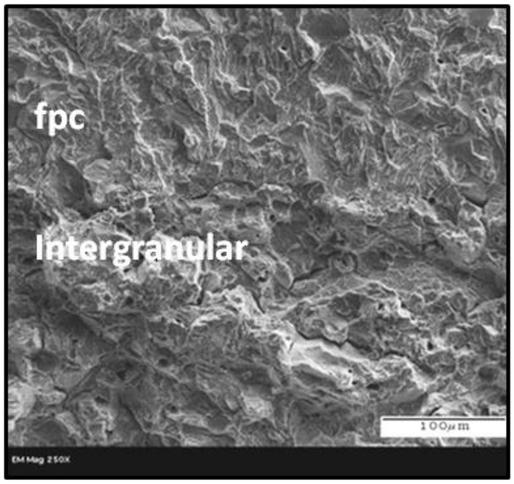
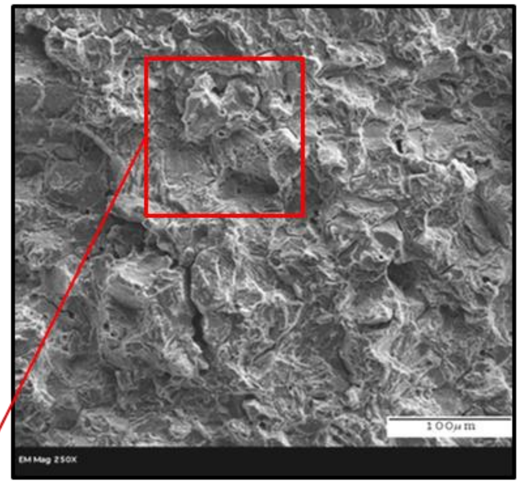


Figure D.6-8: Fracture Face of Rod 1-V-S2-A2-A OD 3, EHE

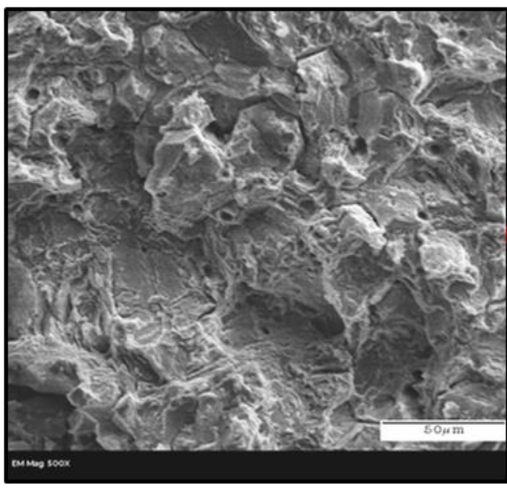
Figure D.6-9: SEM of Rod 1-V-S2-A2-A OD 3, EHE



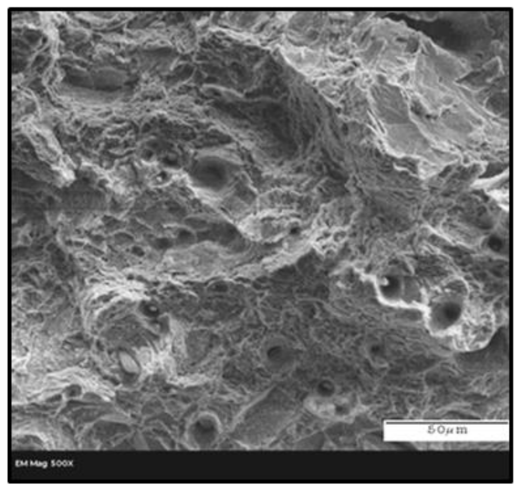
fpc – Intergranular Transition 250X



Intergranular 250X



Intergranular 500X



Overload 500X

D.6.4 OD 4, EHE:

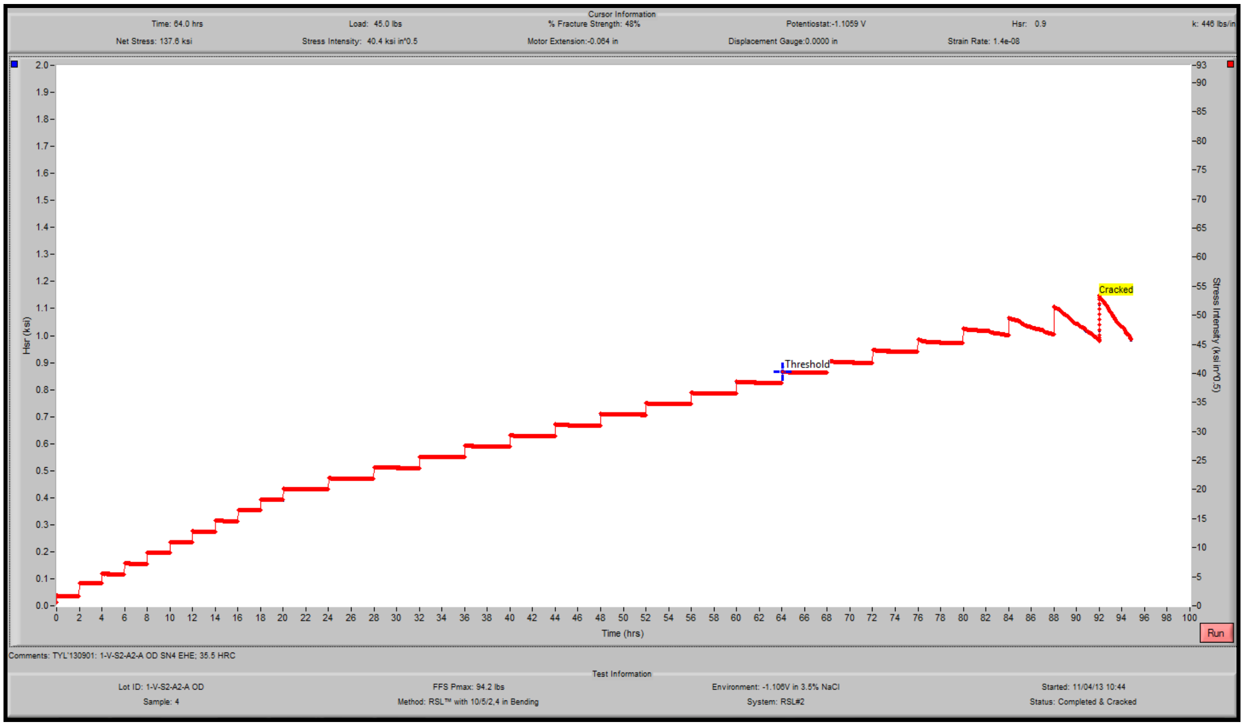


Figure D.6-10: Rod 1-V-S2-A2-A OD 4, Graphical EHE Results

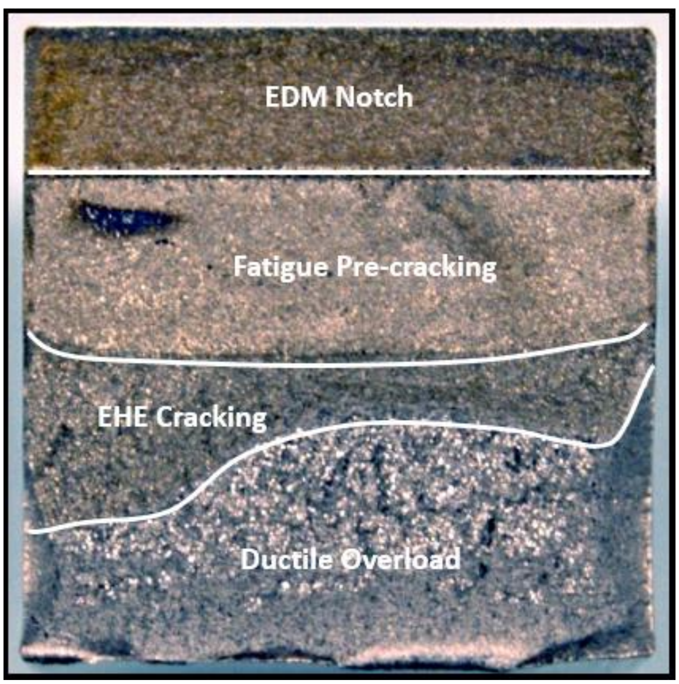


Figure D.6-11: Fracture Face of Rod 1-V-S2-A2-A OD 4, EHE

D.6.5 OD 5, IHE:

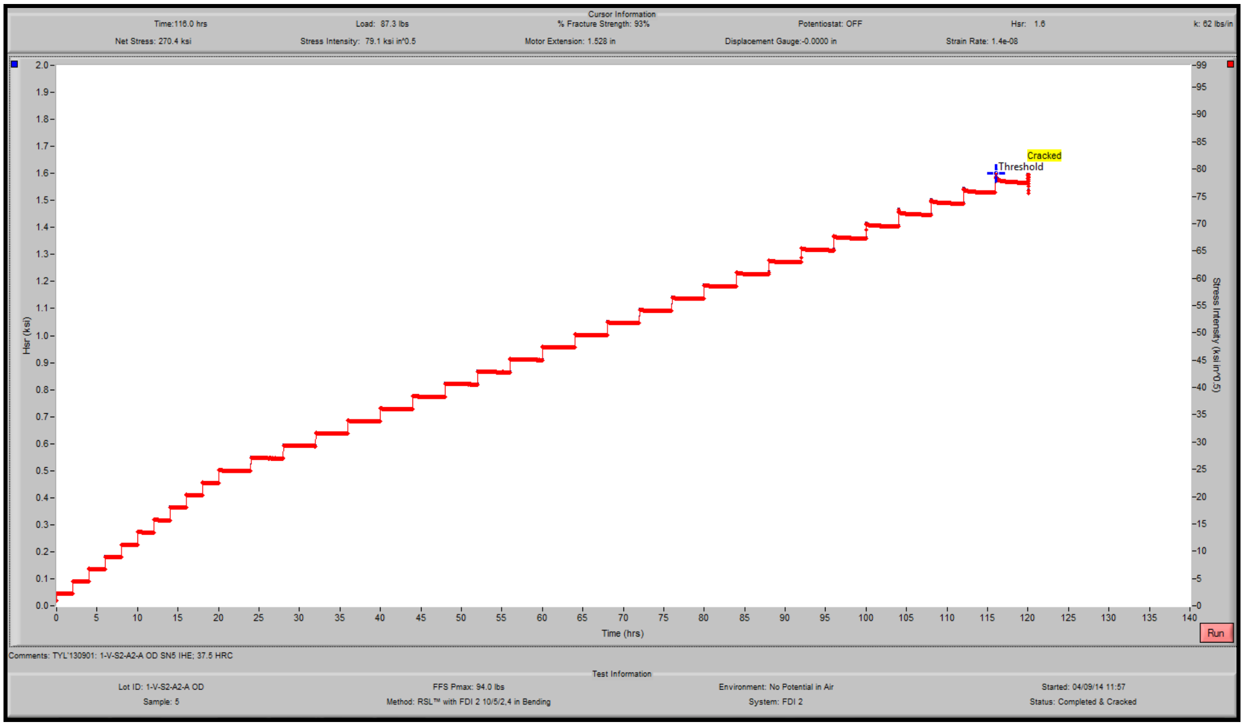


Figure D.6-12: Rod 1-V-S2-A2-A OD 5, Graphical IHE Results

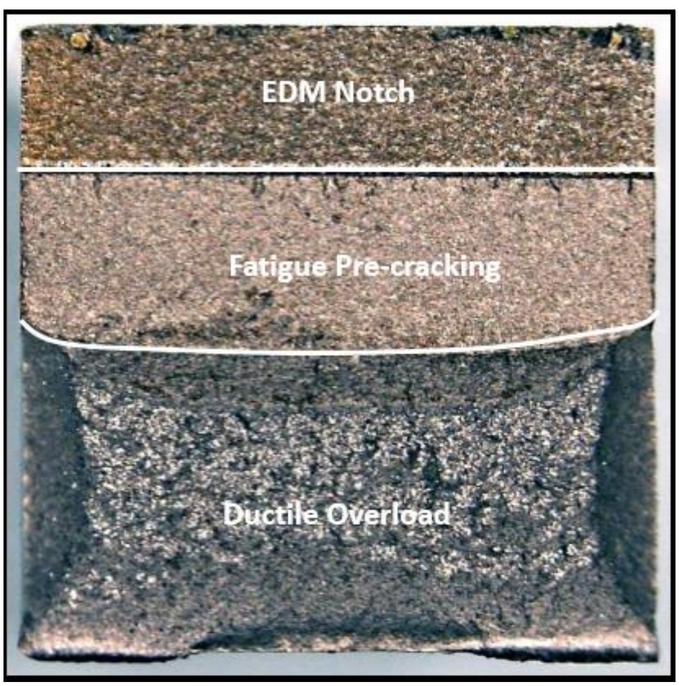


Figure D.6-13: Fracture Face of Rod 1-V-S2-A2-A OD 5, IHE

D.6.6 OD 6, EHE:

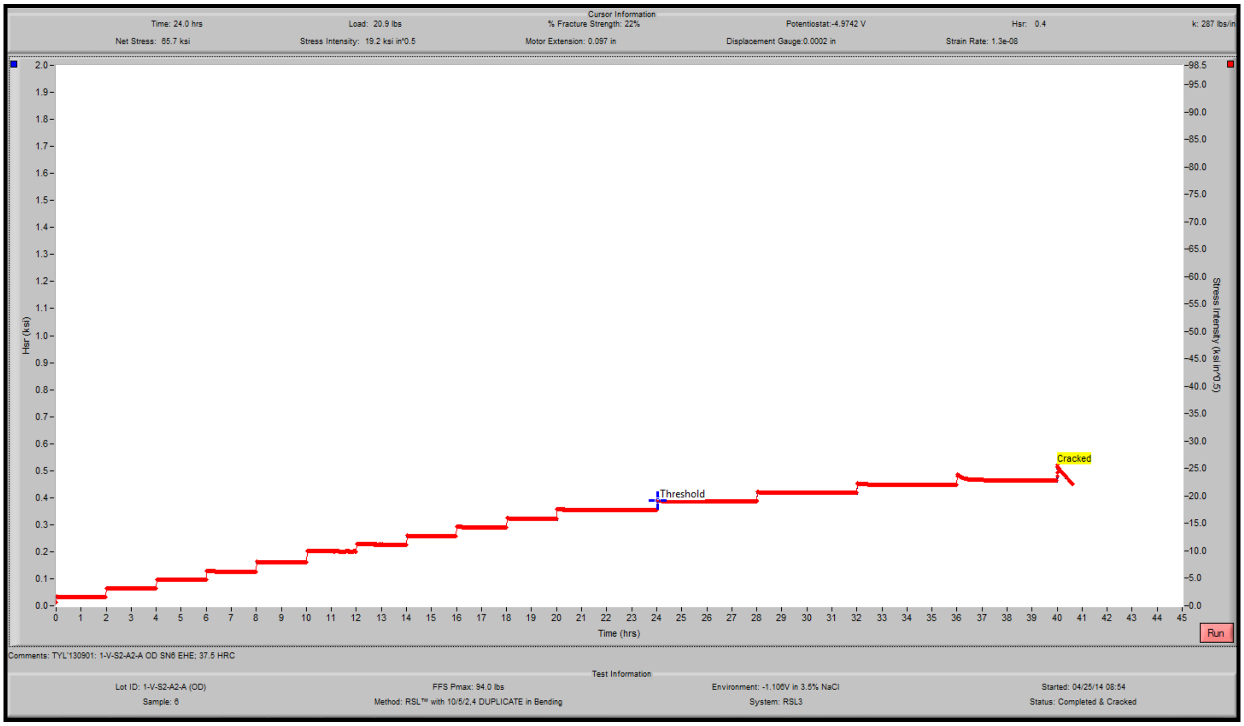


Figure D.6-14: Rod 1-V-S2-A2-A OD 6, Graphical EHE Results

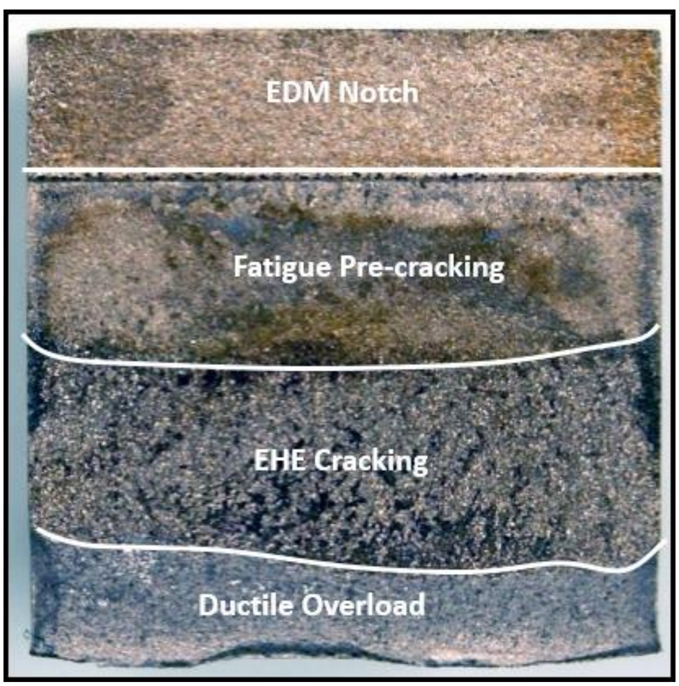


Figure D.6-15: Fracture Face of Rod 1-V-S2-A2-A OD 6, EHE

D.6.7 OD 7, EHE:

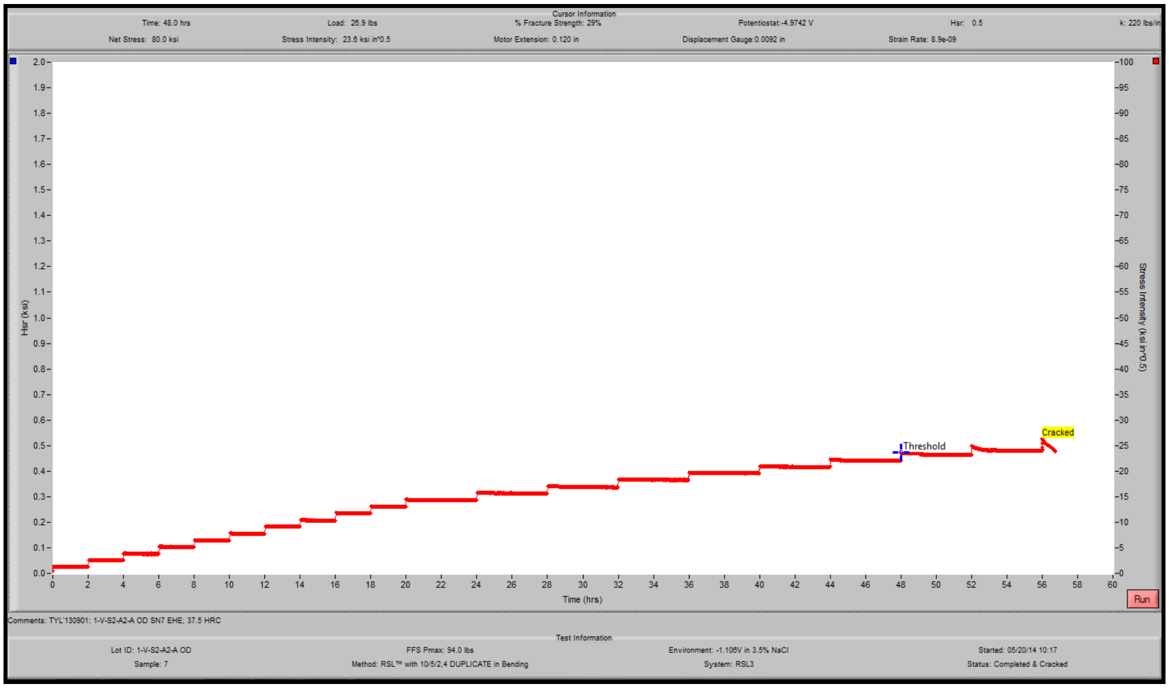


Figure D.6-16: Rod 1-V-S2-A2-A OD 7, Graphical EHE Results

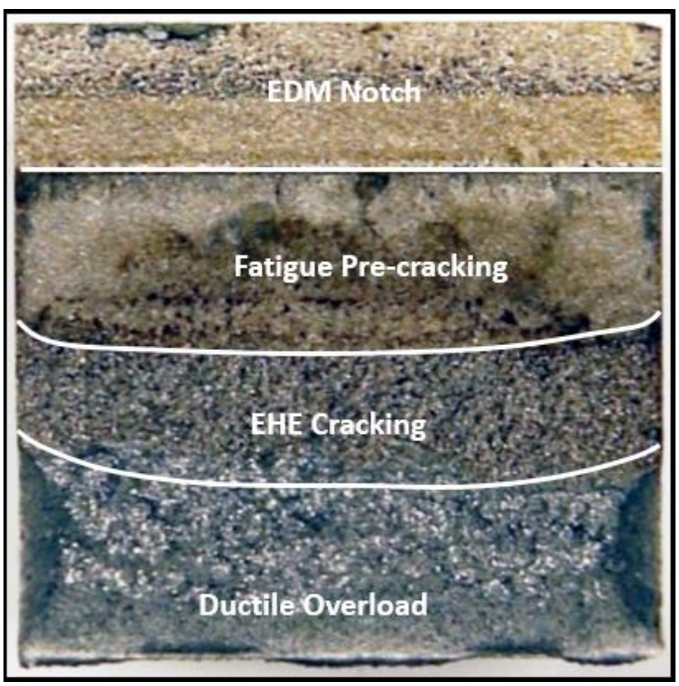


Figure D.6-17: Fracture Face of Rod 1-V-S2-A2-A OD 7, EHE

D.6.8 MR 6, FFS:

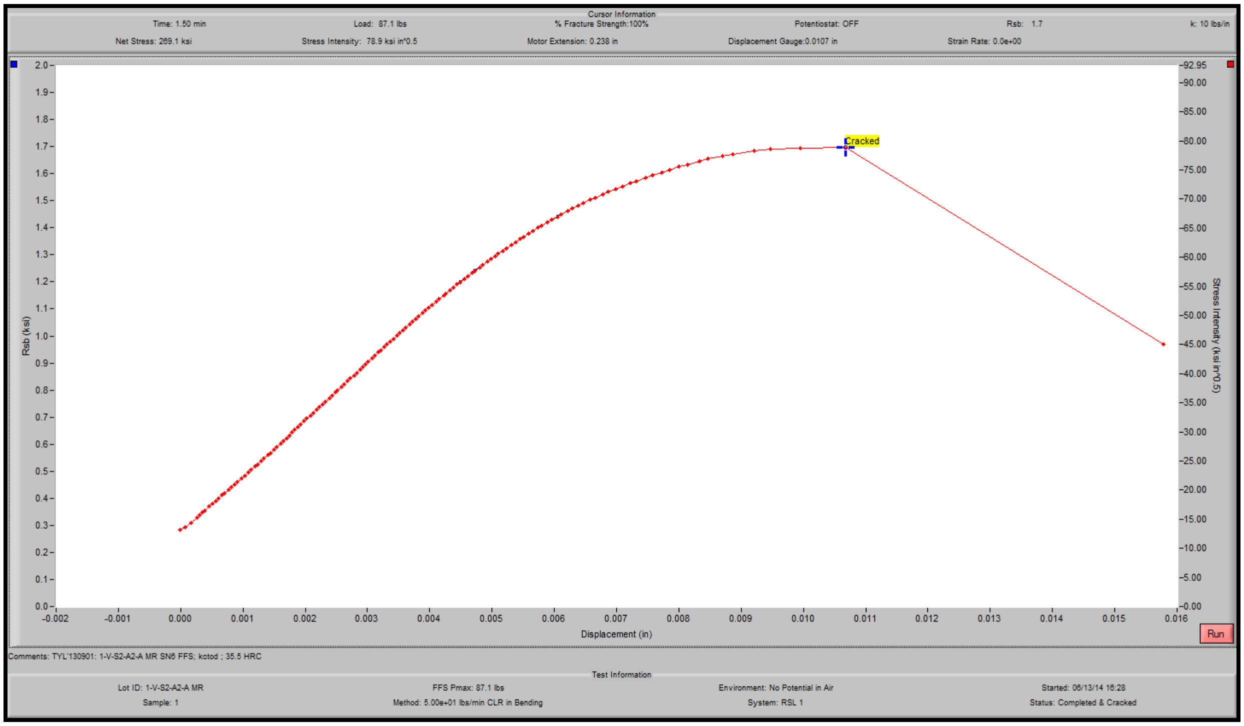


Figure D.6-18: Rod 1-V-S2-A2-A MR 6, Graphical FFS Results

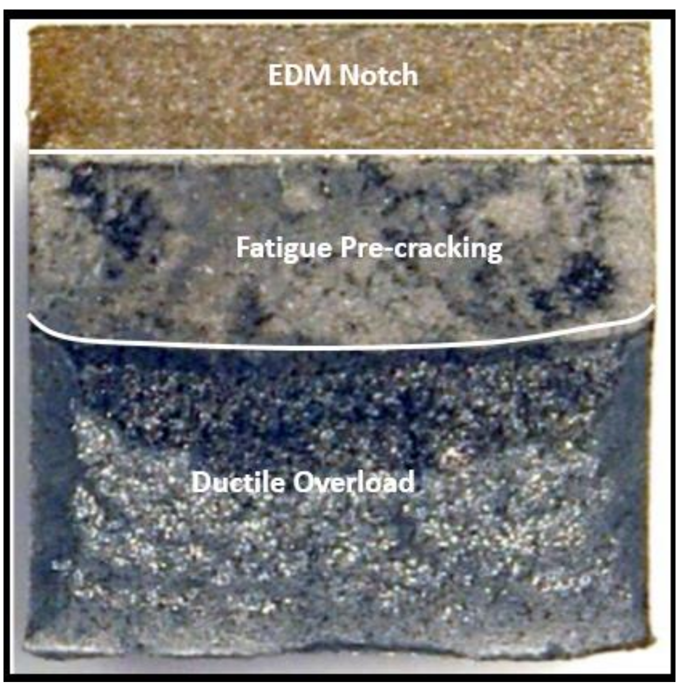


Figure D.6-19: Fracture Face of Rod 1-V-S2-A2-A MR 6, FFS

D.6.9 MR 2, IHE:

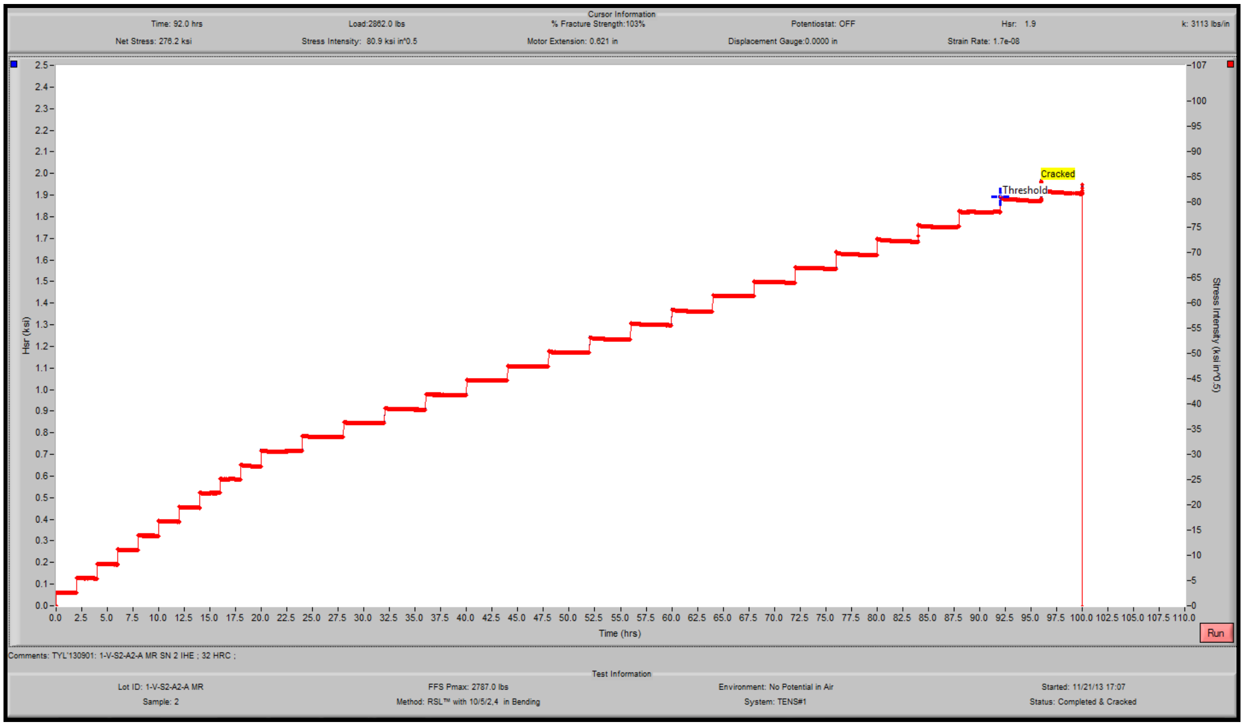


Figure D.6-20: Rod 1-V-S2-A2-A MR 2, Graphical IHE Results

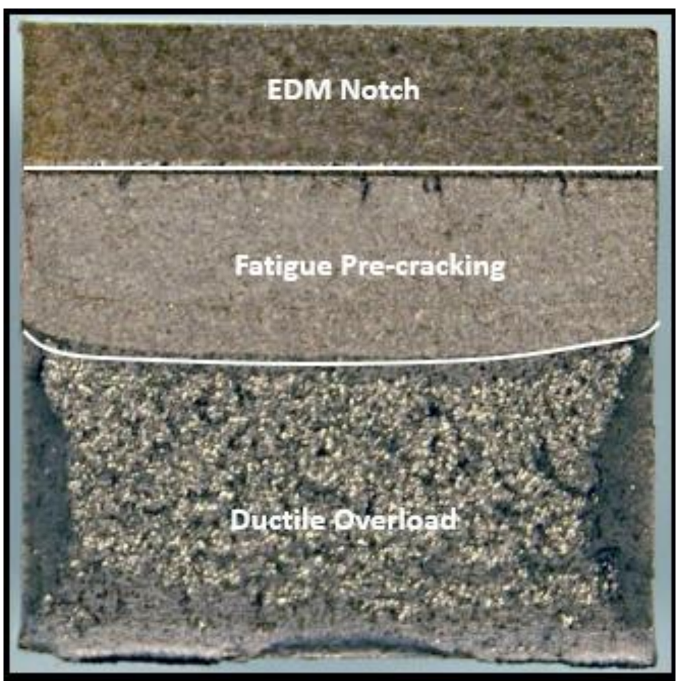


Figure D.6-21: Fracture Face of Rod 1-V-S2-A2-A MR 2, IHE

D.6.10 MR 3, EHE:

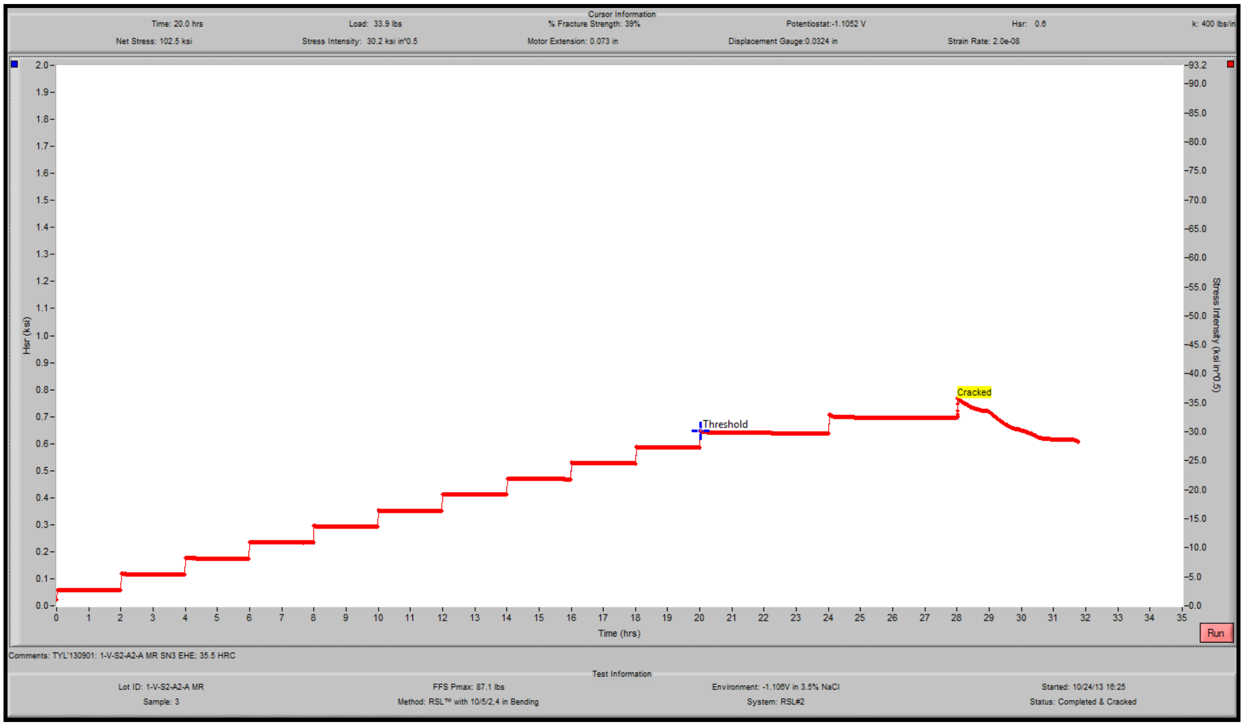


Figure D.6-22: Rod 1-V-S2-A2-A MR 3, Graphical EHE Results

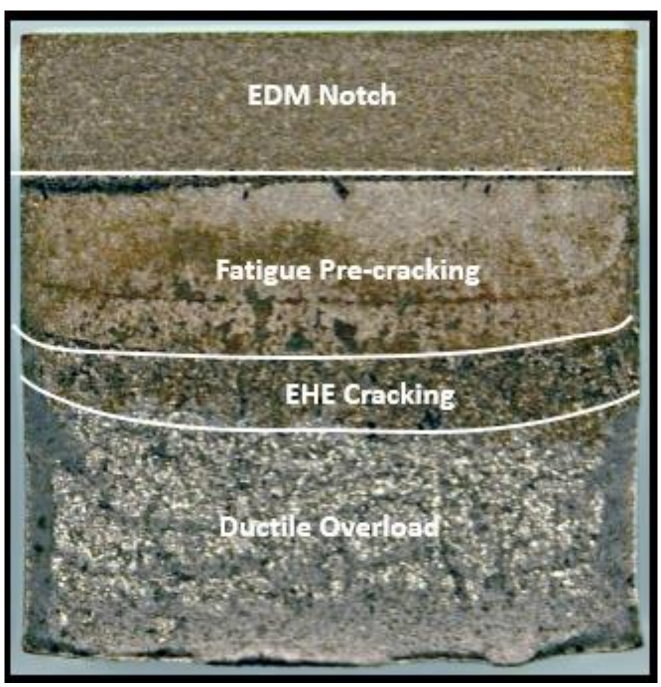
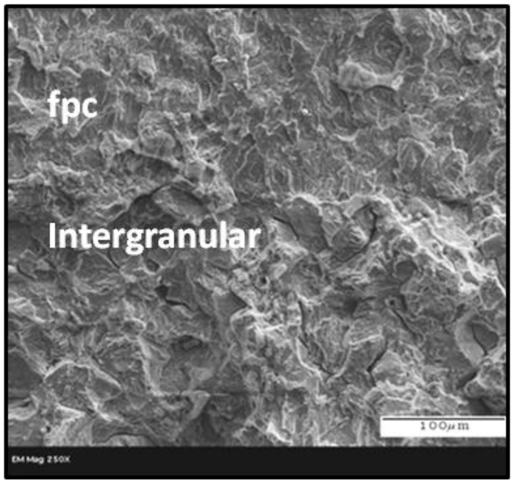
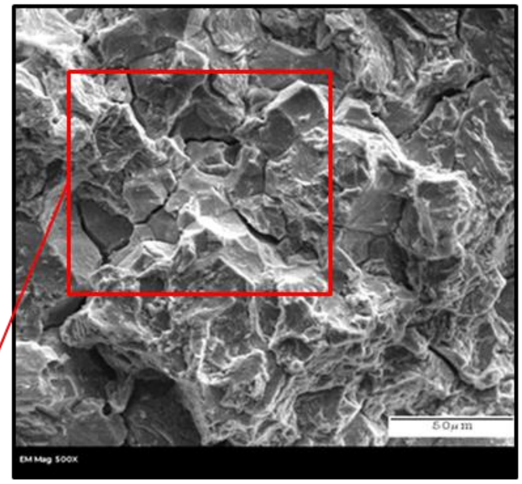


Figure D.6-23: Fracture Face of Rod 1-V-S2-A2-A MR 3, EHE

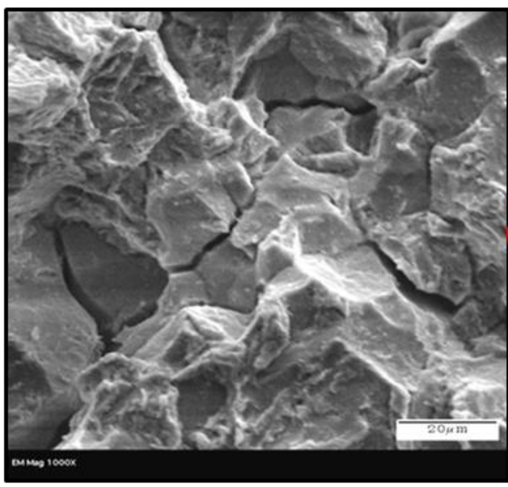
Figure D.6-24: SEM of Rod 1-V-S2-A2-A MR 3, EHE



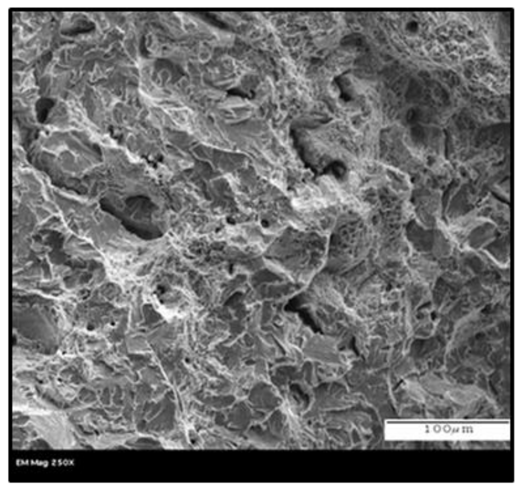
fpc – Intergranular Transition 250X



Intergranular 500X



Intergranular 1000X



Overload and Cleavage 250X

D.6.11 MR 4, EHE:

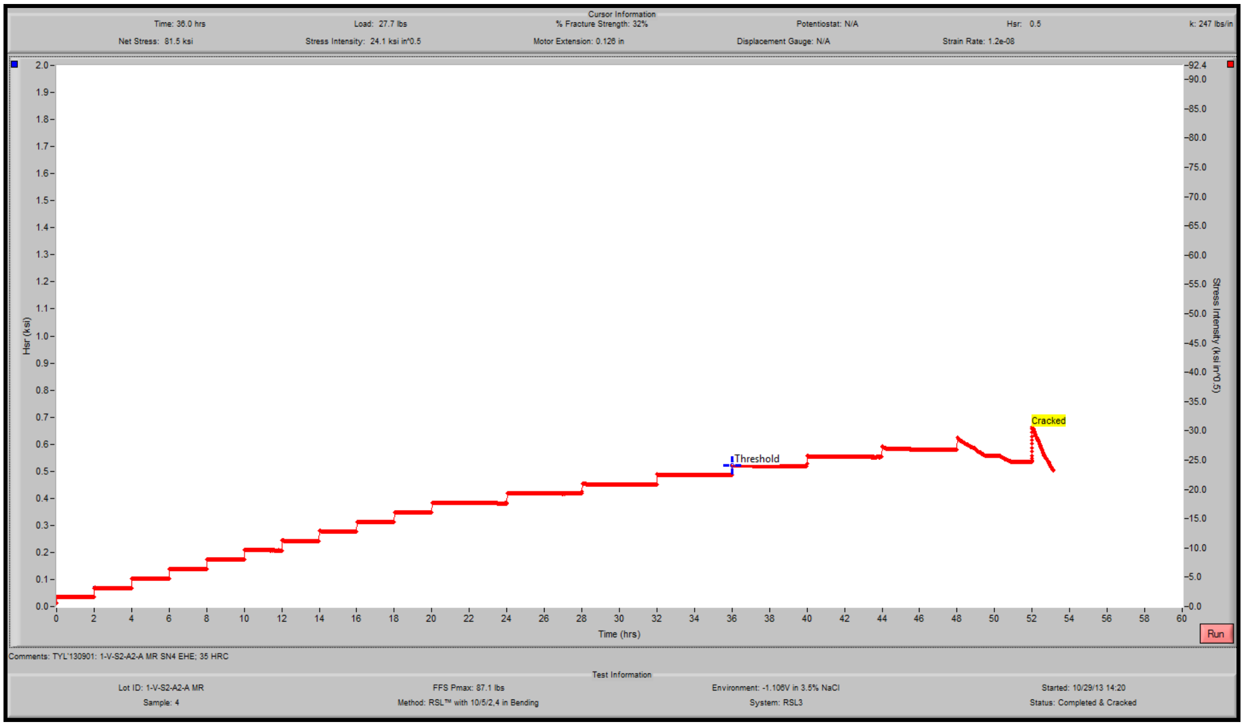


Figure D.6-25: Rod 1-V-S2-A2-A MR 4, Graphical EHE Results

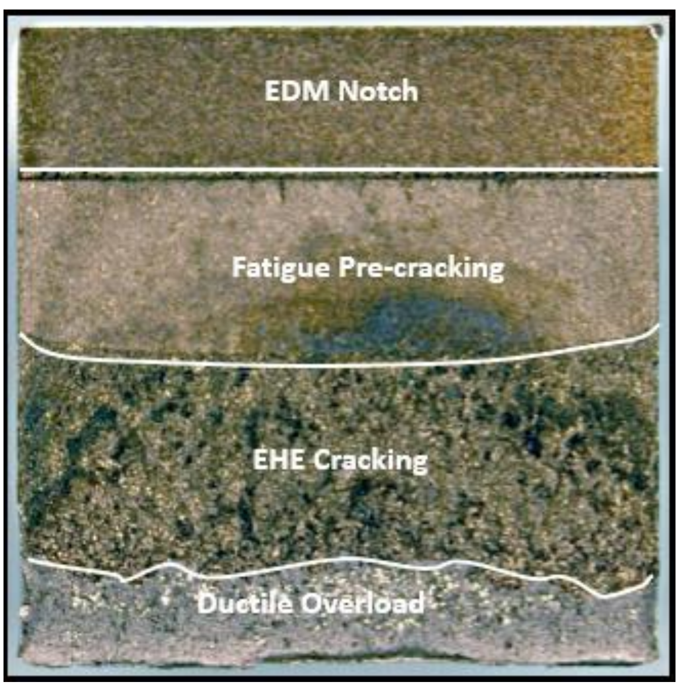
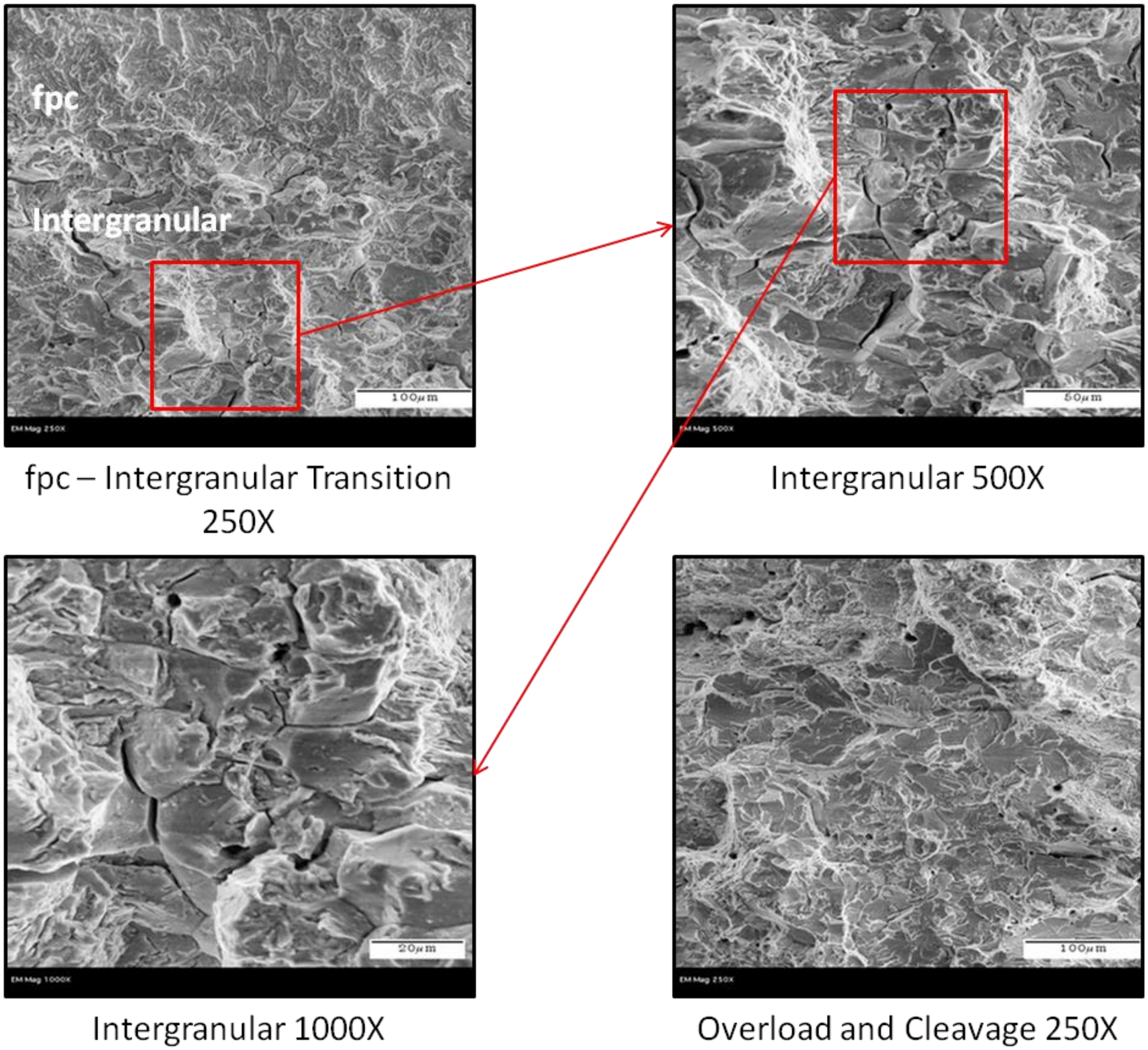


Figure D.6-26: Fracture Face of Rod 1-V-S2-A2-A MR 4, EHE

Figure D.6-27: SEM of Rod 1-V-S2-A2-A MR 4, EHE



D.6.12 MR 5, EHE:

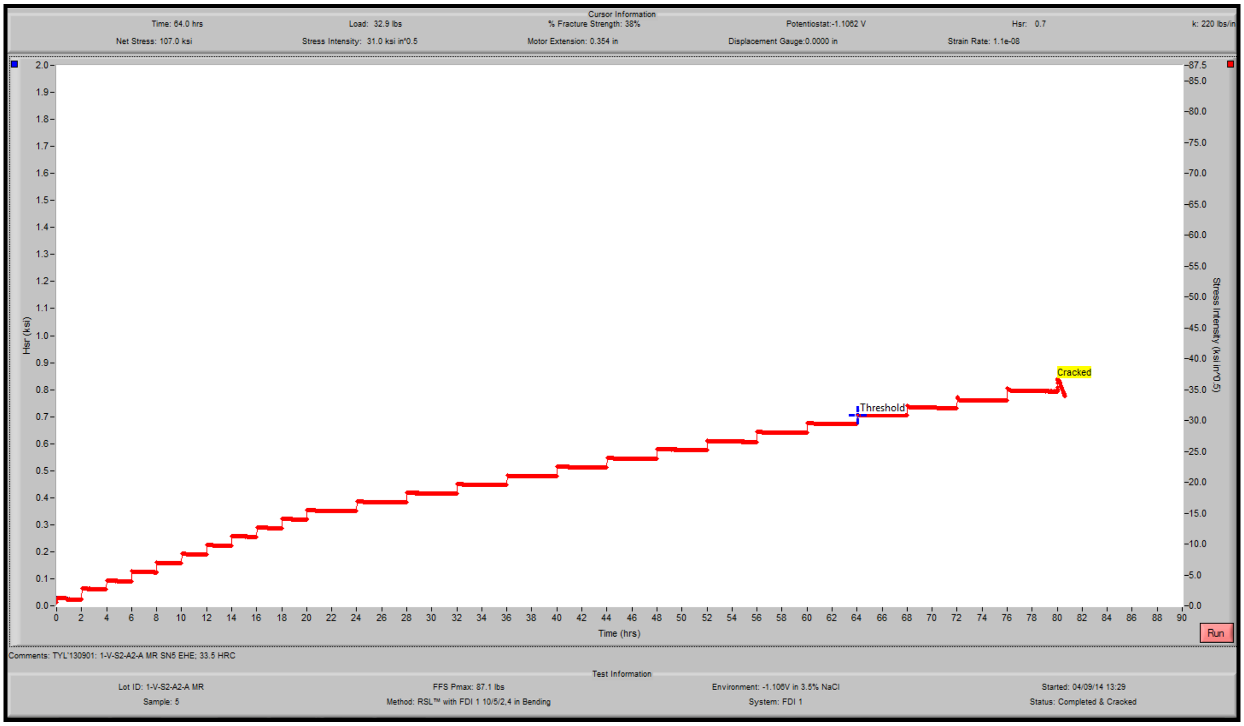


Figure D.6-28: Rod 1-V-S2-A2-A MR 5, Graphical EHE Results

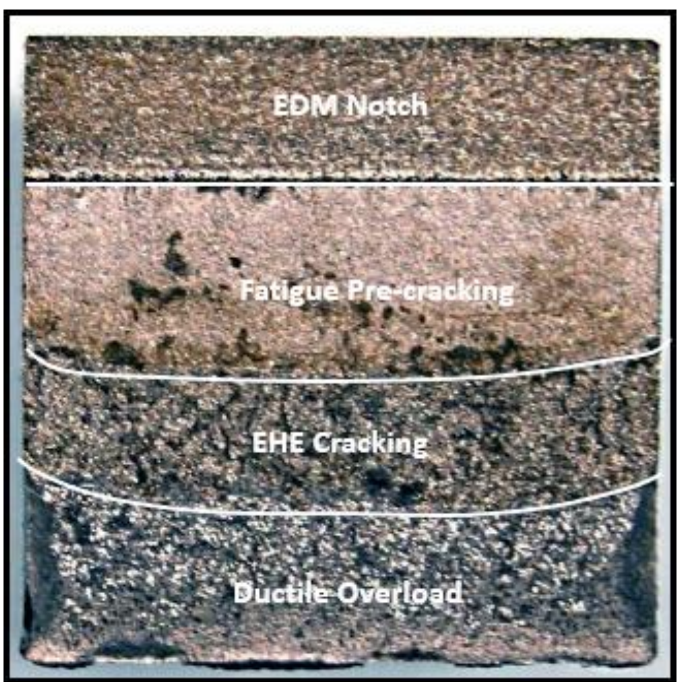


Figure D.6-29: Fracture Face of Rod 1-V-S2-A2-A MR 5, EHE

D.6.13 MR 8, EHE:

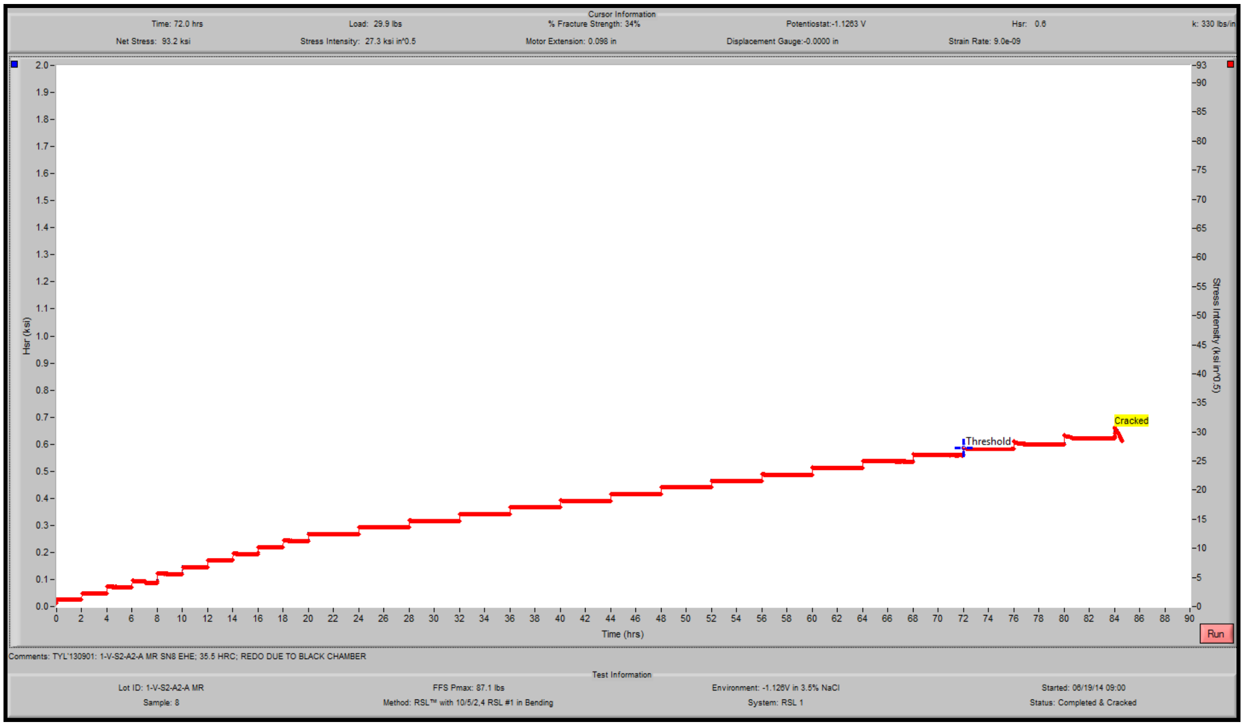


Figure D.6-30: Rod 1-V-S2-A2-A MR 8, Graphical EHE Results

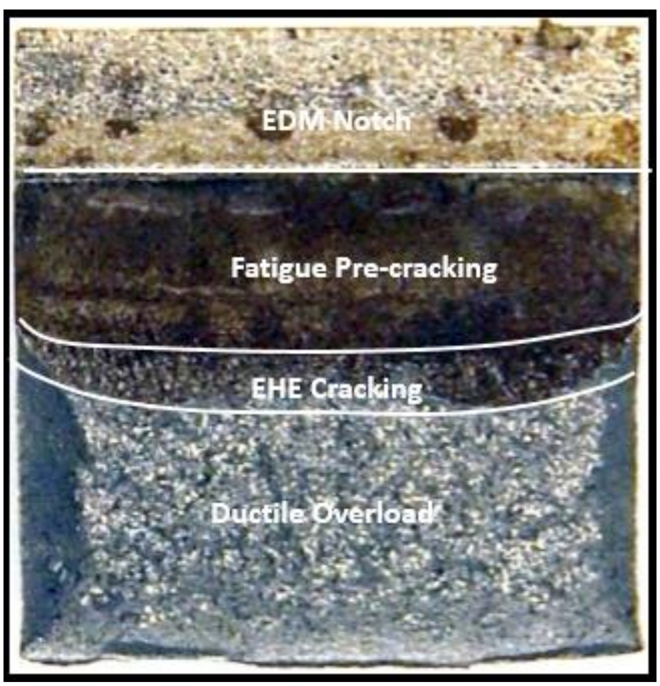


Figure D.6-31: Fracture Face of Rod 1-V-S2-A2-A MR 8, EHE

D.6.14 Center 1, FFS:

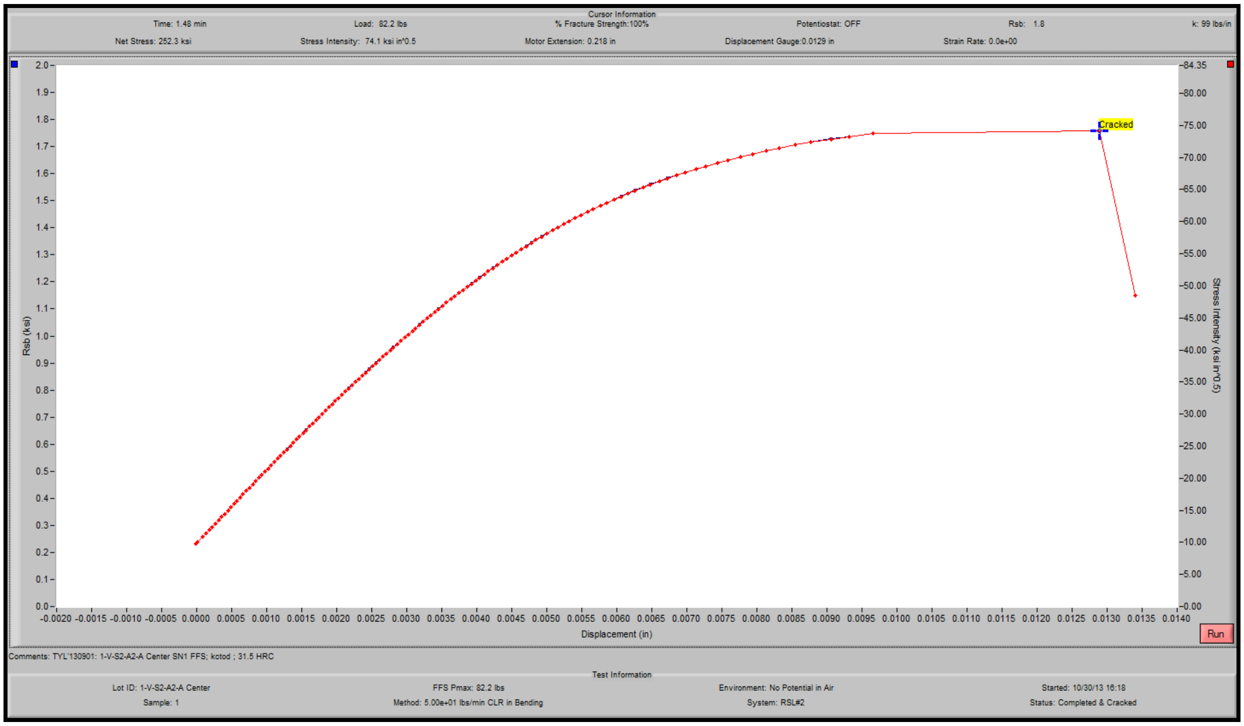


Figure D.6-32: Rod 1-V-S2-A2-A Center 1, Graphical FFS Results

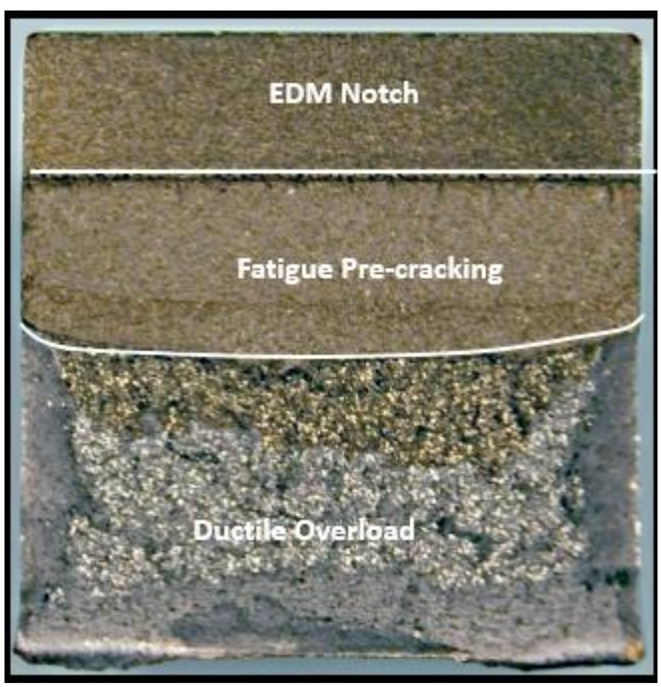
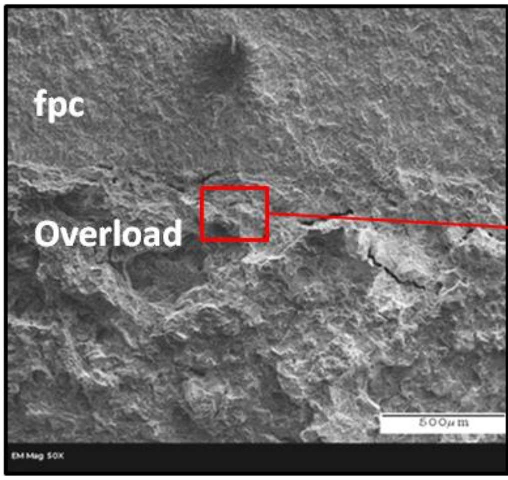
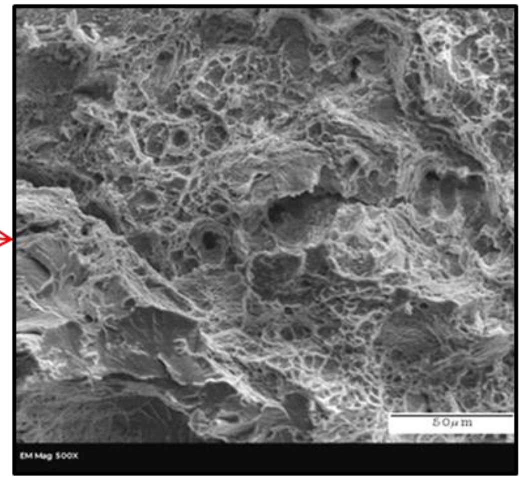


Figure D.6-33: Fracture Face of Rod 1-V-S2-A2-A Center 1, FFS

Figure D.6-34: SEM of Rod 1-V-S2-A2-A Center 1, FFS



fpc – OL transition 50X



Overload 500X

D.7 Threaded Specimen Test Results

D.7.1 Thd 1, FFS:

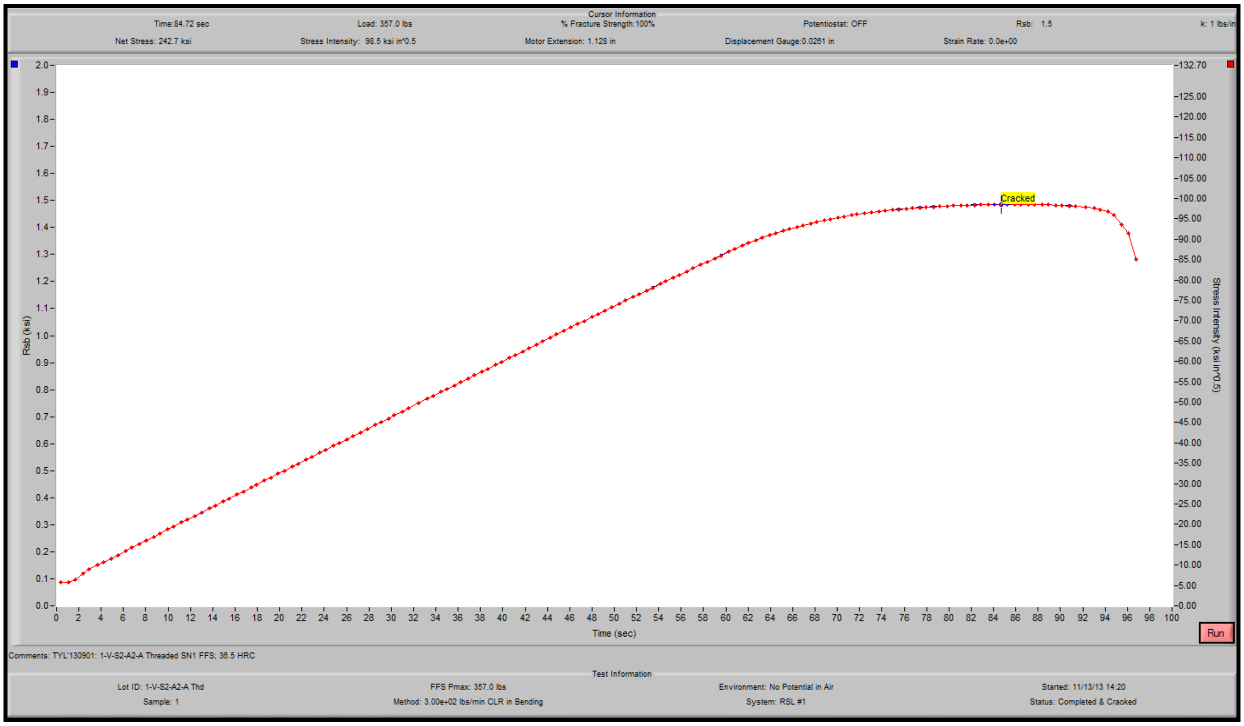
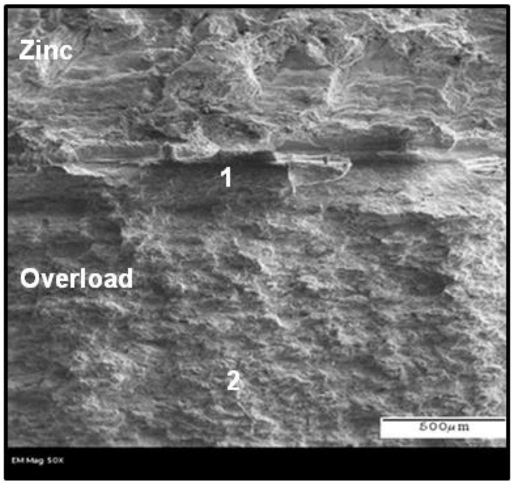


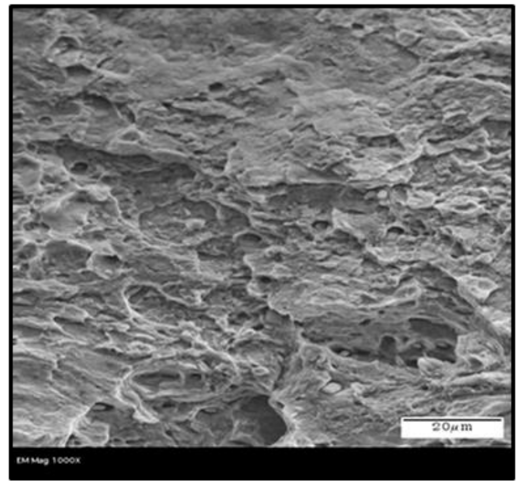
Figure D.7-1: Rod 1-V-S2-A2-A Thd 1, Graphical FFS Results

Figure D.7-2: Rod 1-V-S2-A2-A Thd 1 FFS Fracture Face

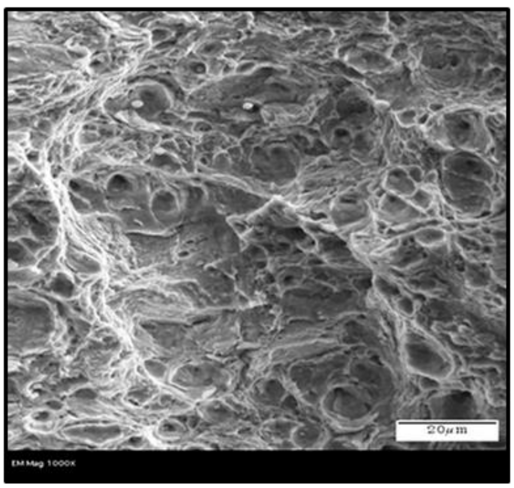
Figure D.7-3: SEM of Rod 1-V-S2-A2-A Thd 1, FFS



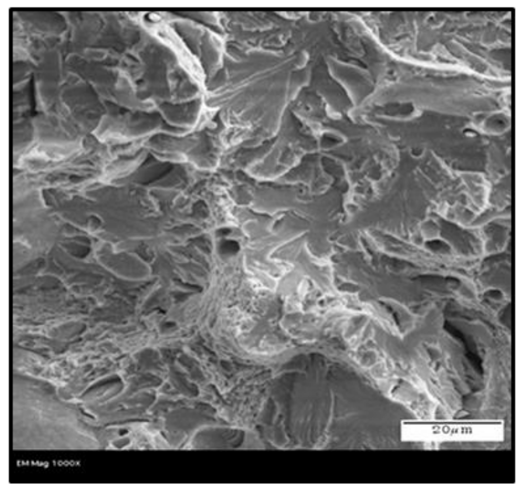
Thread Root 50X



1) Ductile Overload 1000X



2) Ductile Overload 1000X



Impact, Cleavage 1000X

D.7.2 Thd 2, IHE:

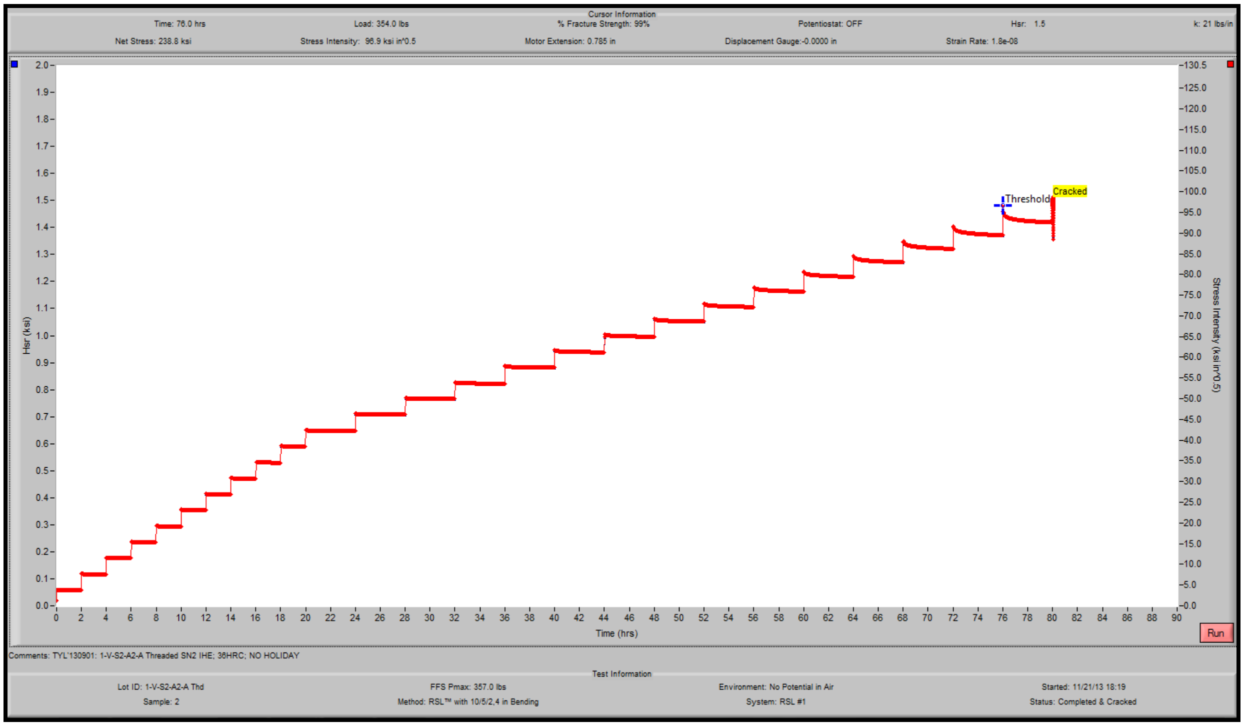


Figure D.7-4: Rod 1-V-S2-A2-A Thd 2, Graphical IHE Results

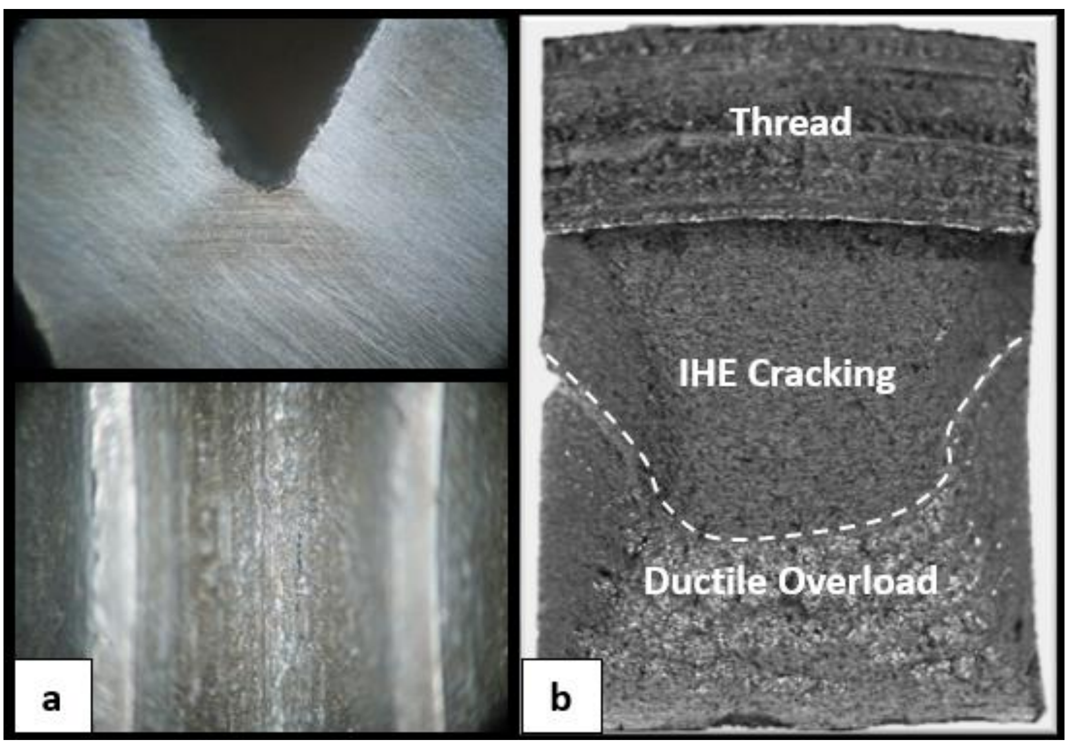


Figure D.7-5: Rod 1-V-S2-A2-A Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

D.7.3 Thd 3, EHE:

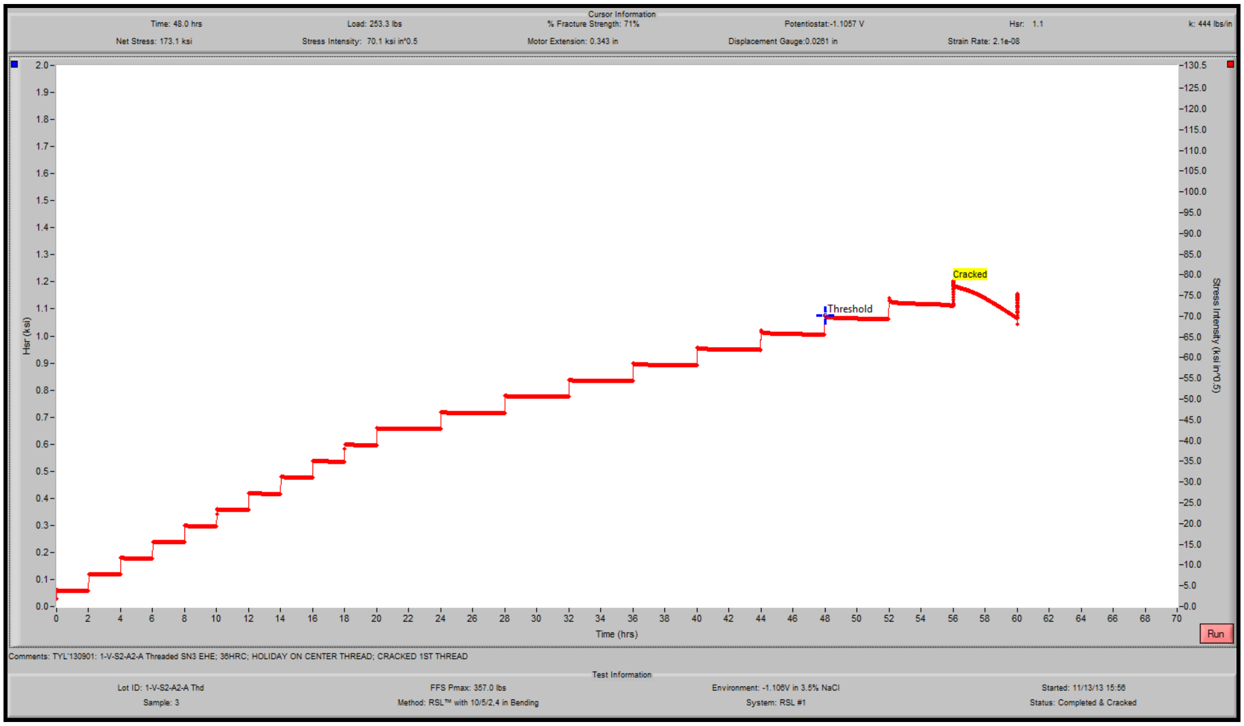


Figure D.7-6: Rod 1-V-S2-A2-A Thd 3, Graphical EHE Results

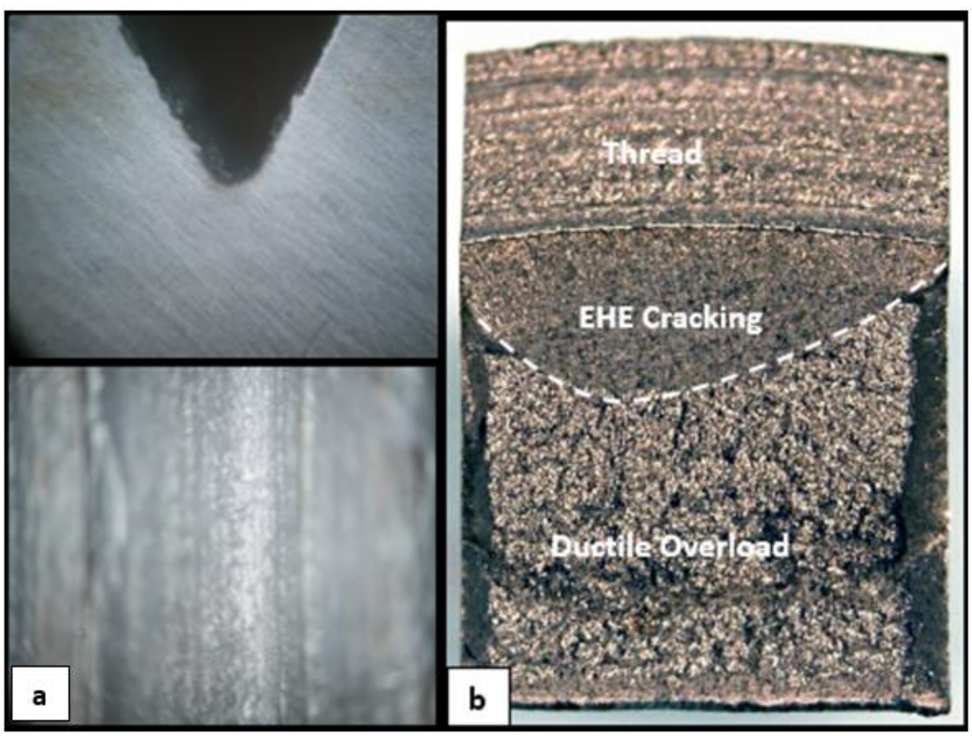
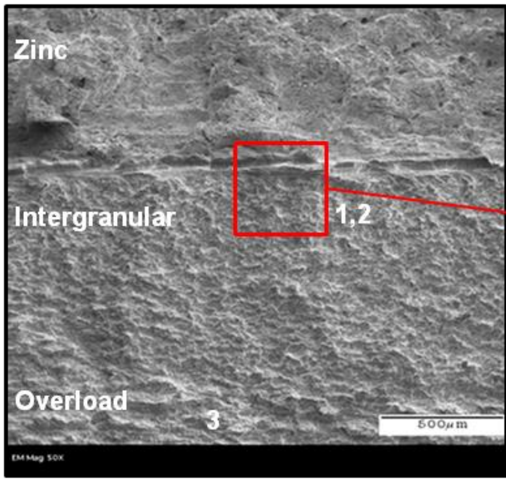
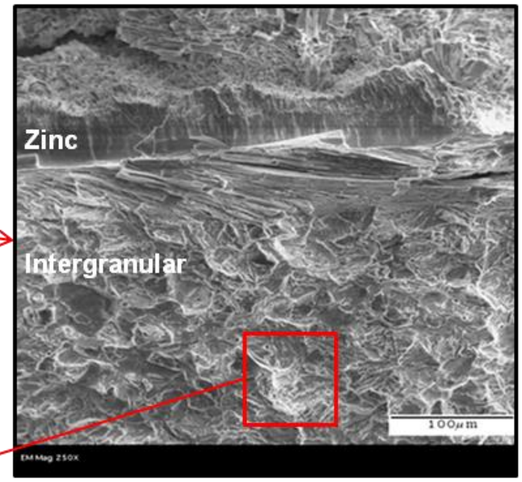


Figure D.7-7: Rod 1-V-S2-A2-A Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

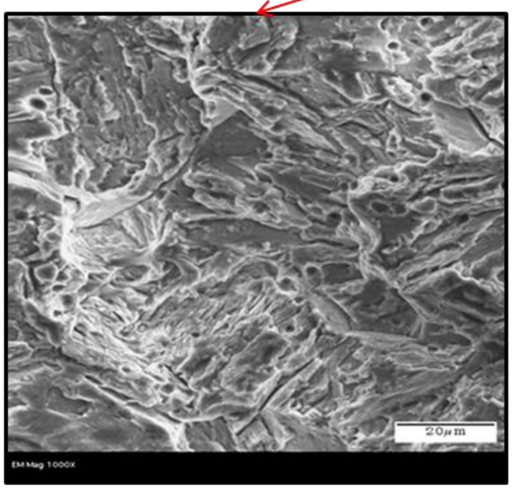
Figure D.7-8: SEM of Rod 1-V-S2-A2-A Thd 3, EHE



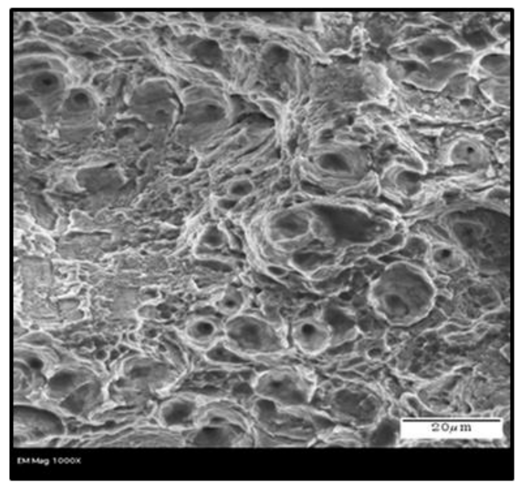
Thread Root 50X



1) Mixed: Brittle Cleavage, Intergranular 250X



2) Mixed: Brittle Cleavage, Intergranular 1000X



3) Ductile Overload 1000X

D.7.4 Thd 4, EHE:

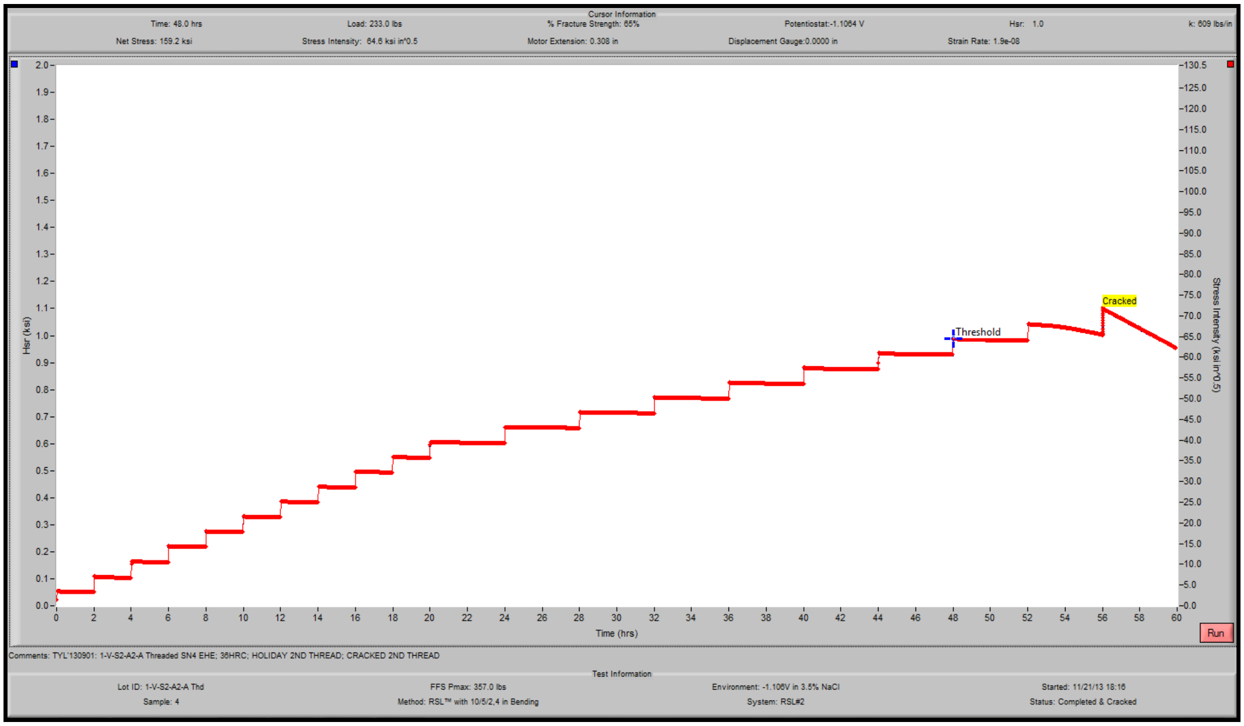


Figure D.7-9: Rod 1-V-S2-A2-A Thd 4, Graphical EHE Results

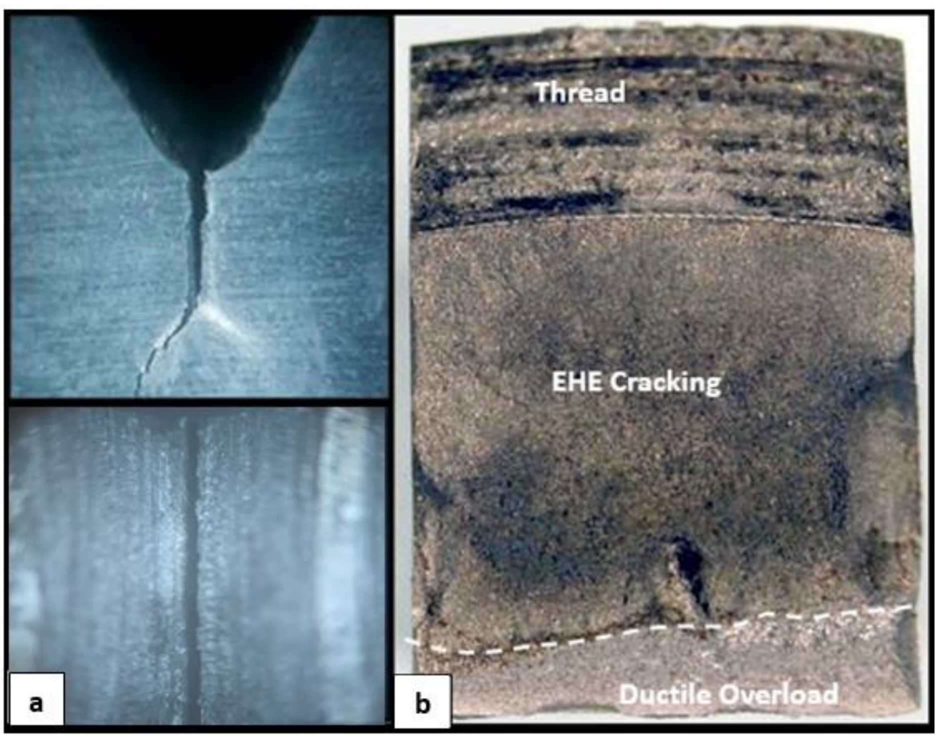
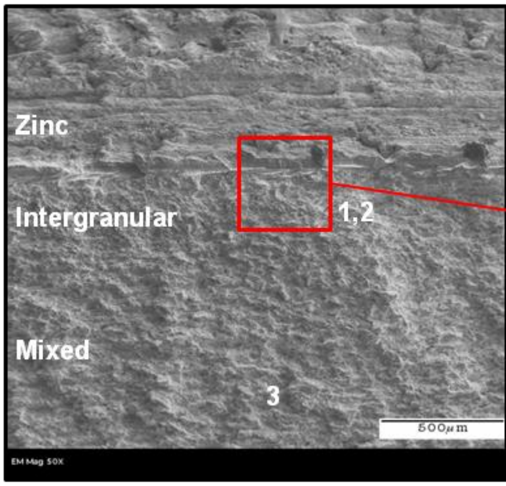
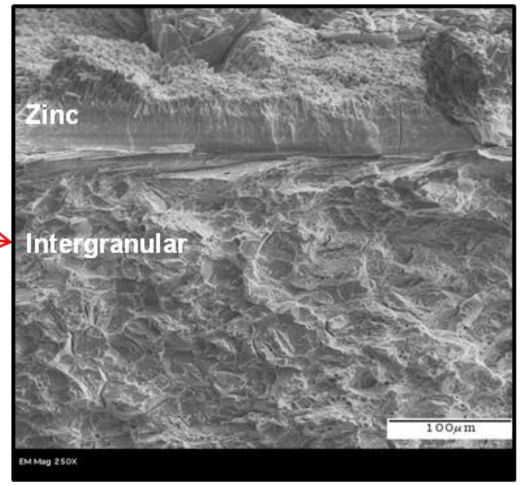


Figure D.7-10: Rod 1-V-S2-A2-A Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

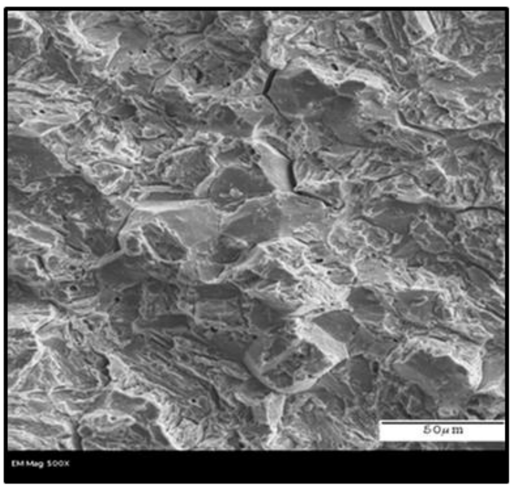
Figure D.7-11: SEM of Rod 1-V-S2-A2-A Thd 4, EHE



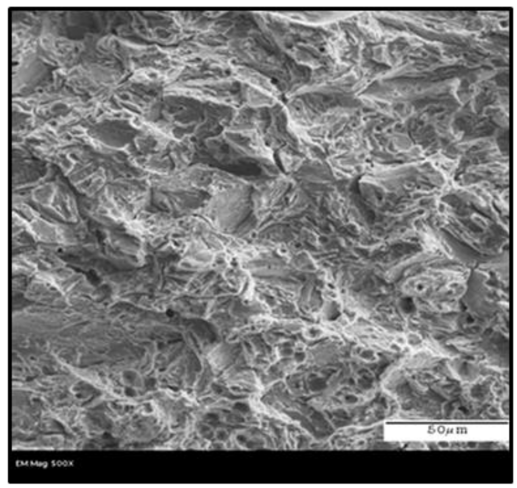
Thread Root 50X



1) Mixed: Ductile Overload, Intergranular 250X



2) Mixed: Ductile Overload, Intergranular 500X



3) Mixed: Ductile Overload, Intergranular 500X

D.7.5 Thd 5, EHE:

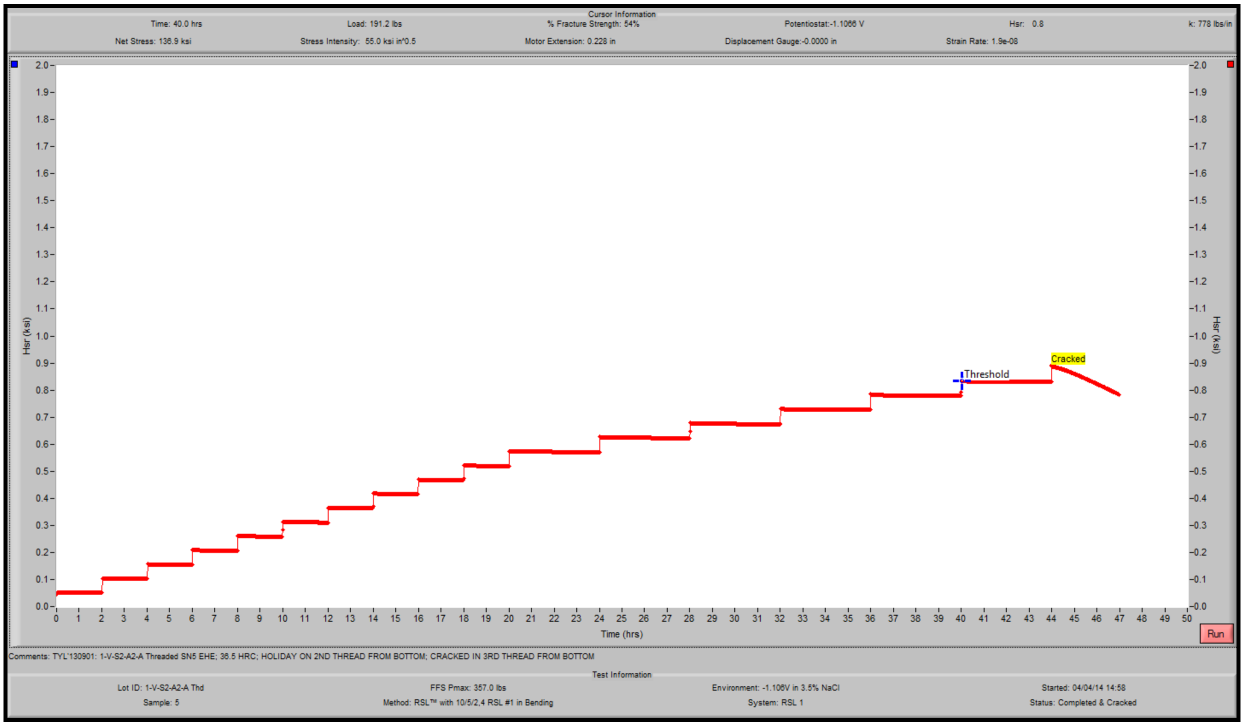


Figure D.7-12: Rod 1-V-S2-A2-A Thd 5, Graphical EHE Results

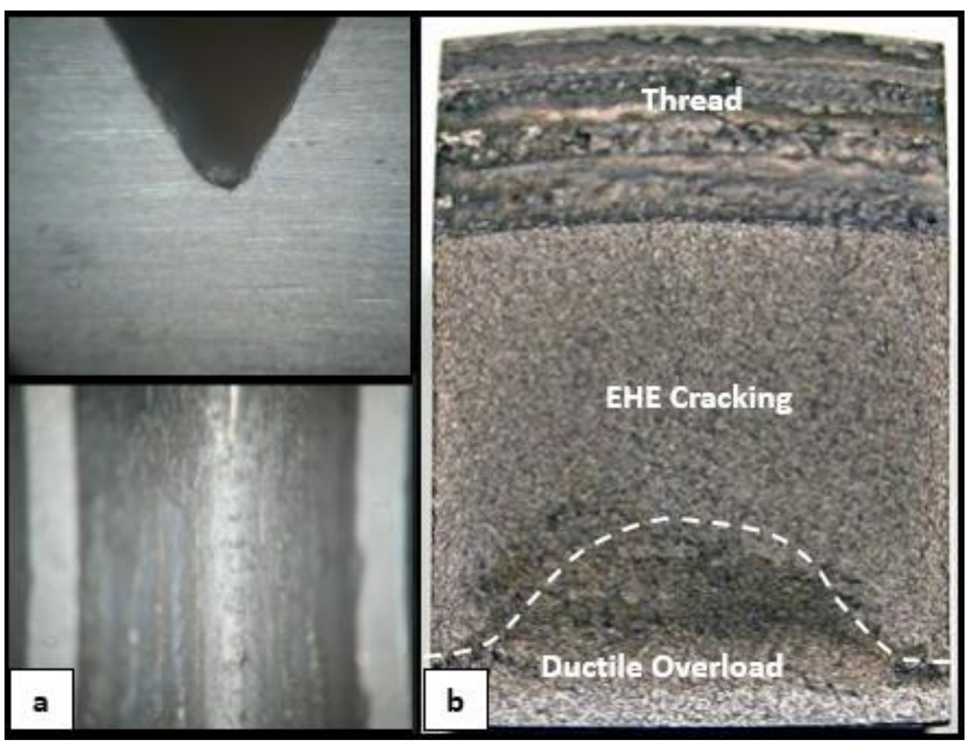


Figure D.7-13: Rod 1-V-S2-A2-A Thd 5 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

D.7.6 Thd 6, EHE:

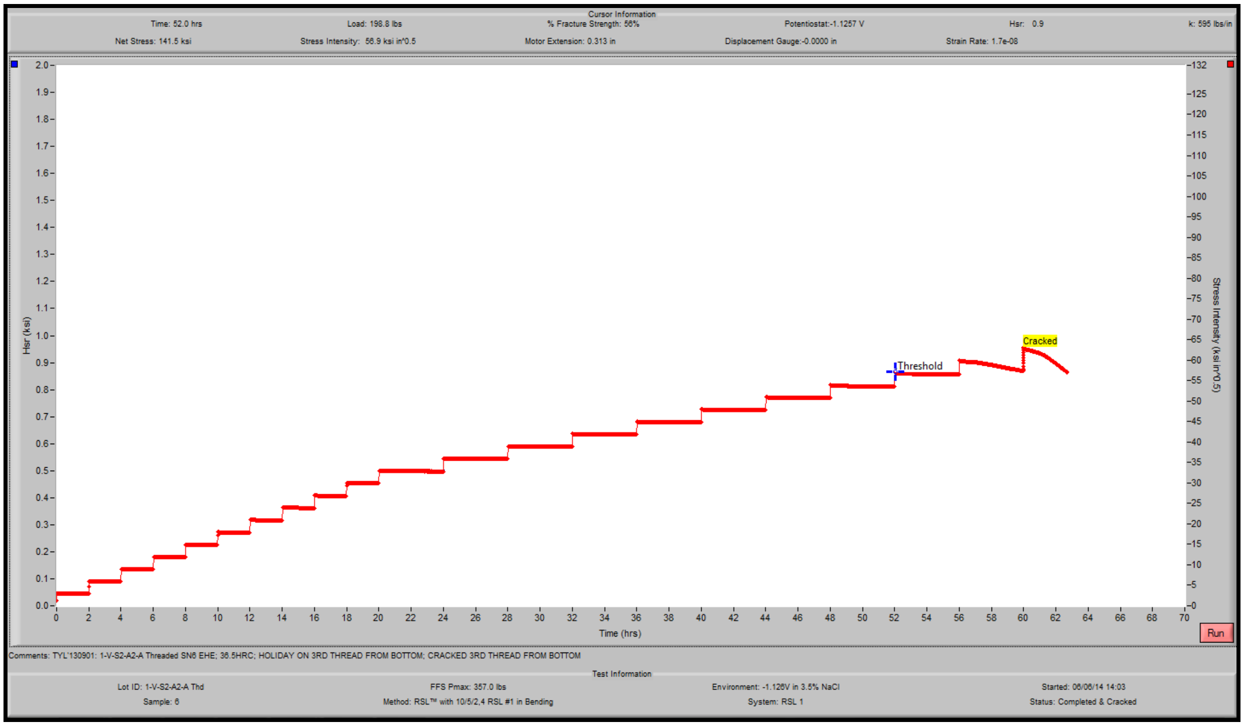


Figure D.7-14: Rod 1-V-S2-A2-A Thd 6, Graphical EHE Results

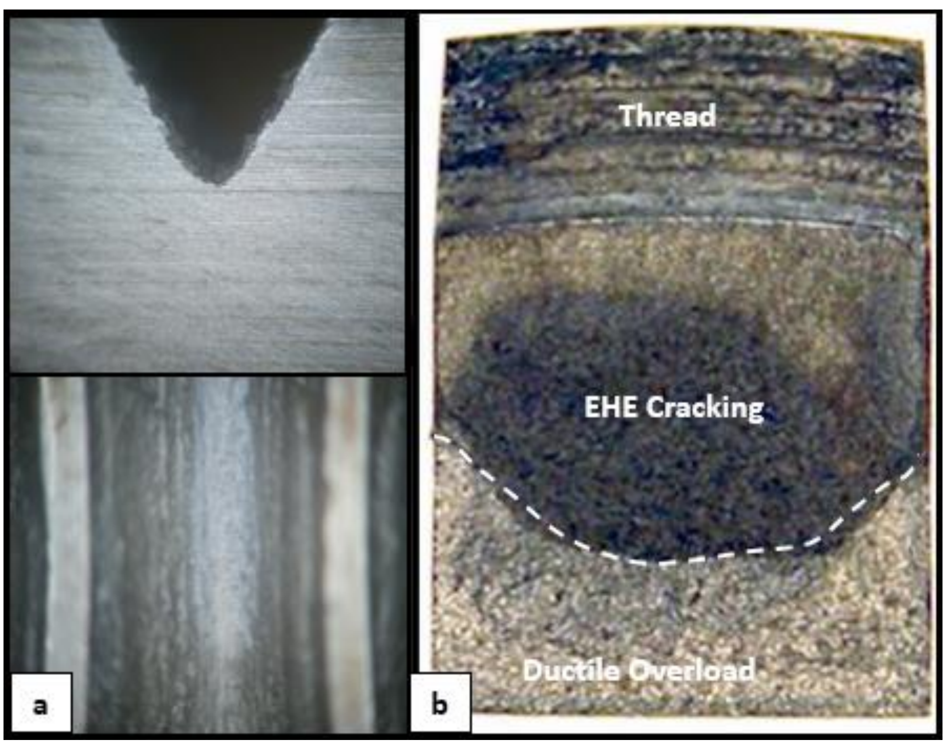


Figure D.7-15: Rod 1-V-S2-A2-A Thd 6 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix E: Rod 1-V-S2-A2-D

E.1 Description of Sample

Rod 1-V-S2-A2-D was located at the bottom of the Shear Key Anchor Bolts on Pier E2 (S1/S2) and was from the same group of material that was tested in Test Rigs 12 and 13 in Test IV. The D at the end of the serial number identifies that this section of the 2008 Rod 1-V-S2-A2 was located near the fracture end (dead end) in March 2013. It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 3 inches in diameter with machined threads. The segment from this section of the rod provided to LRA is shown in **Figure E.1-1**.

Figure E.1-1: Pier E2 Bearing Bolt (Top Housing), Rod 1-V-S2-A2-D

E.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 1-V-S2-A2-D and can be seen versus time in **Figure E.2-1**. The final OCP recorded for Rod 1-V-S2-A2-D was Vsce=-1.073 V.

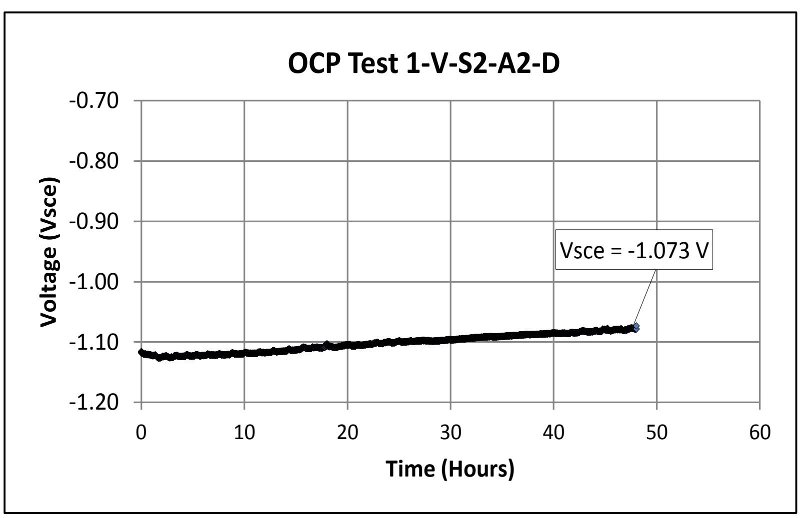


Figure E.2-1: Open Circuit Potential for Rod 1-V-S2-A2-D

E.3 Hardness

The hardness data and profile for sample 1-V-S2-A2-D are shown in **Table E.3-1** and **Figure E.3-1**. The center specimen that was machined to incorrect dimensions and will not be included in the hardness data.

Table E.3-1: Hardness Data of Rod 1-V-S2-A2-D Specimen

S/N	Hardness (HRC)	Average (HRC)
MR 1, FFS	32.0	33.0
MR 3, EHE	34.0	
MR 4, EHE	33.0	
OD 1, FFS	36.0	35.8
OD 3, EHE	35.0	
OD 4, EHE	36.0	
OD 2, IHE	36.0	
OD 5, IHE	36.0	
OD 6, EHE	35.0	
Thd 1, FFS	36.0	
Thd 4, EHE	35.5	
Thd 2, IHE	36.0	
Thd 6, EHE	36.0	
Thd 7, EHE	36.0	

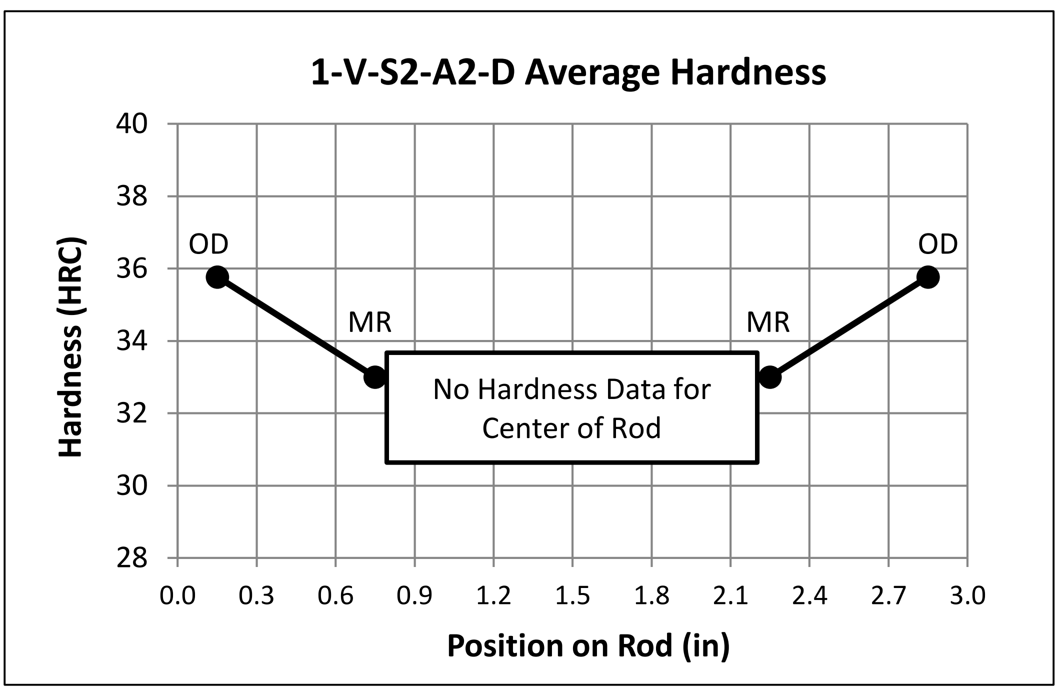


Figure E.3-1: Hardness Profile of Rod 1-V-S2-A2-D

E.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

E.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 1-V-S2-A2-D						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Bottom (S1/S2) **Comments:** Machined Threads; 2008 Near Fracture (Dead End) Same Group of Material as Test Rig #12 and #13 in Test IV				
Rod#:	**1-V-S2-A2-D**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**36.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	84.3 0.52 0.95 8500		
	OD 2, IHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		77.0 0.48 0.87 2.3	
	OD 3, EHE	**35.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			45.4 0.29 0.51 2.2
	OD 4, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			29.3 0.18 0.33 2.0
	OD 5, IHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		78.7 0.49 0.89 1.8	

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 1-V-S2-A2-D						
LRA Job No.:	**TYL130901**	**Structural Component**: Shear Key Anchor Bolts-Bottom (S1/S2)				
Rod#:	**1-V-S2-A2-D**					
Product Form:	**1e**	**Comments:** Machined Threads; 2008 Near Fracture (Dead End) Same Group of Material as Test Rig #12 and #13 in Test IV				
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 6, EHE**	**35.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			29.1 0.19 0.33 1.8
	MR 1, FFS	**32.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	78.0 0.54 0.88 8500		
	MR 3, EHE	**34.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			29.1 0.19 0.33 1.8
	MR 4, EHE	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			29.6 0.20 0.33 1.0

E.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 1-V-S2-A2-D						
LRA Job No.:	TYL130901	**Structural Component**: Shear Key Anchor Bolts-Bottom (S1/S2) **Comments:** Machined Threads; 2008 Near Fracture (Dead End) Same Group of Material as Test Rig #12 and #13 in Test IV				
Rod#:	1-V-S2-A2-D					
Product Form:	1e					
Rod OD:	3"					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**36.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	326.2 1.07 1.5 4300		
	Thd 2, IHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		318.6 1.05 1.4 2.2	
	Thd 4, EHE	**35.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			263.4 0.87 1.2 2.2
	Thd 6, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			178.0 0.59 0.8 0.8
	Thd 7, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			194.1 0.64 0.9 0.8

E.4.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 1-V-S2-A2-D
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**1-V-S2-A2-D**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	36.0	162	92.4	92.4	92.4	100.0%	84.3	0.52	288.7	1.8	8500	0.2121	121.0	50 lbs/min		0.95	
	OD 2, IHE	Air	36.0	162	62.0	86.6	83.1	91.3%	77.0	0.48	264.7	1.6	2.3	0.2159		10/5/2,4		0.87	
	OD 3, EHE	3.5% NaCl @ -1.106V	35.0	157	62.0	62.1	49.5	53.9%	45.4	0.29	155.4	1.0	2.2	0.2114		10/5/2,4		0.51	
	OD 4, EHE	3.5% NaCl @ -1.106V	36.0	162	55.0	35.8	30.2	34.8%	29.3	0.18	101.9	0.6	2.0	0.2193		10/5/2,4		0.33	
	OD 5, IHE	Air	36.0	162	52.0	89.2	87.5	93.4%	78.7	0.49	267.2	1.7	1.8	0.2119		10/5/2,4		0.89	
	OD 6, EHE	3.5% NaCl @ -1.106V	35.0	157	33.0	34.7	31.2	34.5%	29.1	0.19	100.3	0.6	1.8	0.2158		10/5/2,4		0.33	
	MR 1, FFS	Air	32.0	145	86.1	86.1	86.1	100.0%	78.0	0.54	266.5	1.8	8500	0.2112	121.9	50 lbs/min		0.88	
	MR 3, EHE	3.5% NaCl @ -1.106V	34.0	153	56.0	42.1	30.7	37.3%	29.1	0.19	100.4	0.7	1.8	0.2175		10/5/2,4		0.33	
	MR 4, EHE	3.5% NaCl @ -1.106V	33.0	149	25.0	38.8	29.9	37.9%	29.6	0.20	103.6	0.7	1.0	0.2224		10/5/2,4		0.33	
Threaded	Thd 1, FFS	Air	36.0	162	343.0	343.0	343.0	100.0%	95.1	0.59	236.1	1.5	4300	N/A		0.4 in/min	326.2	1.07	
	Thd 2, IHE	Air	36.0	162	280.0	338.1	336.1	97.7%	92.9	0.57	230.3	1.4	2.2	N/A		10/5/2,4	318.6	1.05	
	Thd 4, EHE	3.5% NaCl @ -1.106V	35.5	159	280.0	294.0	278.1	80.8%	76.8	0.48	190.5	1.2	2.2	N/A		10/5/2,4	263.4	0.87	Cracked In Holiday
	Thd 6, EHE	3.5% NaCl @ -1.106V	36.0	162	200.0	189.0	178.5	54.6%	51.9	0.32	129.1	0.8	0.8	N/A		10/5/2,8	178.0	0.59	Did Not Crack In Holiday Changed to 10/5/2,8 After 2 hour Steps
	Thd 7, EHE	3.5% NaCl @ -1.106V	36.0	162	175.0	203.5	194.1	59.5%	56.6	0.35	141.0	0.9	0.8	N/A		10/5/2,8	194.1	0.64	Did Not Crack in Holiday 10/5/2,8 Ran for 24 Hours at -1.068 Vsce Due to Power Outage

E.5 Fatigue Pre-cracked Specimen Test Results

E.5.1 OD 1, FFS:

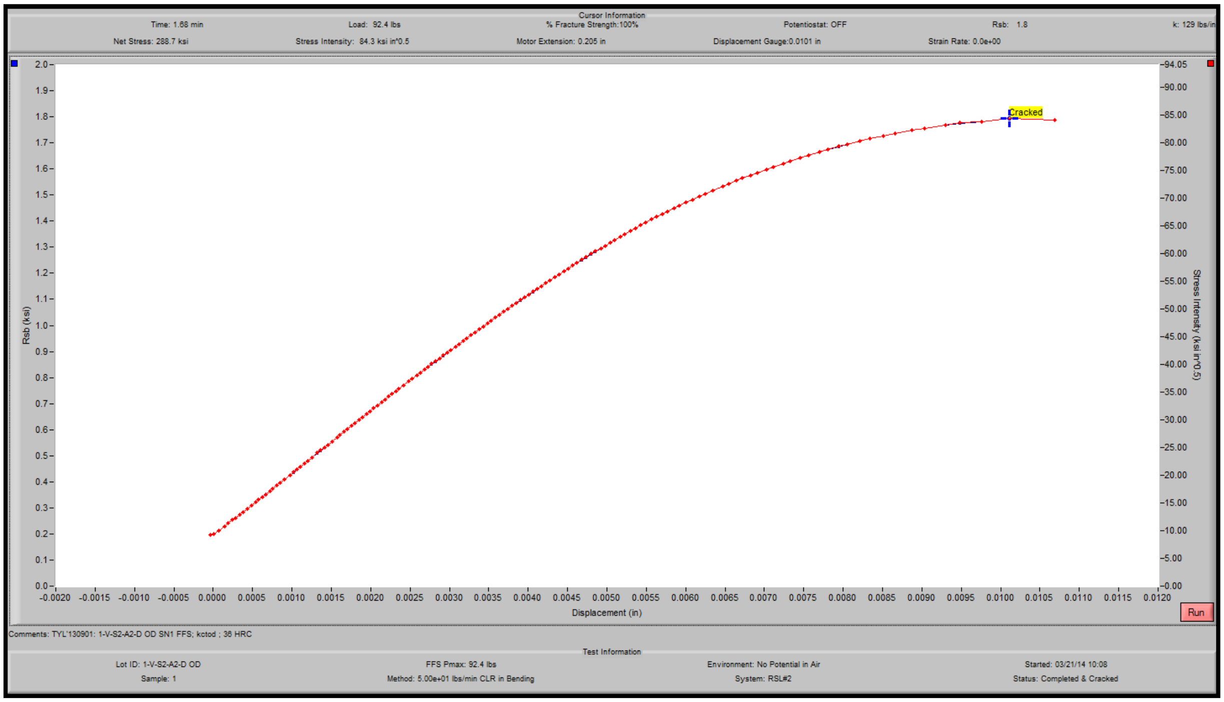


Figure E.5-1: Rod 1-V-S2-A2-D OD 1, Graphical FFS Results

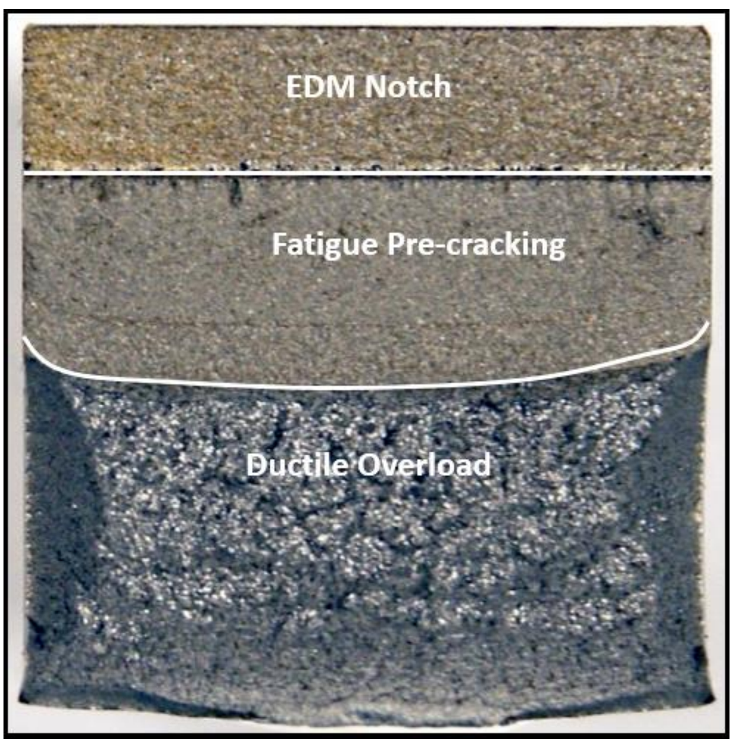


Figure E.5-2: Fracture Face of Rod 1-V-S2-A2-D OD 1, FFS

E.5.2 OD 2, IHE:

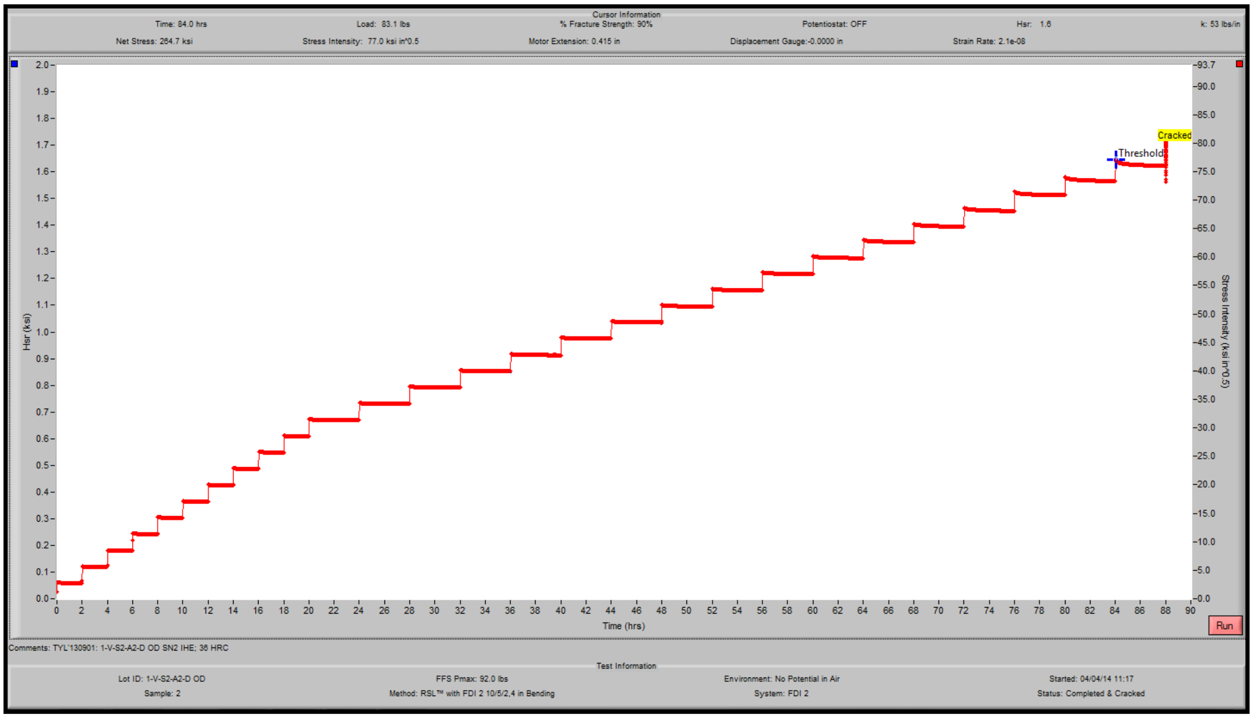


Figure E.5-3: Rod 1-V-S2-A2-D OD 2, Graphical IHE Results

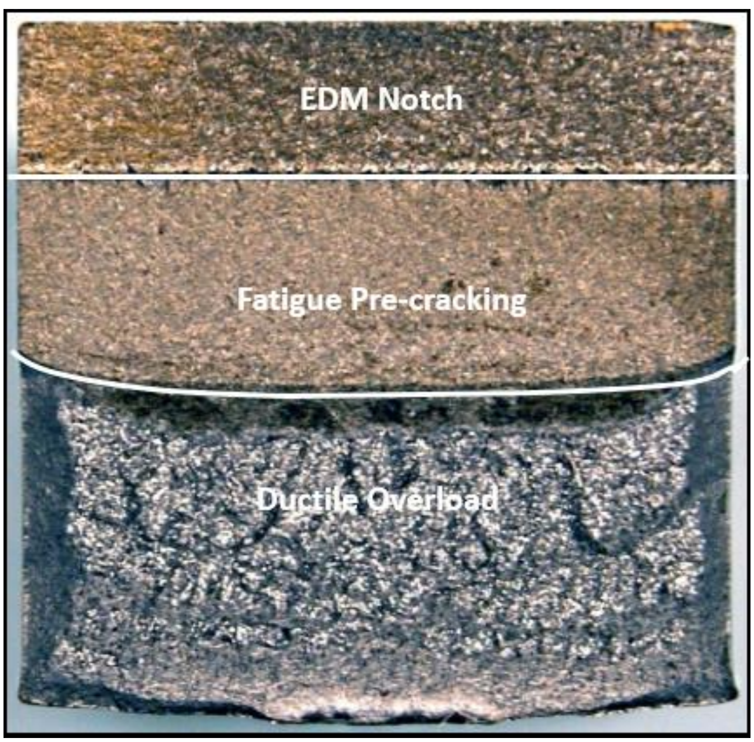


Figure E.5-4: Fracture Face of Rod 1-V-S2-A2-D OD 2, IHE

OD 3, EHE:

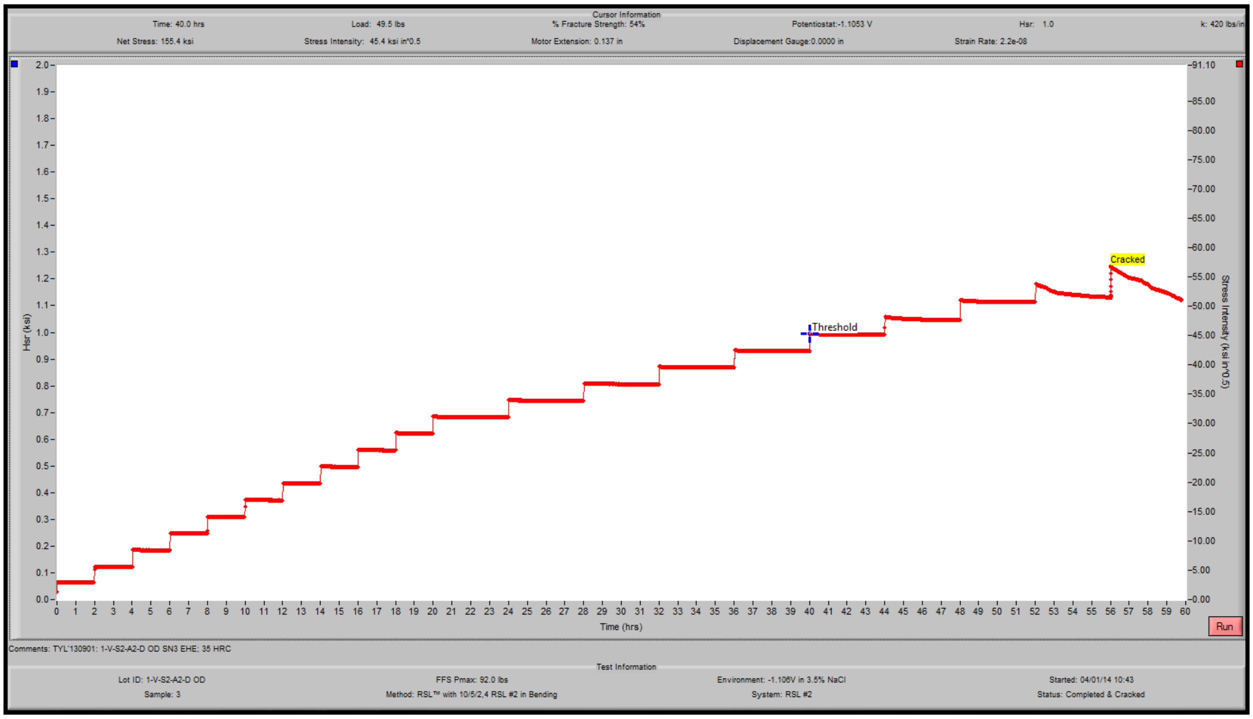


Figure E.5-5: Rod 1-V-S2-A2-D OD 3, Graphical EHE Results

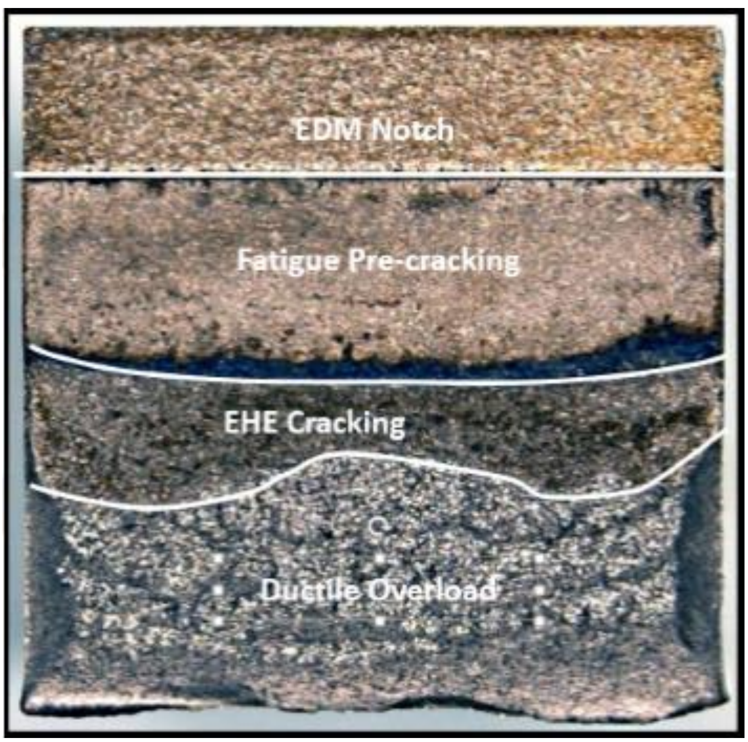


Figure E.5-6: Fracture Face of Rod 1-V-S2-A2-D OD 3, EHE

E.5.3 OD 4, EHE:

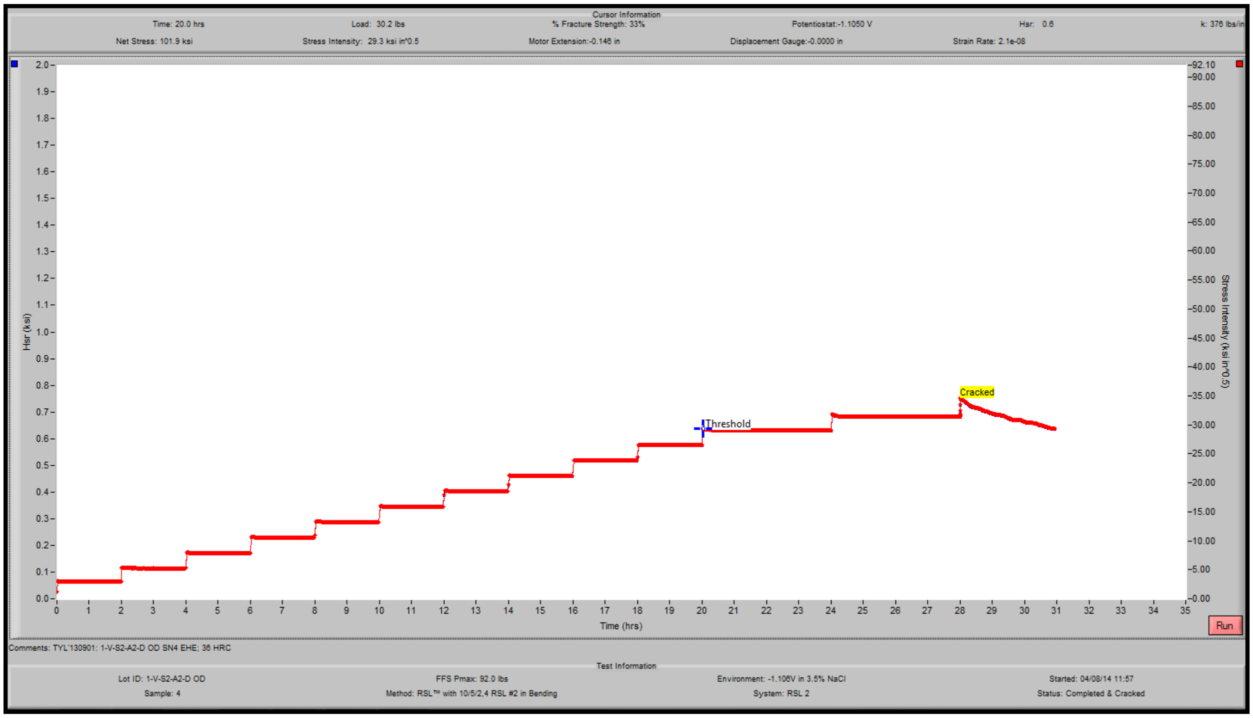


Figure E.5-7: Rod 1-V-S2-A2-D OD 4, Graphical EHE Results

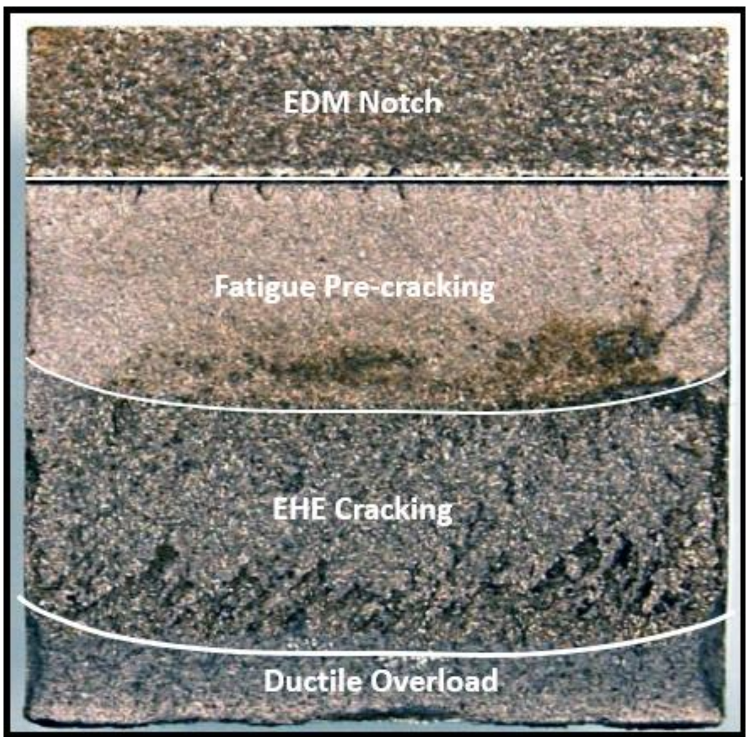


Figure E.5-8: Fracture Face of Rod 1-V-S2-A2-D OD 4, EHE

E.5.4 OD 5, IHE:

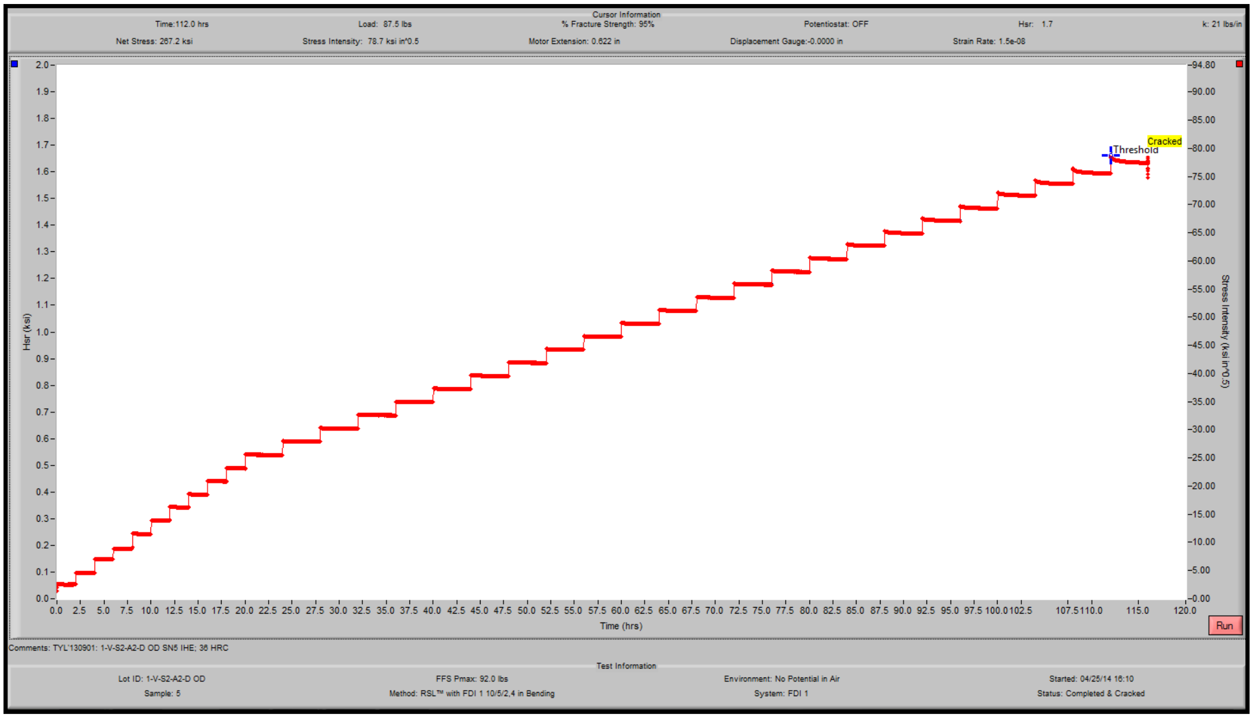


Figure E.5-9: Rod 1-V-S2-A2-D OD 5, Graphical IHE Results

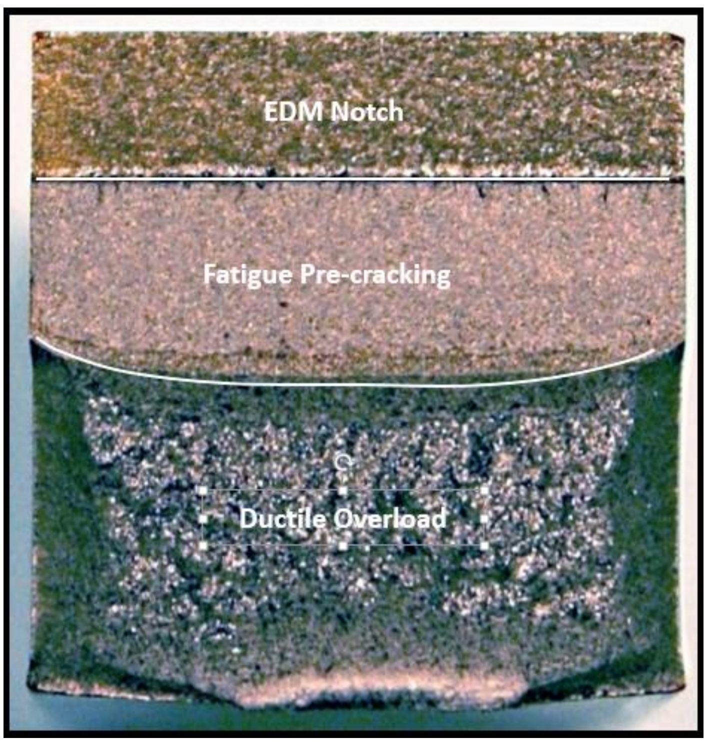


Figure E.5-10: Fracture Face of Rod 1-V-S2-A2-D OD 5, IHE

E.5.5 OD 6, EHE:

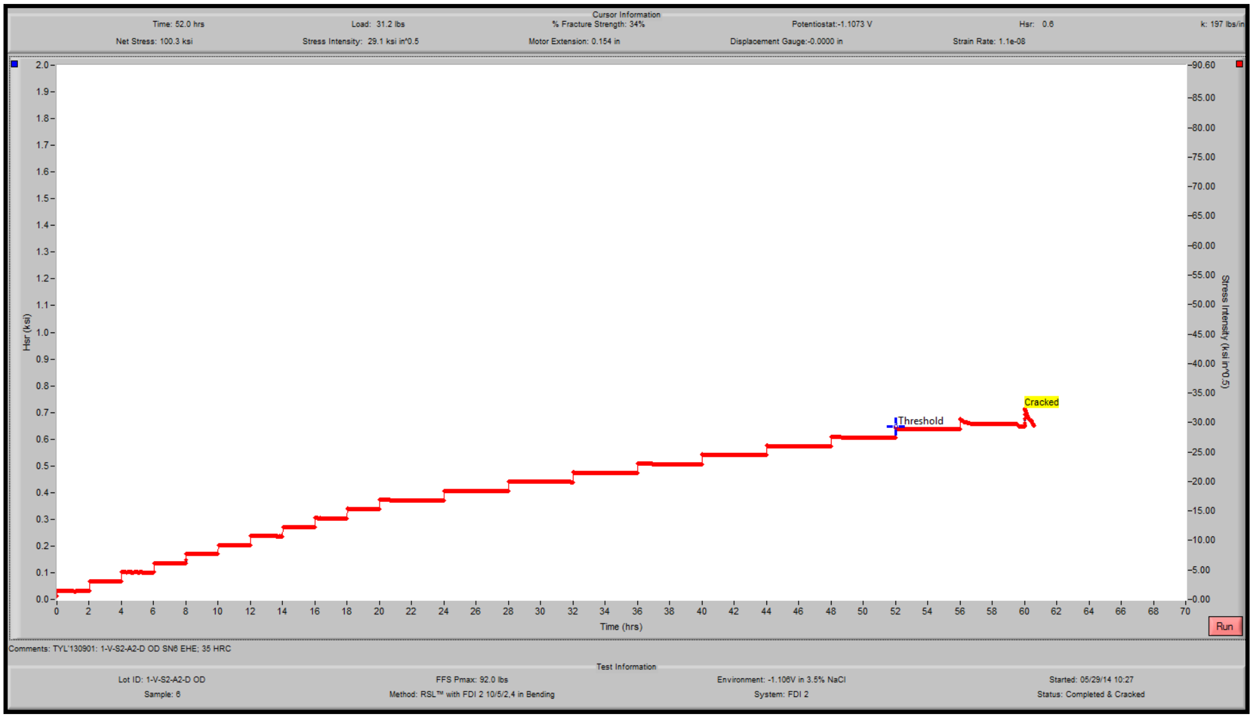


Figure E.5-11: Rod 1-V-S2-A2-D OD 6, Graphical EHE Results

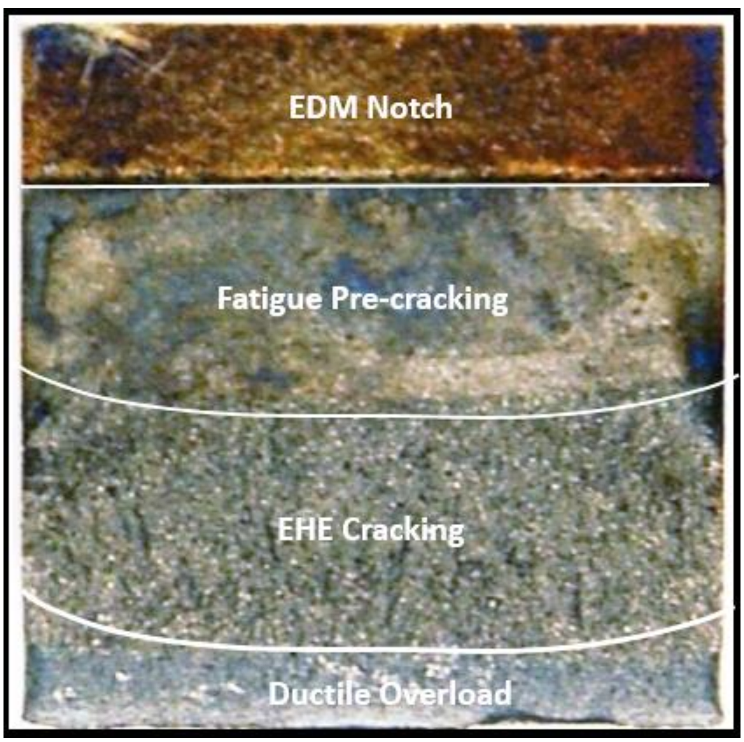


Figure E.5-12: Fracture Face of Rod 1-V-S2-A2-D OD 6, EHE

E.5.6 MR 1, FFS:

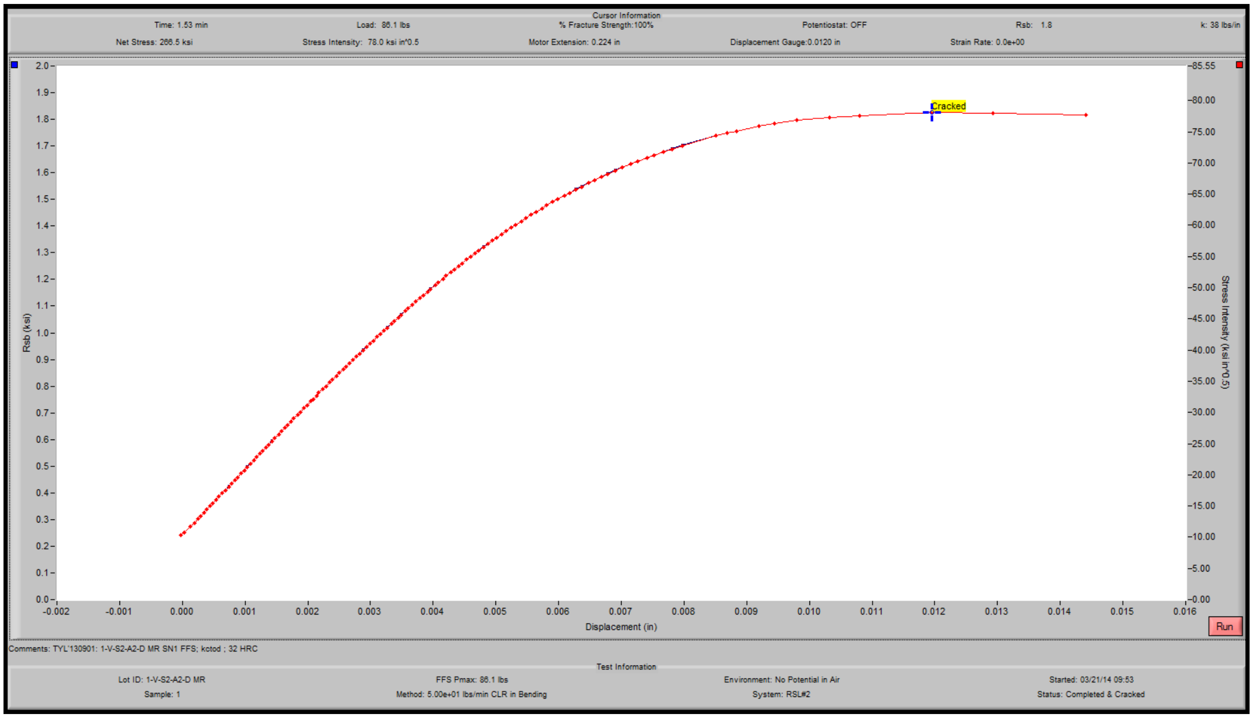


Figure E.5-13: Rod 1-V-S2-A2-D MR 1, Graphical FFS Results

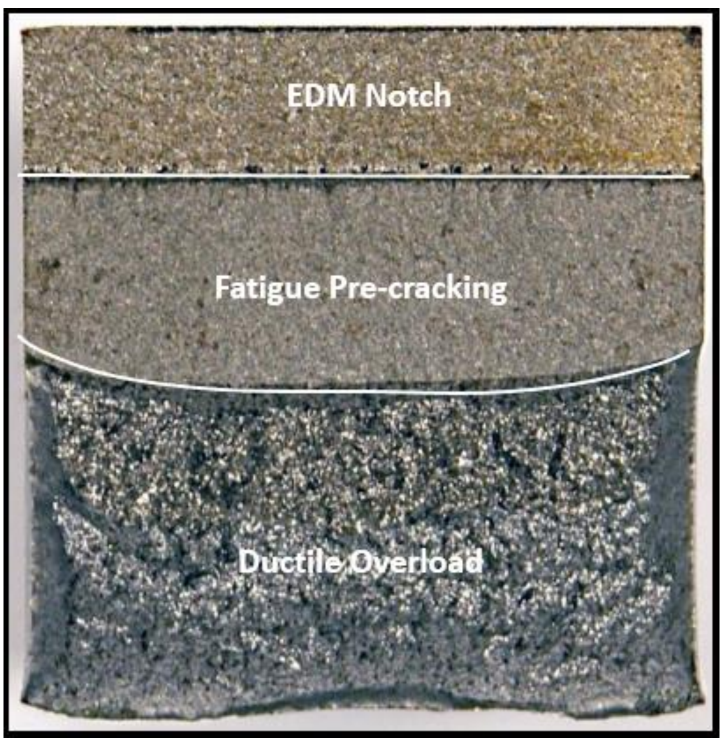


Figure E.5-14: Fracture Face of Rod 1-V-S2-A2-D MR 1, FFS

E.5.7 MR 3, EHE:

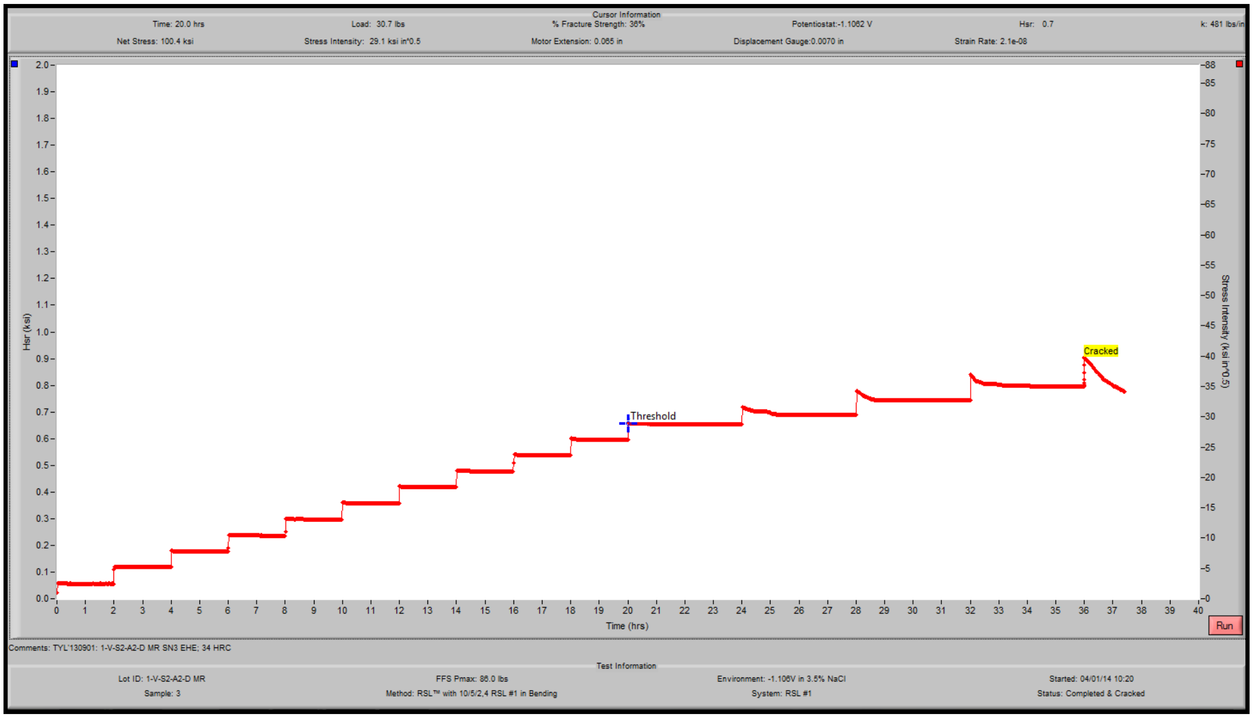


Figure E.5-15: Rod 1-V-S2-A2-D MR 3, Graphical EHE Results

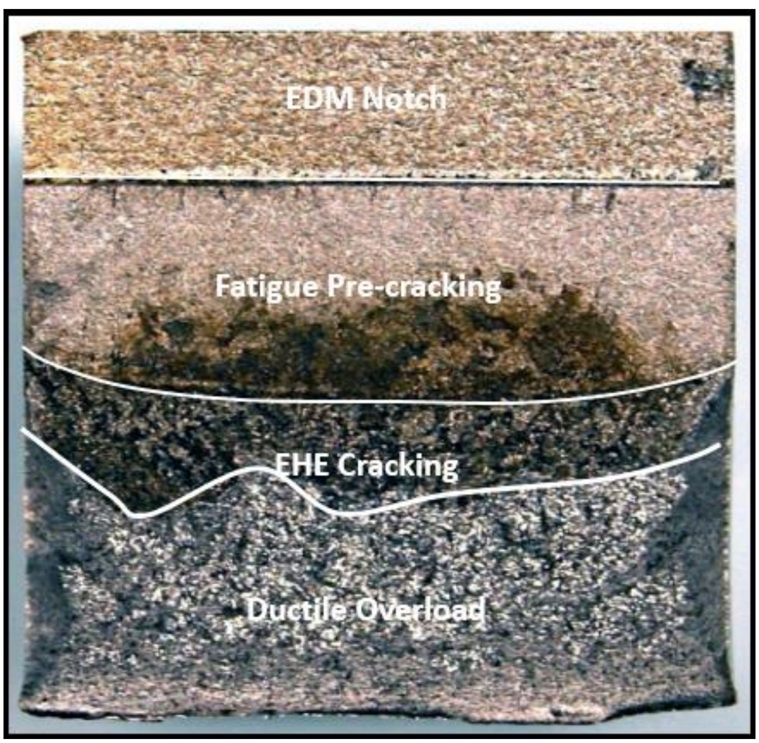


Figure E.5-16: Fracture Face of Rod 1-V-S2-A2-D MR 3, EHE

E.5.8 MR 4, EHE:

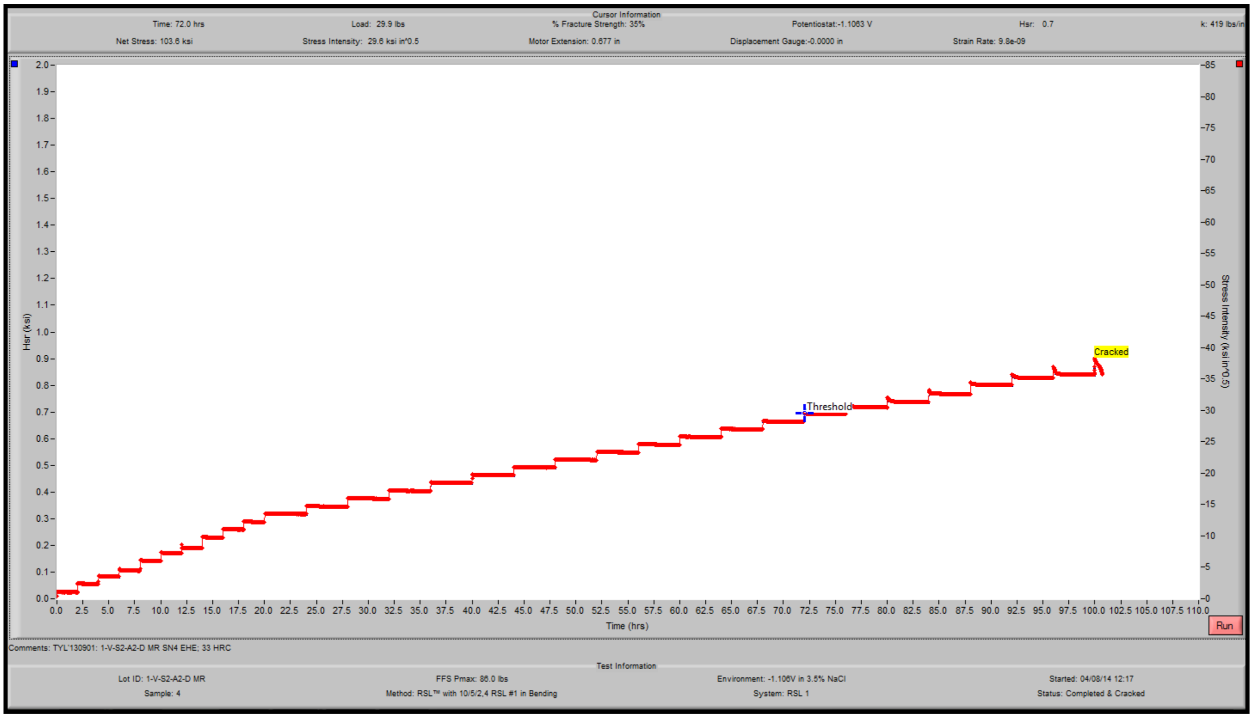


Figure E.5-17: Rod 1-V-S2-A2-D MR 4, Graphical EHE Results

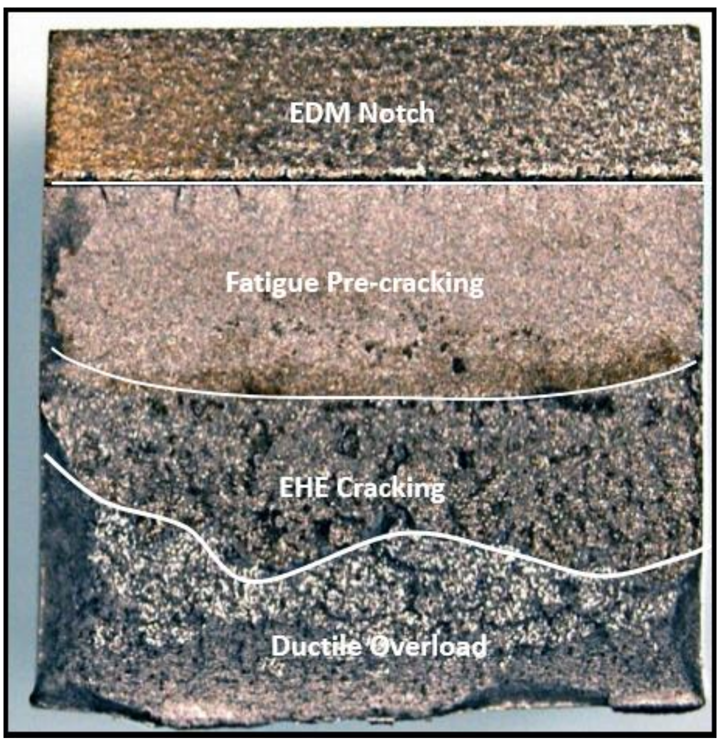


Figure E.5-18: Fracture Face of Rod 1-V-S2-A2-D MR 4, EHE

E.6 Threaded Specimen Test Results

E.6.1 Thd 1, FFS:

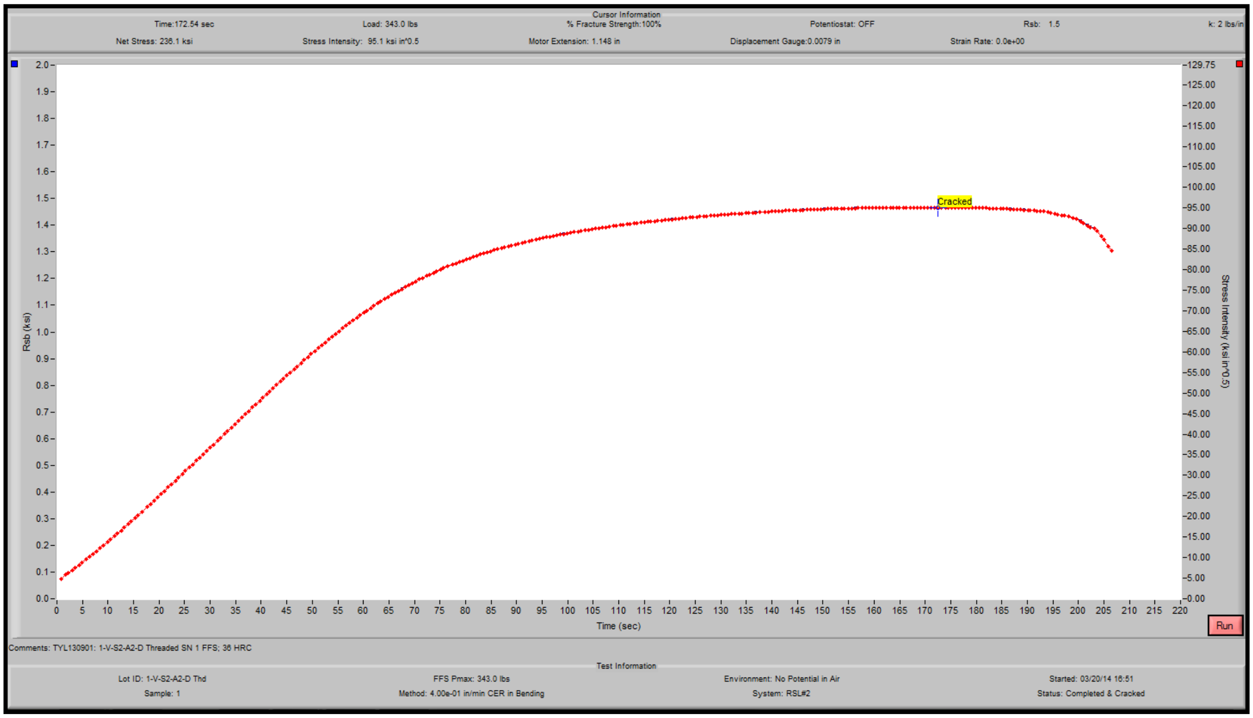


Figure E.6-1: Rod 1-V-S2-A2-D Thd 1, Graphical FFS Results

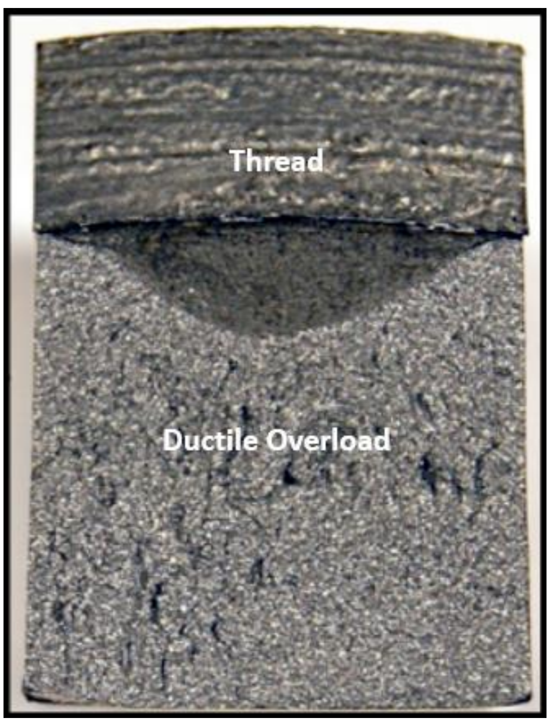


Figure E.6-2: Rod 1-V-S2-A2-A Thd 1 FFS Fracture Face

E.6.2 Thd 2, IHE:

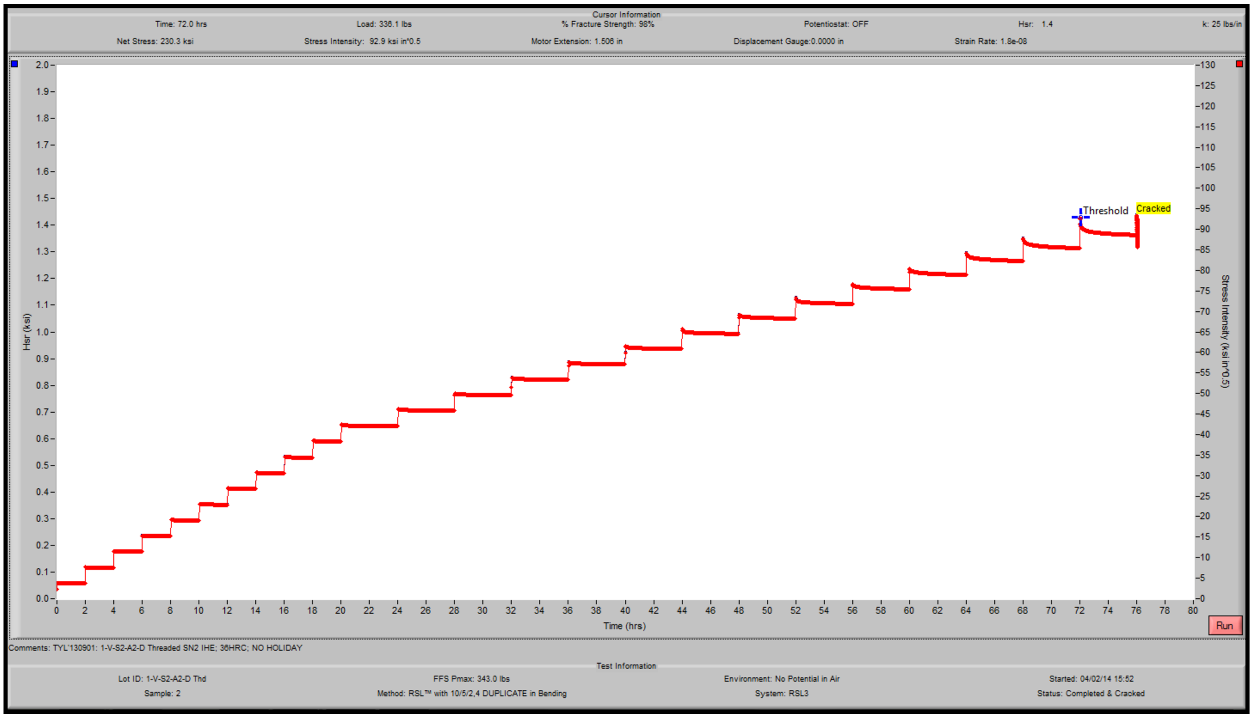


Figure E.6-3: Rod 1-V-S2-A2-D Thd 2, Graphical IHE Results

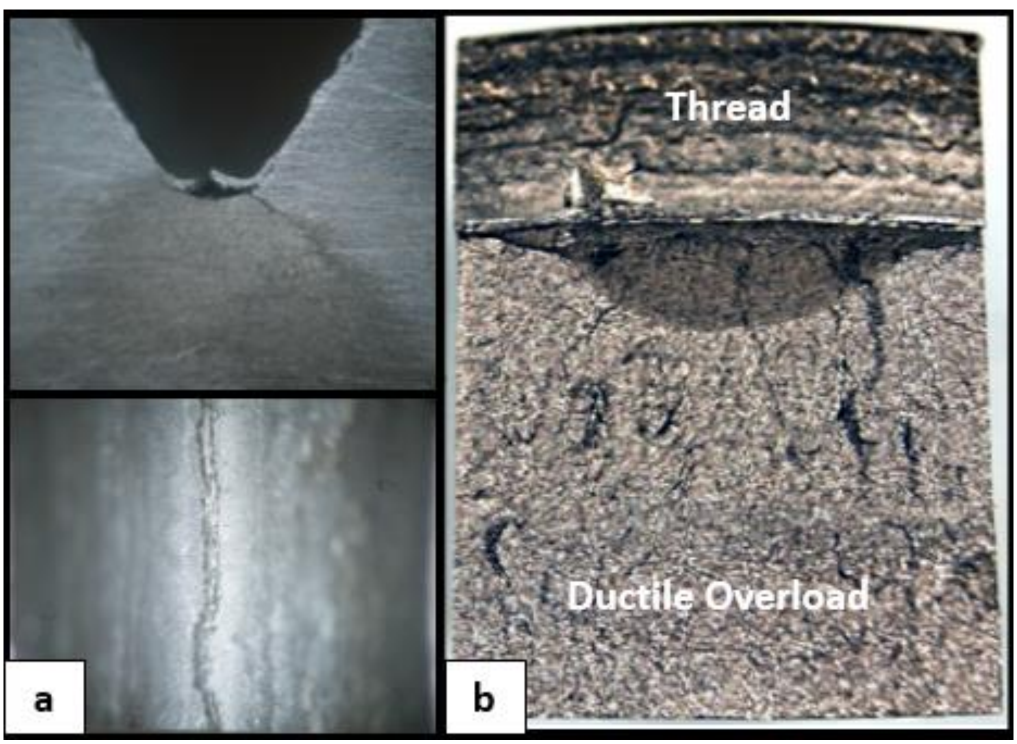


Figure E.6-4: Rod 1-V-S2-A2-A Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

E.6.3 Thd 4, EHE:

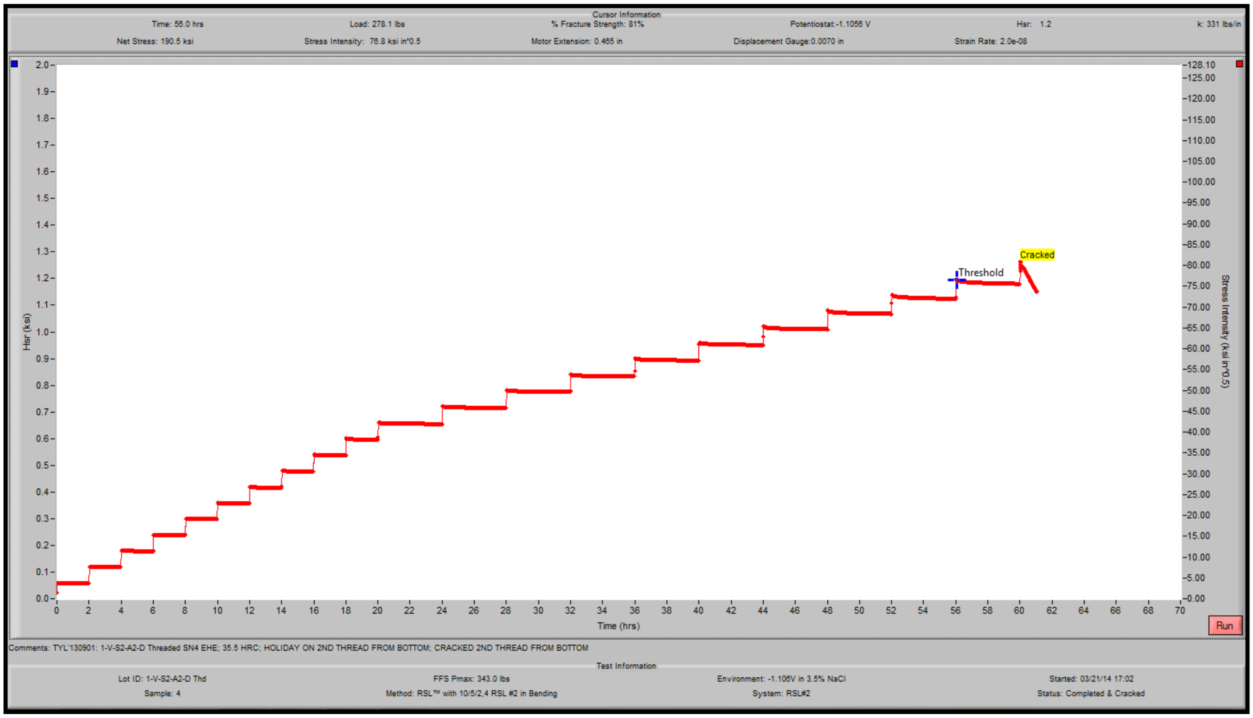


Figure E.6-5: Rod 1-V-S2-A2-D Thd 4, Graphical EHE Results

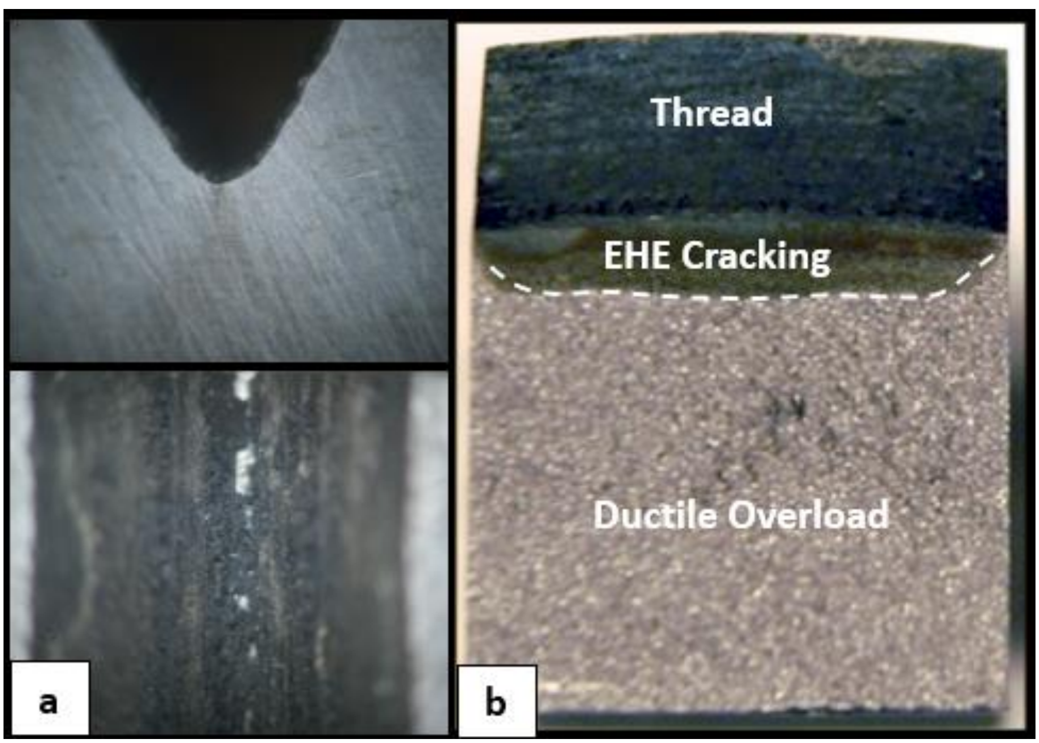
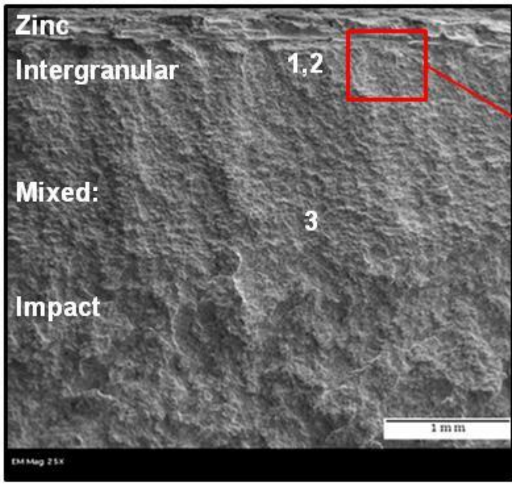
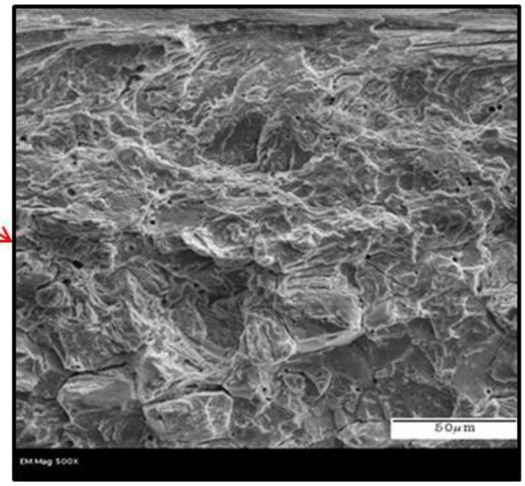


Figure E.6-6: Rod 1-V-S2-A2-A Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

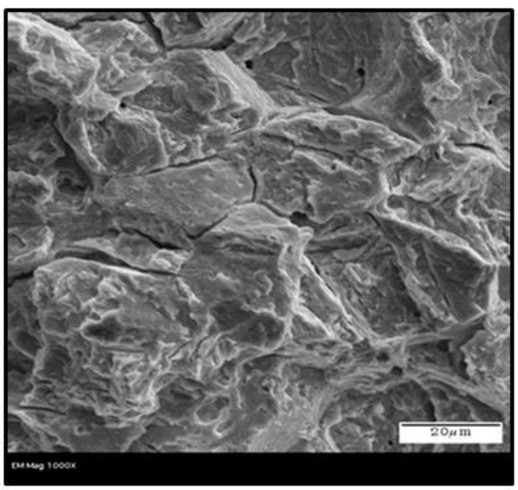
Figure E.6-7: SEM of Rod 1-V-S2-A2-D Thd 4, EHE



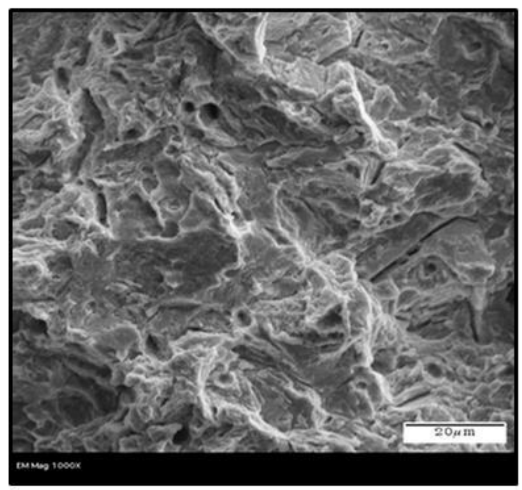
Thread Root 25X



1) Intergranular 500X



2) Intergranular 1000X



3) Mixed: Ductile Overload, Intergranular 1000X

E.6.4 Thd 6, EHE:

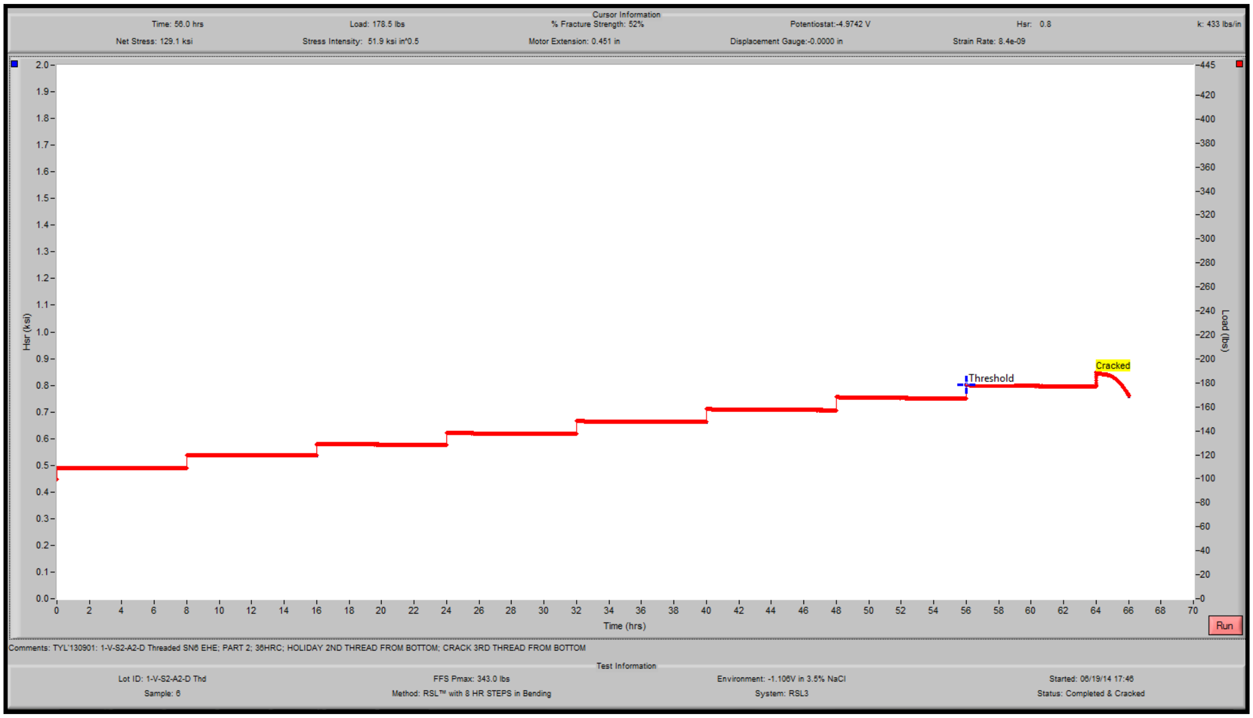


Figure E.6-8: Rod 1-V-S2-A2-D Thd 6, Graphical EHE Results

Figure E.6-9: Rod 1-V-S2-A2-A Thd 6 Thread Root from Side and Normal Views Post EHE Test

E.6.5 Thd 7, EHE:

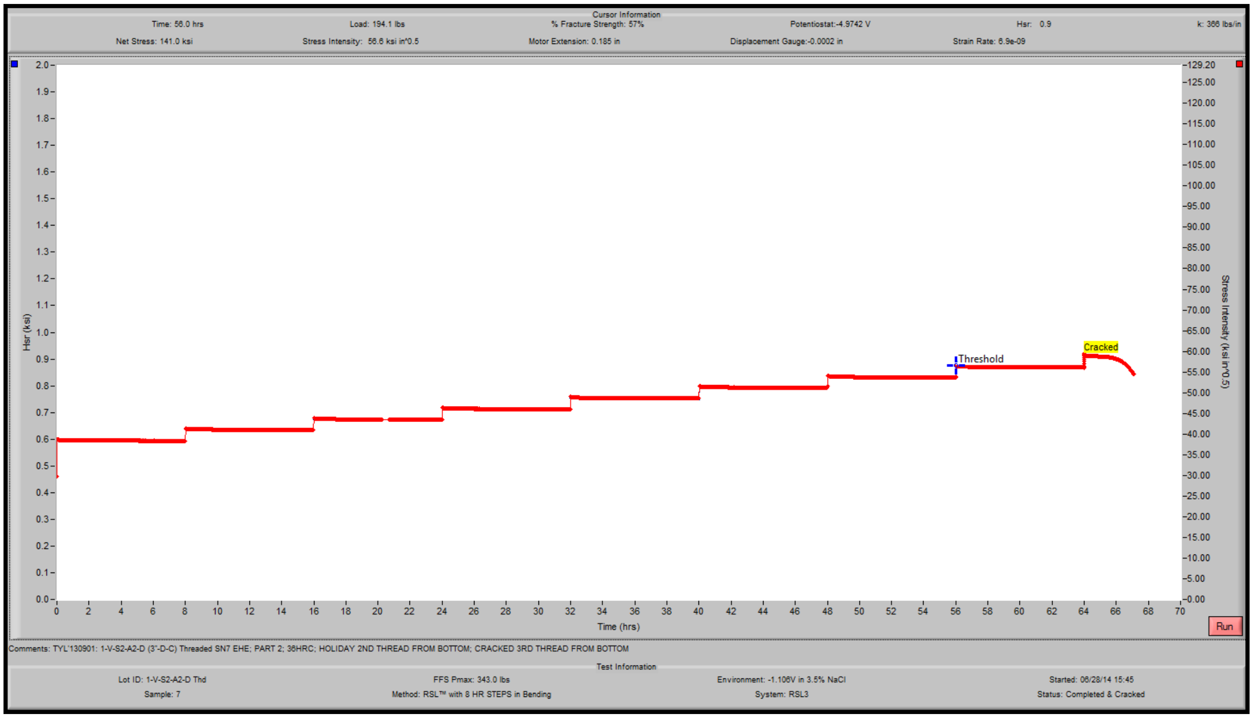


Figure E.6-10: Rod 1-V-S2-A2-D Thd 7, Graphical EHE Results

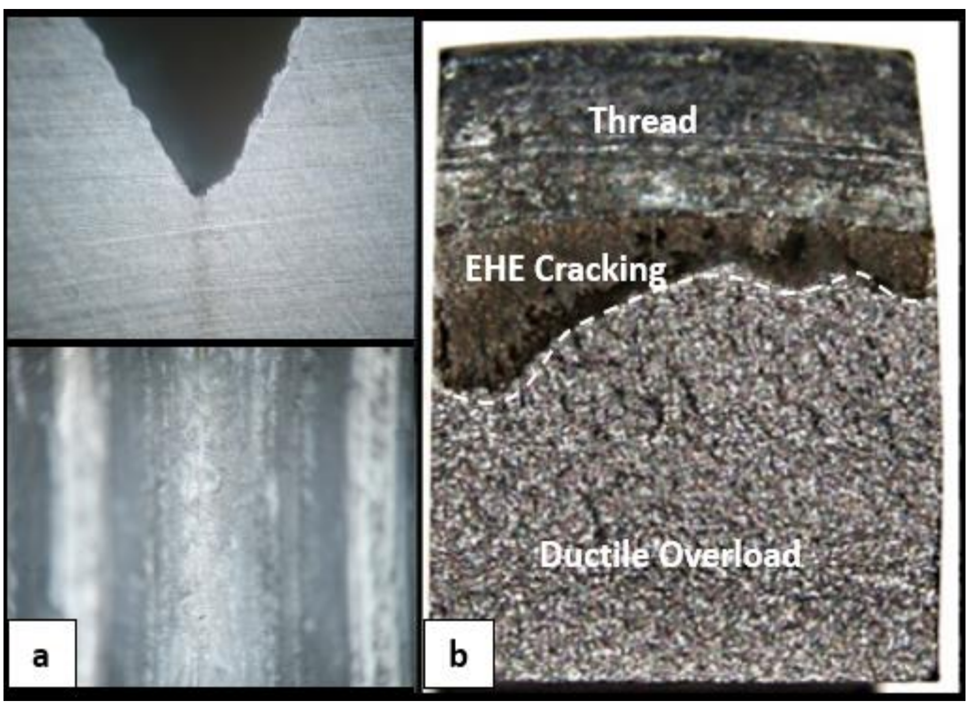


Figure E.6-11: Rod 1-V-S2-A2-A Thd 7 a) EHE Fracture Face

LRA@LouRaymond.com
Phone: 949 474-0218

Appendix F: Rod 3-V-9

F.1 Description of Sample

Rod 3-V-9 was a Shear Key Anchor Bolt located at the top of the Pier E2 (S1/S2) from a similar heat of material as was tested in Test Rigs 1, 2, 3 and 4 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 3 inches in diameter with machined threads. The segment from one of four spares from this rod provided to LRA is shown in **Figure F.1-1**.

Figure F.1-1: Pier E2 Shear Key Anchor Bolt (Top), Rod 3-V-9

F.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 3-V-9 can be seen in **Figure F.2-1** where the black portion of the Shadowgraph represents the rod material. As can be seen from **Figure F.2-1**, these machined thread roots show non-uniformity and exhibit a sharp radius.

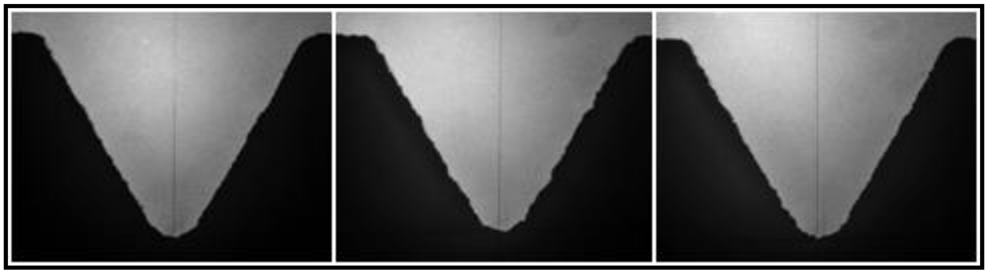


Figure F.2-1: Thread Comparison of Three Threads of Rod 3-V-9

F.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 3-V-9 and can be seen versus time in **Figure F**.3-1. The final OCP recorded for Rod 3-V-9 was Vsce=-1.013 V.

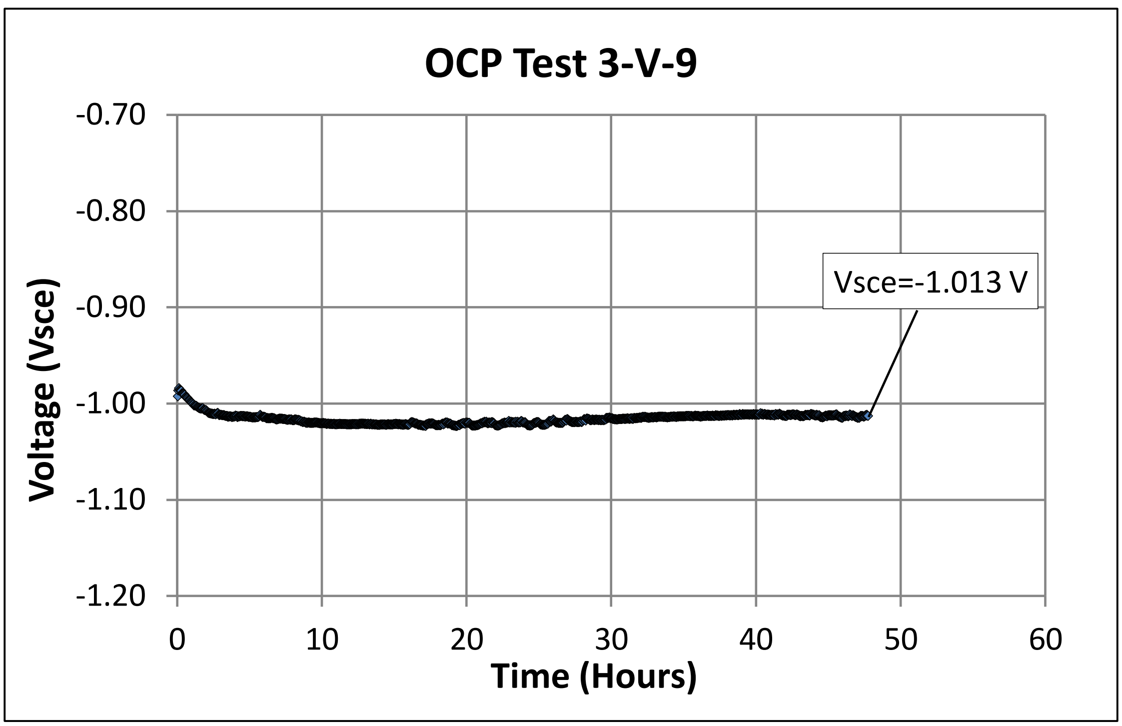


Figure F.3-1: Open Circuit Potential for Rod 3-V-9

F.4 Hardness

The hardness data and profile for sample 3-V-9 are shown in **Table F.4-1** and **Figure F.4-1**.

Table F.4-1: Hardness Data of Rod 3-V-9 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	30.5	30.5
MR 1, FFS	32.5	33.1
MR 2, IHE	33.5	
MR 6, EHE	33.0	
MR 7, EHE	33.5	
OD 3, IHE	36.0	35.6
OD 6, IHE	36.0	
OD 9, EHE	35.5	
OD 11, FFS	36.0	
OD 13, EHE	35.5	
Thd 15, FFS	35.5	
Thd 2, EHE	35.5	
Thd 3, IHE	35.0	
Thd 4, EHE	35.0	

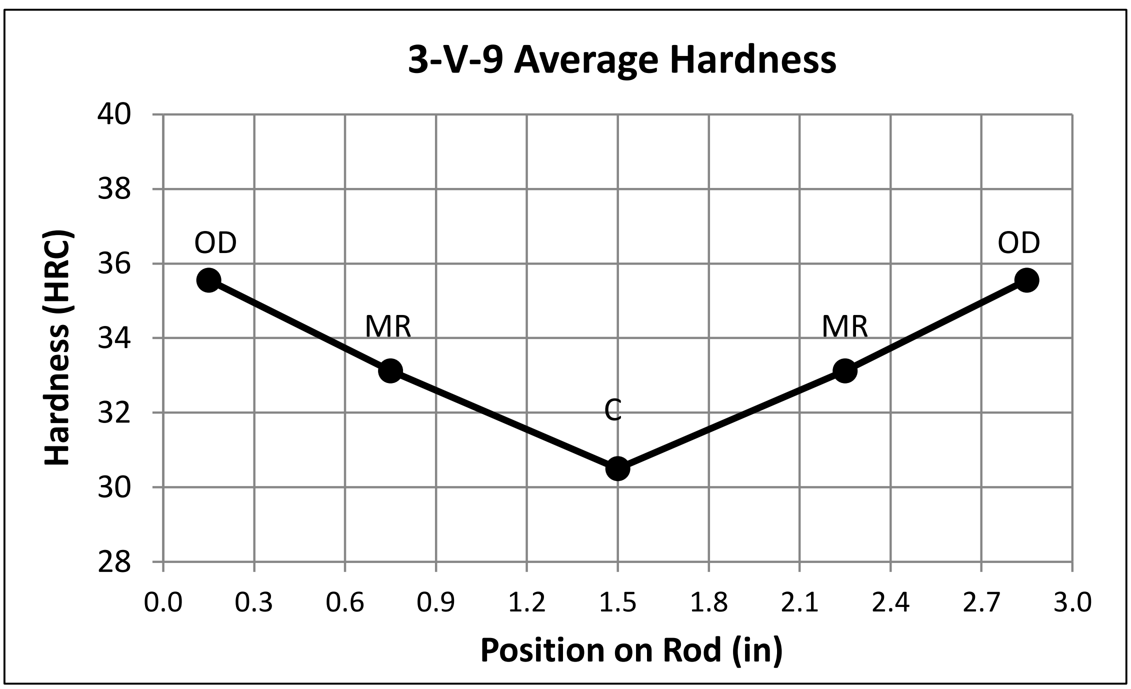


Figure F.4-1: Hardness Profile of Rod 3-V-9

F.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following “checker board” tables.

F.5.1 Fatigue Pre-crack Results:

#NAME? Threaded Rod ID # 3-V-9						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top (S1/S2)				
Rod#:	**3-V-9**					
Product Form:	**1e**	**Comments**: 2010 Machined Threads				
Rod OD:	**3"**	Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 11, FFS**	**36.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	86.4 0.53 0.98 8900		
	OD 3, IHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		86.2 0.53 0.97 1.5	
	OD 6, IHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		95.4 0.59 1.08 1.7	
	OD 9, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			28.2 0.18 0.32 1.8
	OD 13, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			30.0 0.19 0.34 1.2

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-9						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top (S1/S2) **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-9**					
Product Form:	**1e**					
Rod OD:	**3"**					
Fatigue Pre-cracked	**Sample #/ID**	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
	MR 1, FFS	**32.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	81.6 0.56 0.92 8300		
	MR 2, IHE	**33.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		95.8 0.64 1.08 2.5	
	MR 6, EHE	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			38.0 0.26 0.43 1.7
	MR 7, EHE	**33.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			35.1 0.23 0.40 1.2
	Center 1, FFS	**30.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	80.9 0.58 0.91 9000		

F.5.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-9						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top (S1/S2) **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-9**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 15, FFS**	**35.5**	Pmax* (lbs)	342.6		
			Fu	1.13		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	3500		
	Thd 3, IHE	**35.0**	$P_{threshold}$* (lbs)		345.7	
			Fu		1.14	
			Hsr		1.6	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.1	
	Thd 2, EHE	**35.5**	$P_{threshold}$* (lbs)			216.1
			Fu			0.71
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			1.8
	Thd 4, EHE	**35.0**	$P_{threshold}$* (lbs)			213.7
			Fu			0.70
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			1.2

F.5.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 3-V-9
RSL™ (B) 4-pt Bend Test

LRA Job No.:	TYL130901
Rod #:	3-V-9
Product Form:	1e
Rod OD:	3"

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 11, FFS	Air	36.0	162	95.7	95.7	95.7	100.0%	86.4	0.53	294.4	1.8	8900	0.2112	123.7	50 lbs/min		0.98	Had Noisy Data
	OD 3, IHE	Air	36.0	162	2100.0	2853.0	2837.0	99.8%	86.2	0.53	300.8	1.9	1.5	0.2198		10/5/2,4		0.97	Tensile Frame
	OD 6, IHE	Air	36.0	162	1500.0	3193.5	3119.2	110.4%	95.4	0.59	333.6	2.1	1.7	0.2230		10/5/2,4		1.08	Collection Error
	OD 9, EHE	3.5% NaCl @ -1.106V	35.5	159	62.0	37.2	30.9	32.6%	28.2	0.18	96.5	0.6	1.8	0.2143		10/5/2,4		0.32	Threshold in two hour steps.
	OD 13, EHE	3.5% NaCl @ -1.106V	35.5	159	34.0	35.7	32.2	34.7%	30.0	0.19	103.1	0.6	1.2	0.2172		10/5/2,4		0.34	Corrosion Began After Specimen Began Cracking. Good Data
	MR 1, FFS	Air	32.5	147	91.4	91.4	91.4	100.0%	81.6	0.56	277.6	1.9	8300	0.2133	144.6	50 lbs/min		0.92	
	MR 2, IHE	Air	33.5	151	2240.0	3383.1	3383.1	117.4%	95.8	0.64	327.3	2.2	2.5	0.2130		10/5/2,4		1.08	Tensile Frame
	MR 6, EHE	3.5% NaCl @ -1.106V	33.0	149	45.0	49.6	40.4	46.6%	38.0	0.26	131.4	0.9	1.7	0.2176		10/5/2,4		0.43	
	MR 7, EHE	3.5% NaCl @ -1.106V	33.5	151	35.0	45.5	38.4	43.0%	35.1	0.23	119.9	0.8	1.2	0.2136		10/5/2,4		0.40	
	Center 1, FFS	Air	30.5	139	84.1	84.1	84.1	100.0%	80.9	0.58	281.3	2.0	9000	0.2224	140.4	50 lbs/min		0.91	
Threaded	Thd 15, FFS	Air	35.5	159	352.0	352.0	352.0	100.0%	99.9	0.63	245.9	1.5	3500	x	x	0.4 in/min	342.6	1.13	
	Thd 2, EHE	3.5% NaCl @ -1.106V	35.5	159	250.0	325.3	236.2	63.1%	63.0	0.40	152.9	1.0	1.8	x	x	10/5/2,4	216.1	0.71	Water Ran Low Cracked in Holiday
	Thd 3, IHE	Air	35.0	157	250.0	359.7	359.7	100.9%	100.8	0.64	247.8	1.6	2.1	x	x	10/5/2,4	345.7	1.14	
	Thd 4, EHE	3.5% NaCl @ -1.106V	35.0	157	175.0	335.1	243.9	62.4%	62.3	0.40	150.1	1.0	1.2	x	x	10/5/2,4	213.7	0.70	Did Not Crack in Holiday.

F.6 Fatigue Pre-cracked Specimen Test Results

F.6.1 OD 11, FFS:

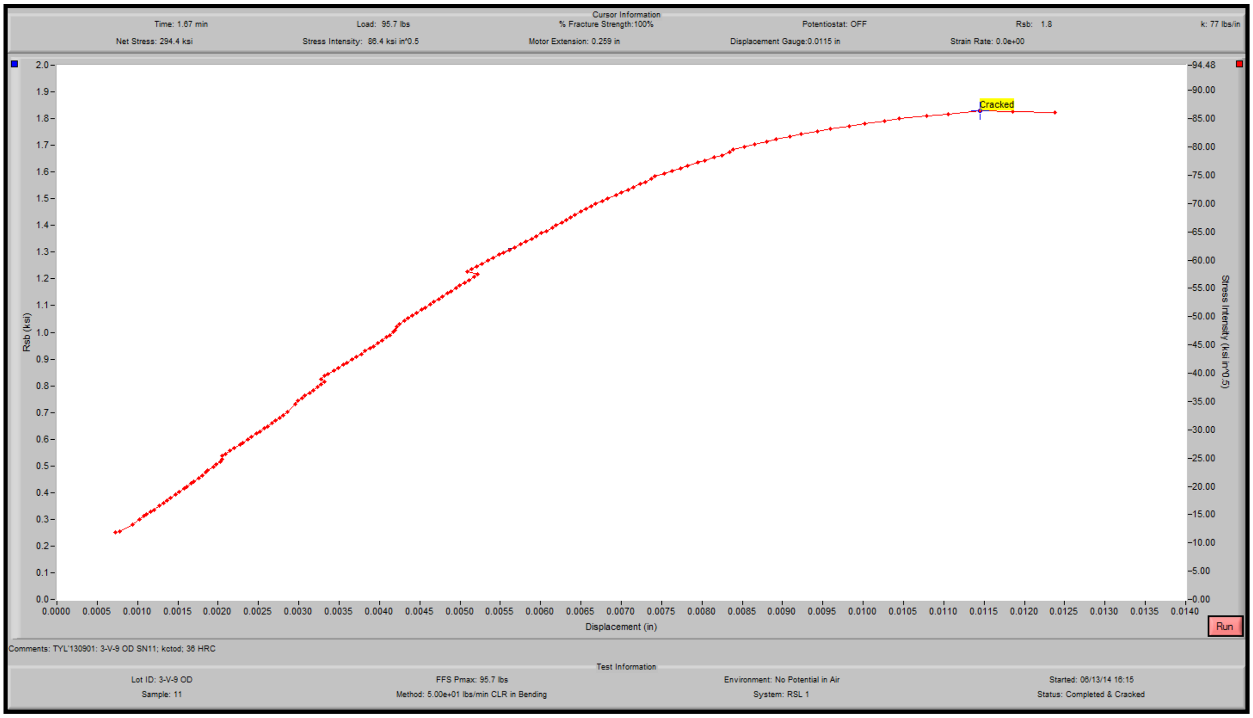


Figure F.6-1: Rod 3-V-9 OD 11, Graphical FFS Results

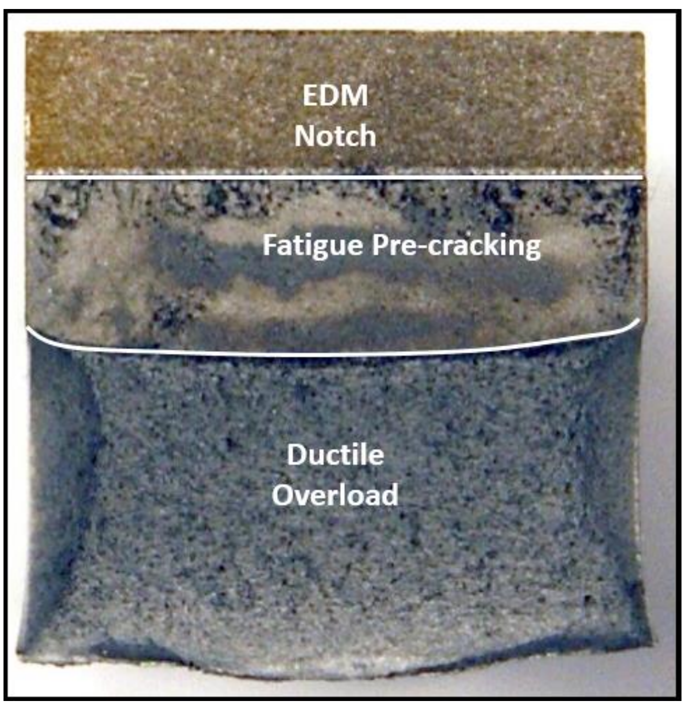


Figure F.6-2: Fracture Face of Rod 3-V-9 OD 11, FFS

F.6.2 OD 3, IHE:

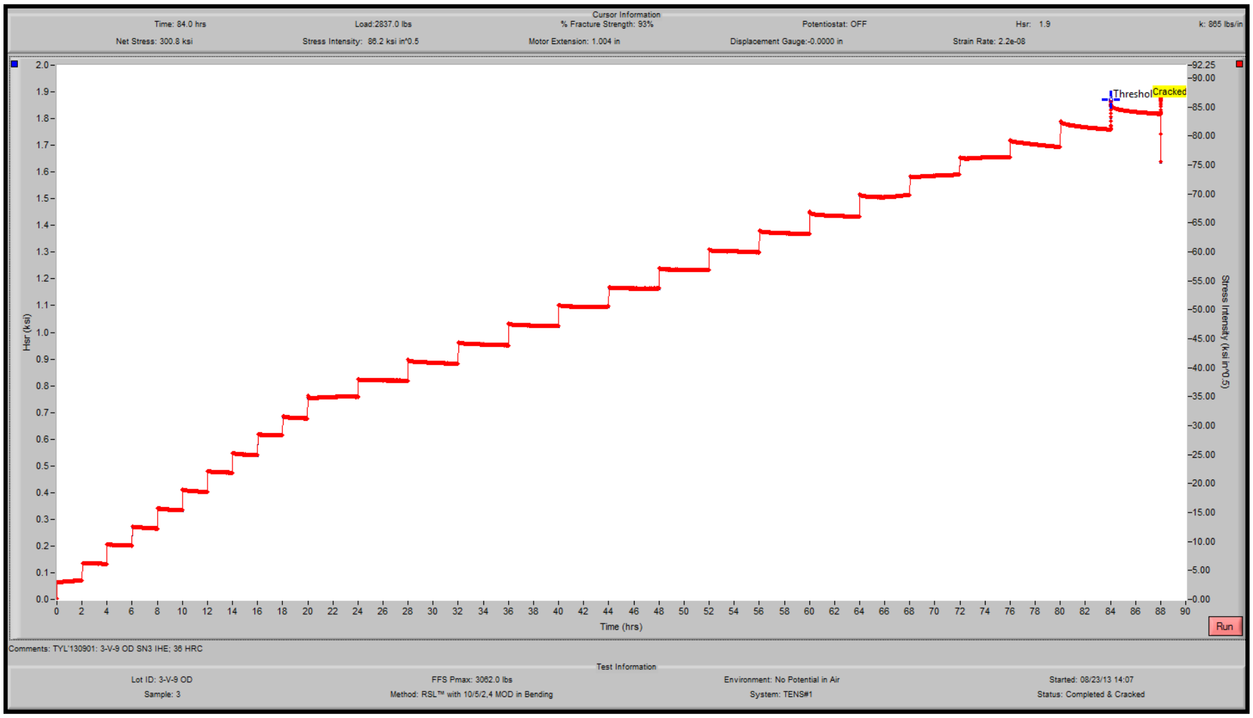


Figure F.6-3: Rod 3-V-9 OD 3, Graphical IHE Results

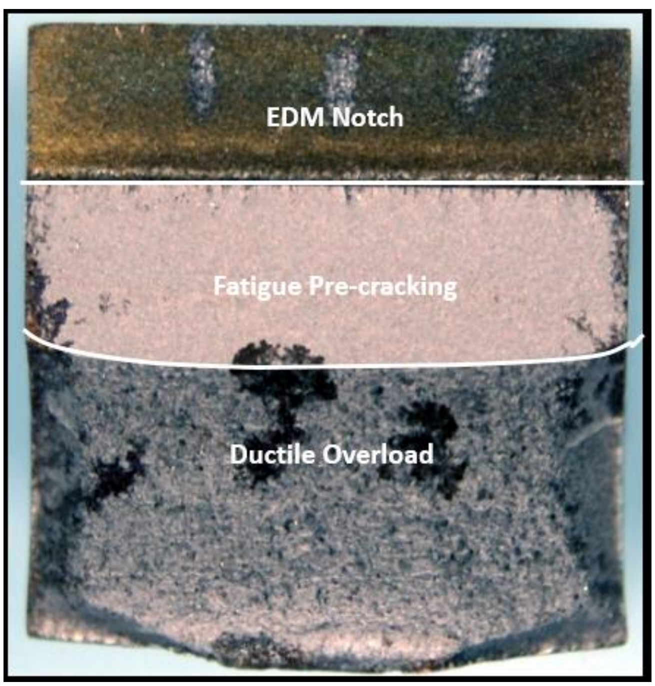


Figure F.6-4: Fracture Face of Rod 3-V-9 OD 3, IHE

F.6.3 OD 6, IHE:

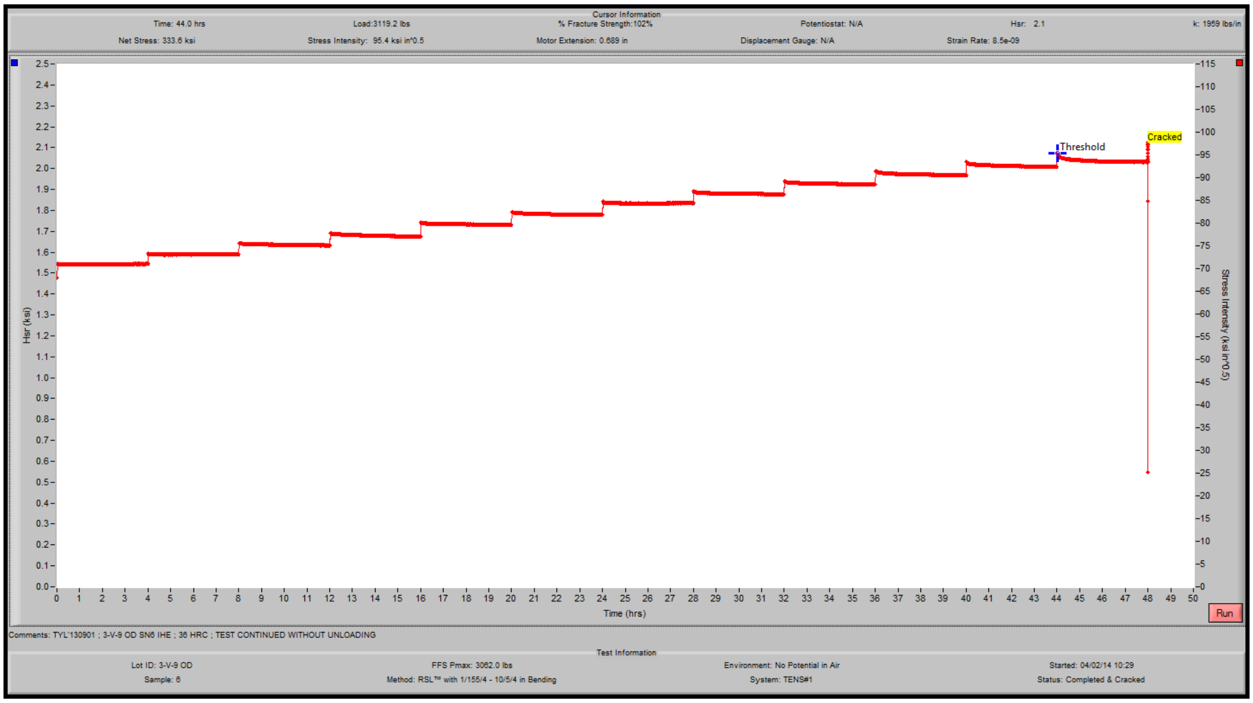


Figure F.6-5: Rod 3-V-9 OD 6, Graphical IHE Results

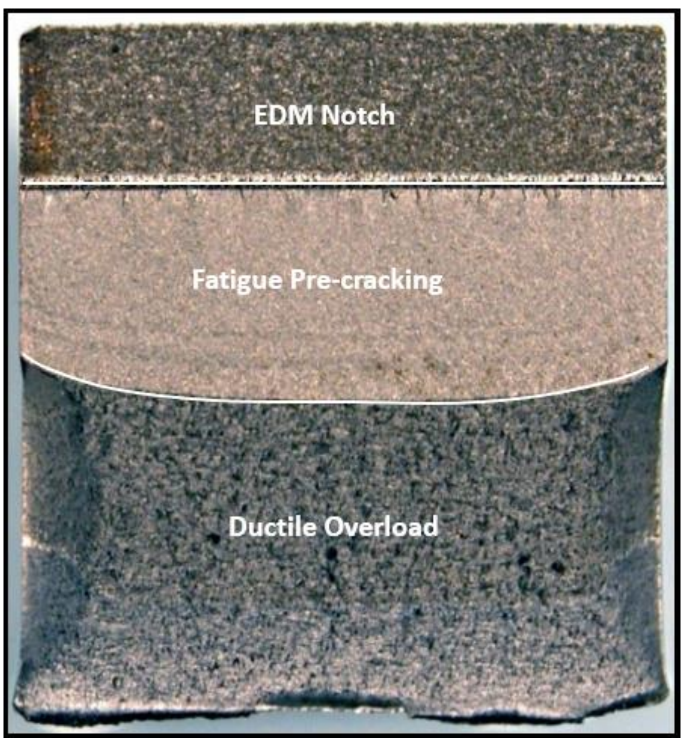


Figure F.6-6: Fracture Face of Rod 3-V-9 OD 6, IHE

F.6.4 OD 9, EHE:

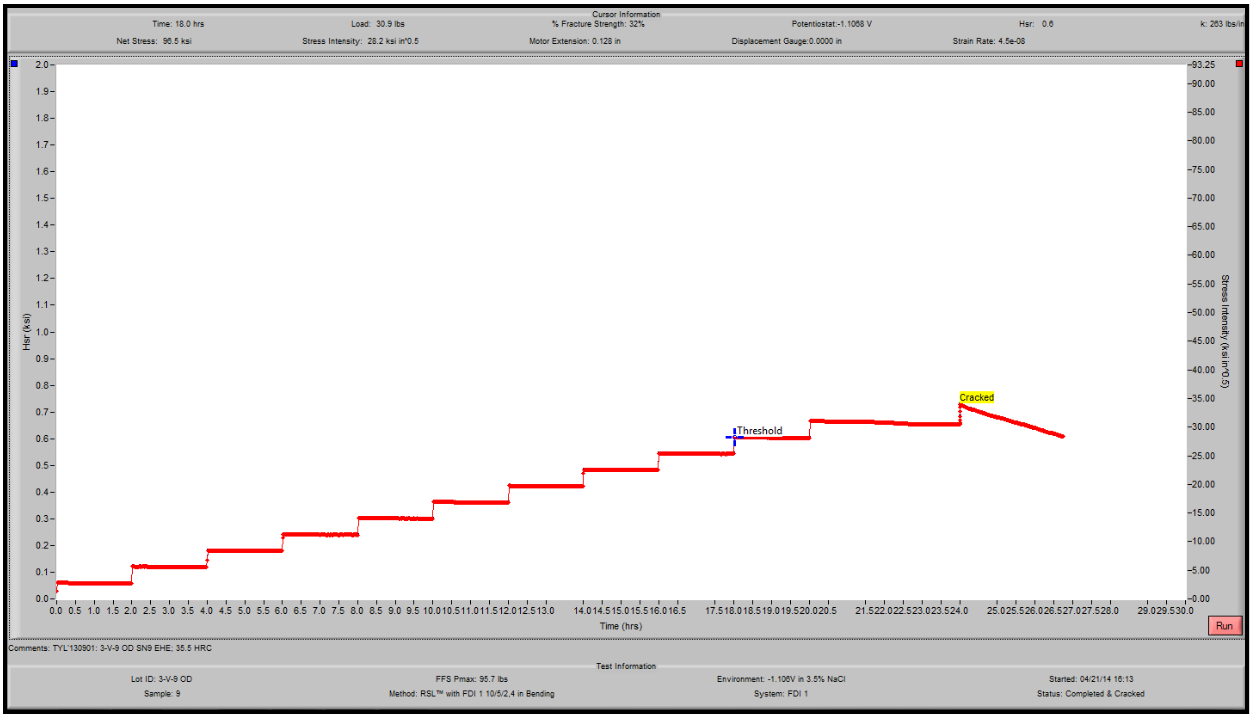


Figure F.6-7: Rod 3-V-9 OD 9, Graphical EHE Results

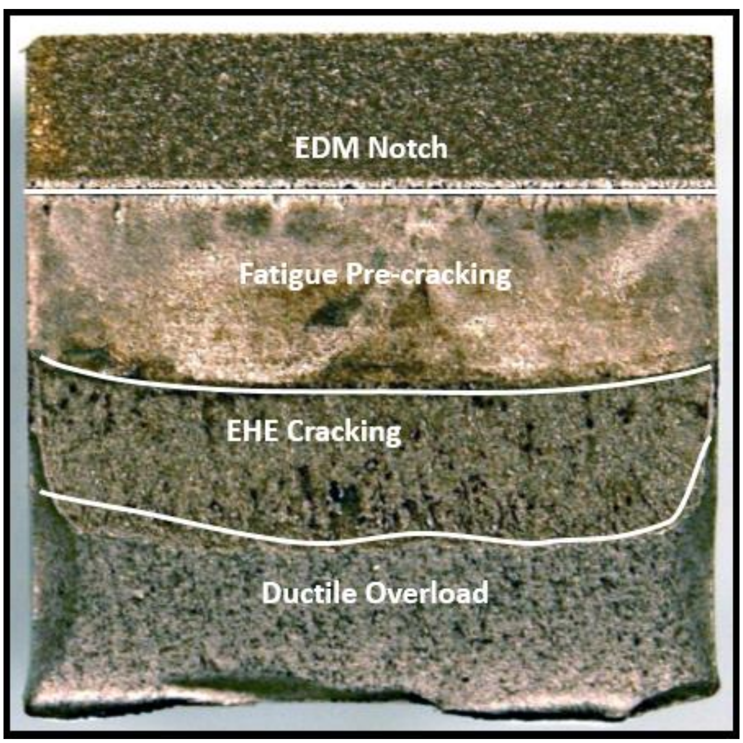


Figure F.6-8: Fracture Face of Rod 3-V-9 OD 9, EHE

F.6.5 OD 13, EHE:

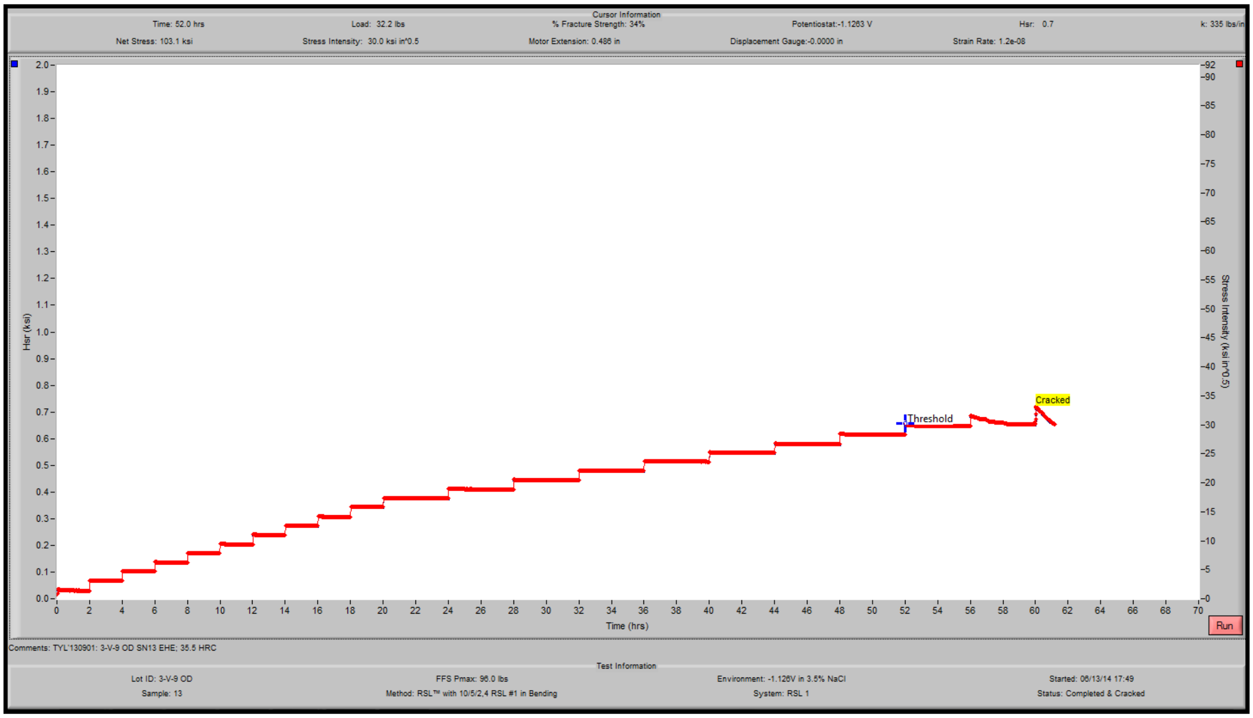


Figure F.6-9: Rod 3-V-9 OD 13, Graphical EHE Results

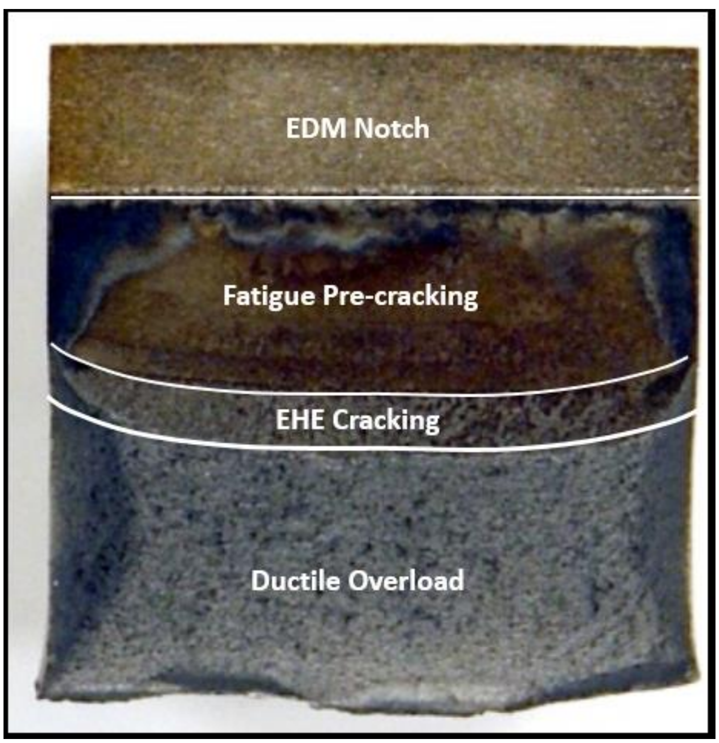


Figure F.6-10: Fracture Face of Rod 3-V-9 OD 13, EHE

F.6.6 MR 1, FFS:

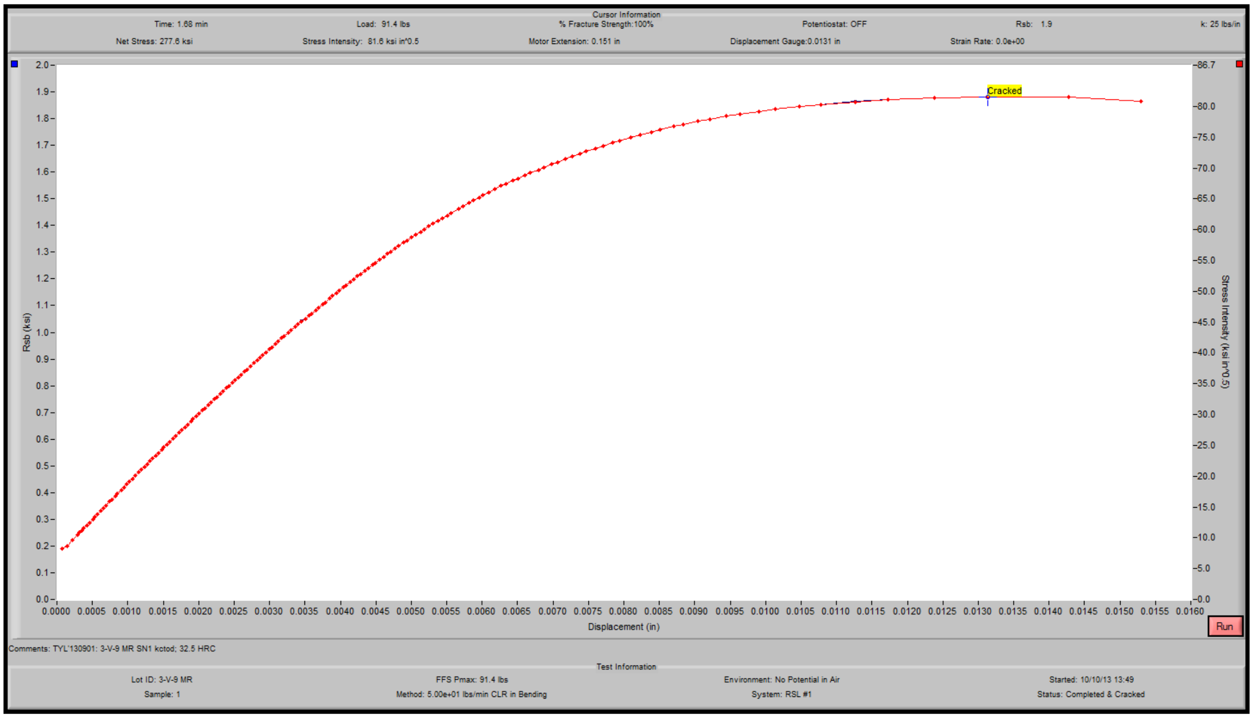


Figure F.6-11: Rod 3-V-9 MR 1, Graphical FFS Results

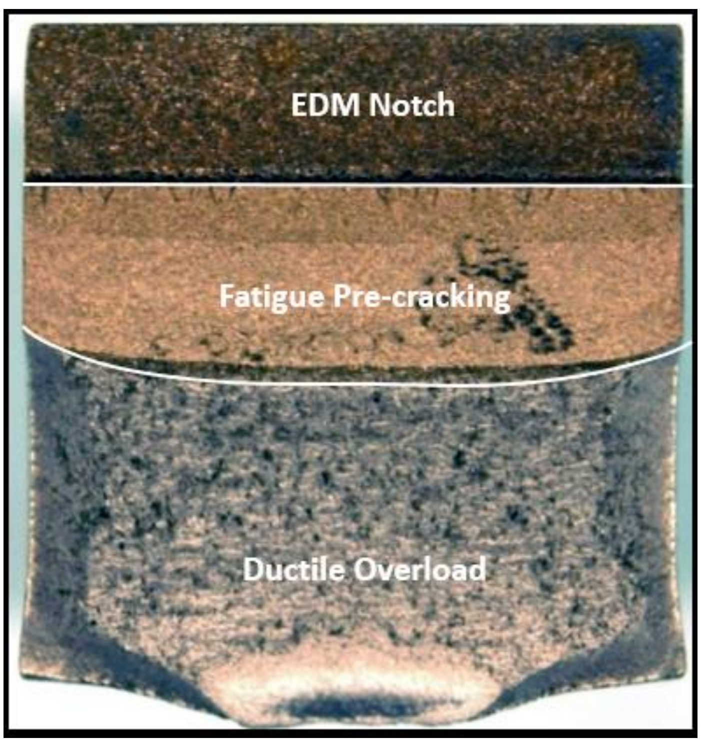
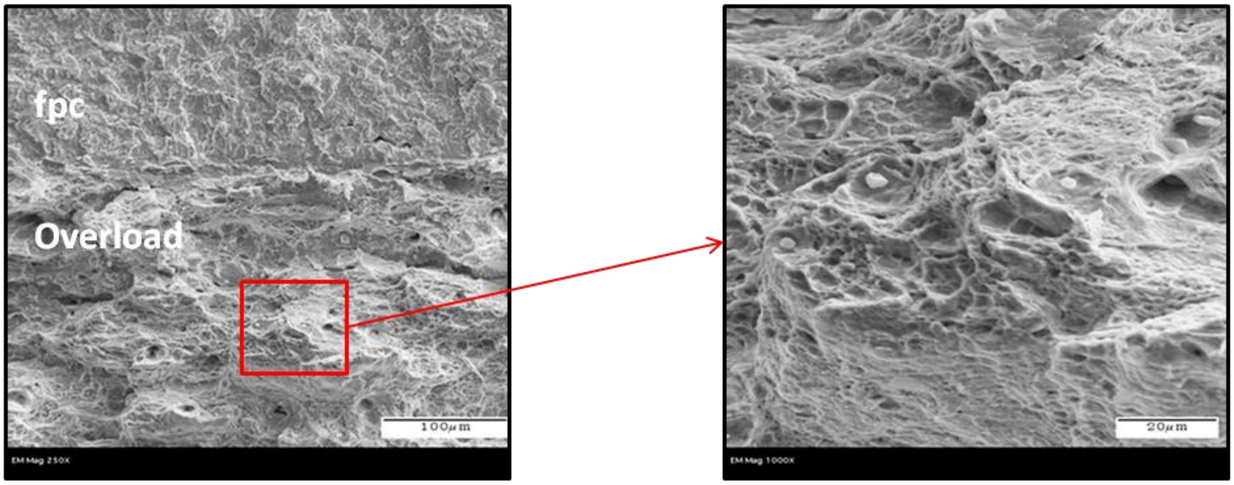


Figure F.6-12: Fracture Face of Rod 3-V-9 MR 1, FFS

Figure F.6-13: SEM of Rod 3-V-9 MR 1, FFS



fpc – OL transition 250X

Overload 1000X

LRA@LouRaymond.com
Phone: 949 474-0218

F.6.7 MR 2, IHE:

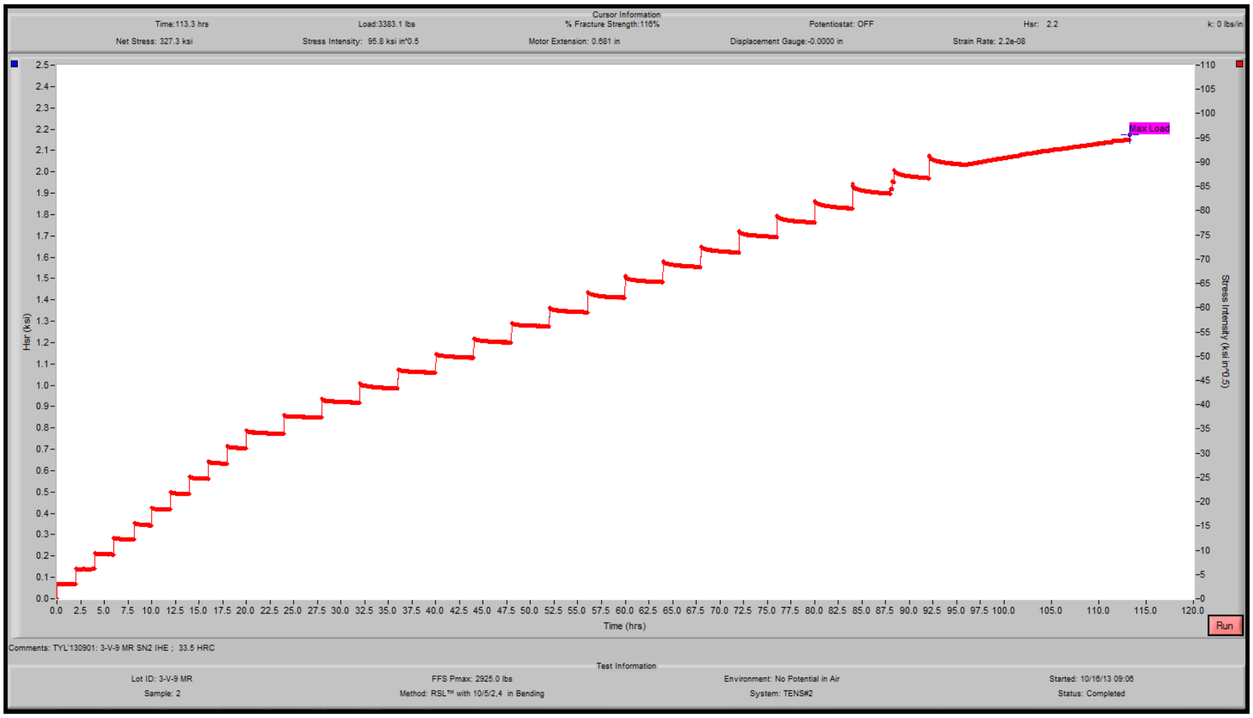


Figure F.6-14: Rod 3-V-9 MR 2, Graphical IHE Results

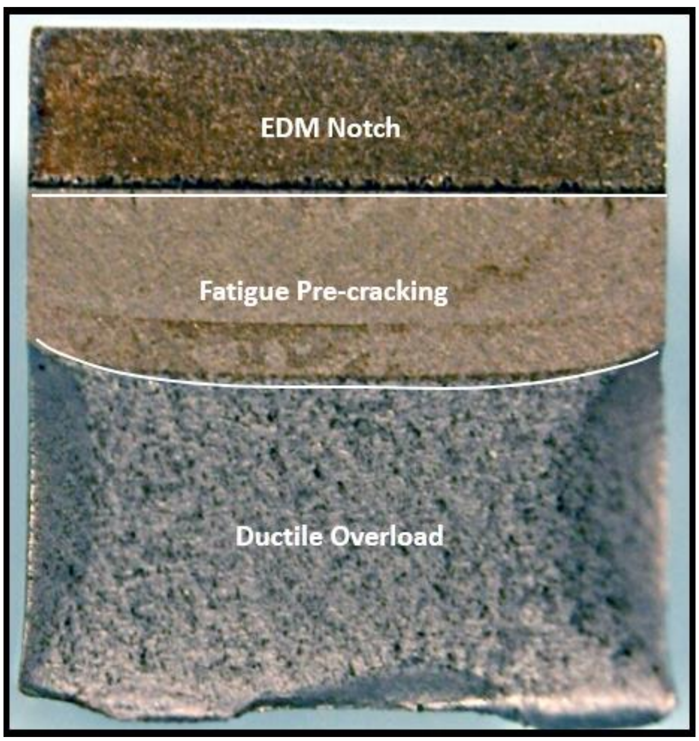


Figure F.6-15: Fracture Face of Rod 3-V-9 MR 2, IHE

F.6.8 MR 6, EHE:

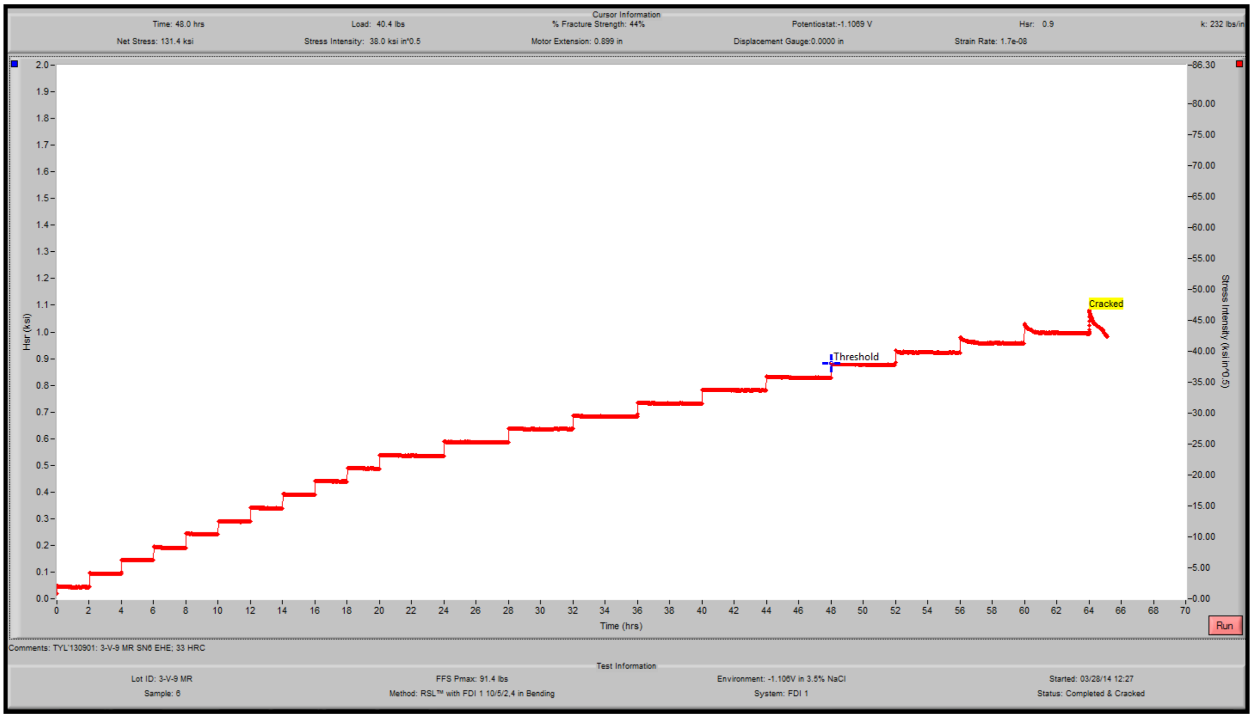


Figure F.6-16: Rod 3-V-9 MR 6, Graphical EHE Results

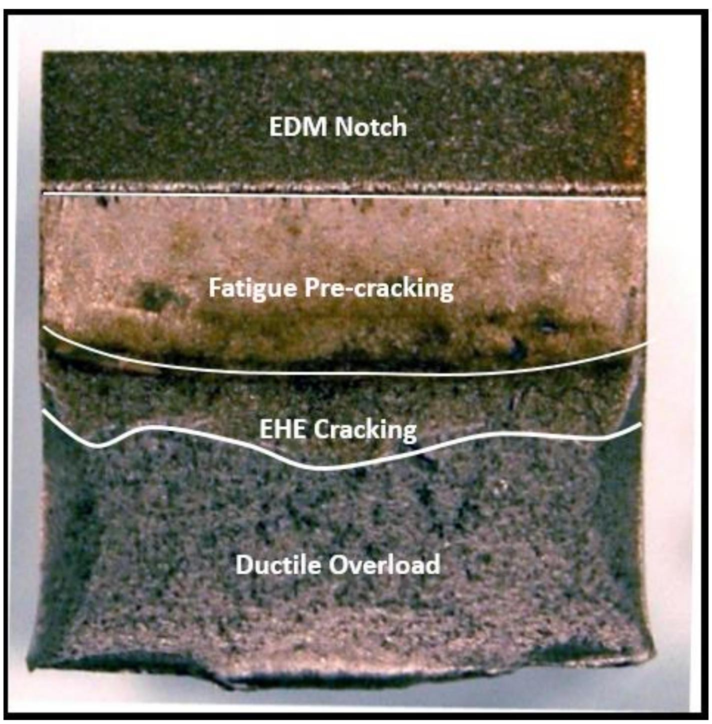


Figure F.6-17: Fracture Face of Rod 3-V-9 MR 6, EHE

F.6.9 MR 7, EHE:

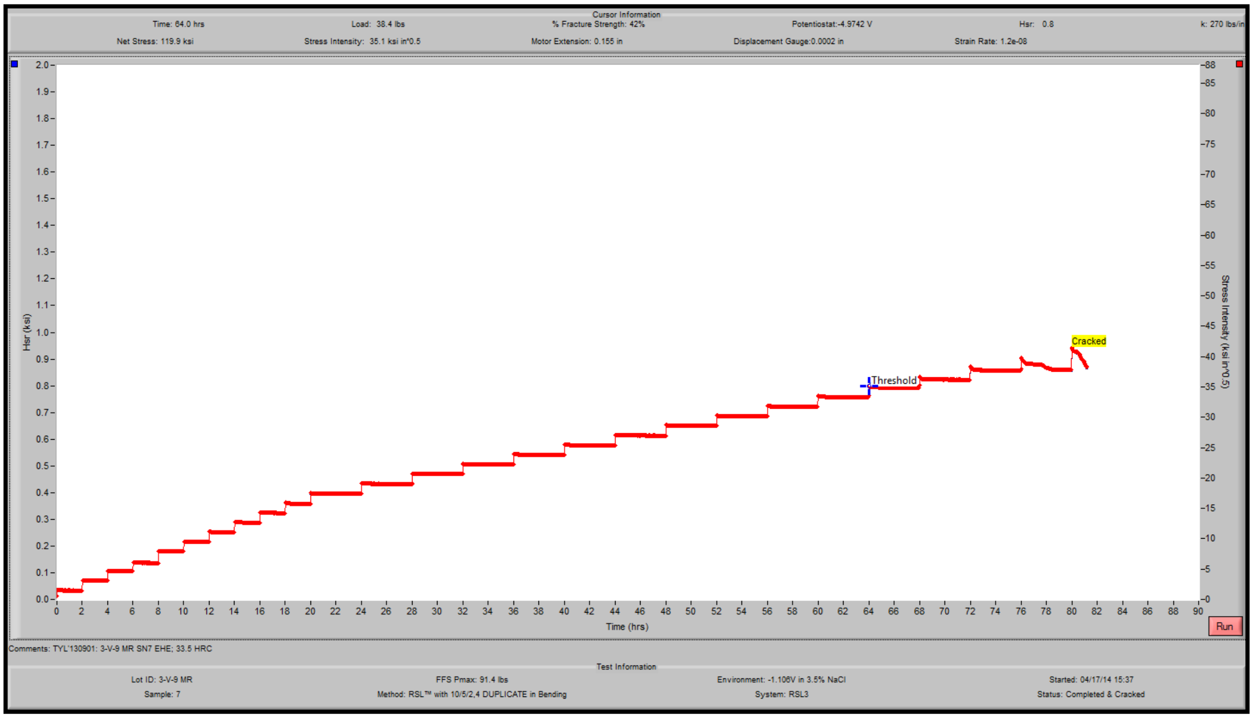


Figure F.6-18: Rod 3-V-9 MR 7, Graphical EHE Results

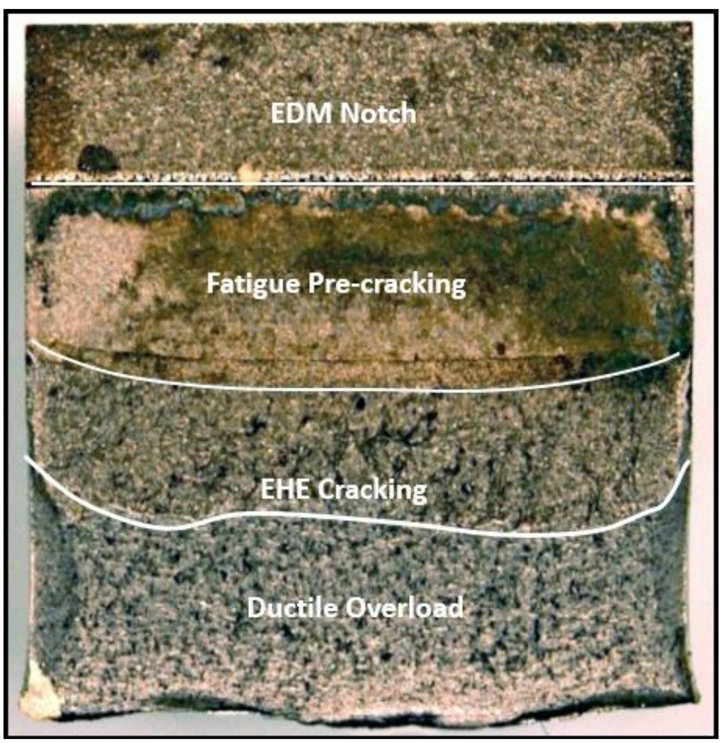


Figure F.6-19: Fracture Face of Rod 3-V-9 MR 7, EHE

F.6.10 Center 1, FFS:

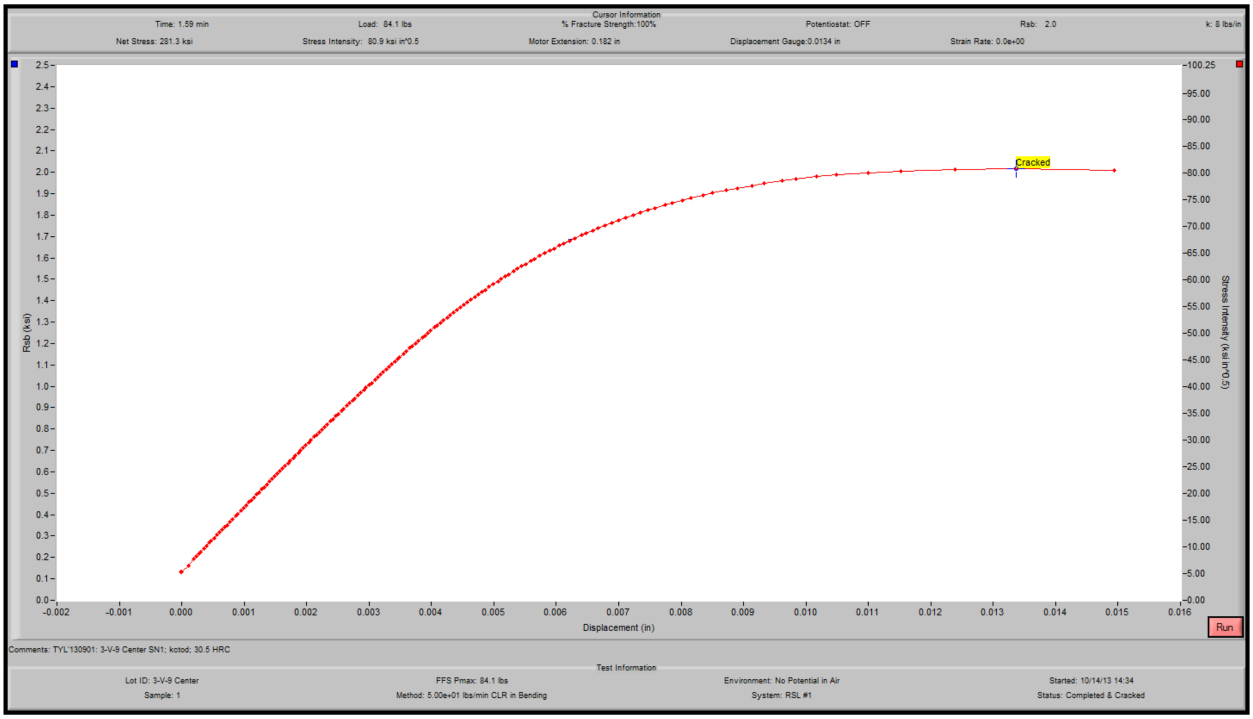


Figure F.6-20: Rod 3-V-9 Center 1, FFS Graphical RSL FFS Results

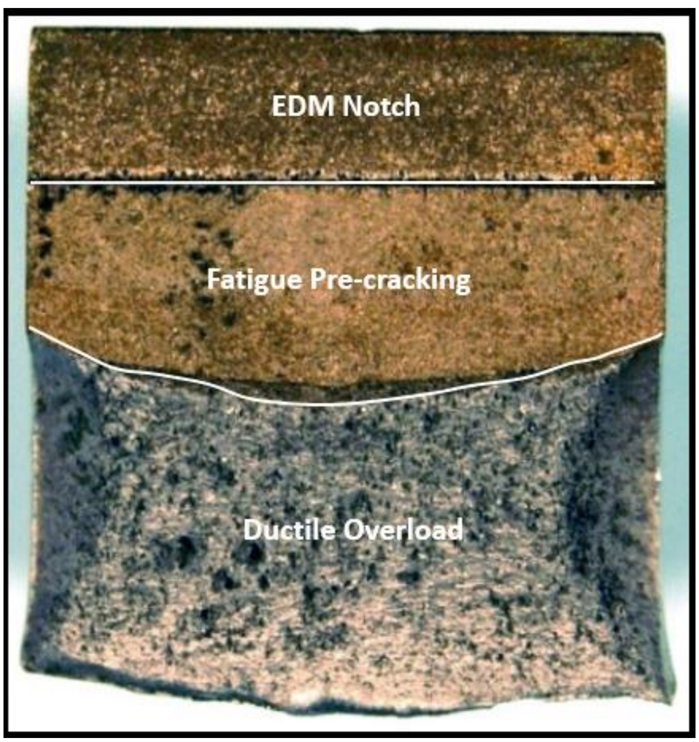


Figure F.6-21: Fracture Face of Rod 3-V-9 Center 1, FFS

F.7 Threaded Specimen Test Results

F.7.1 Thd 15, FFS:

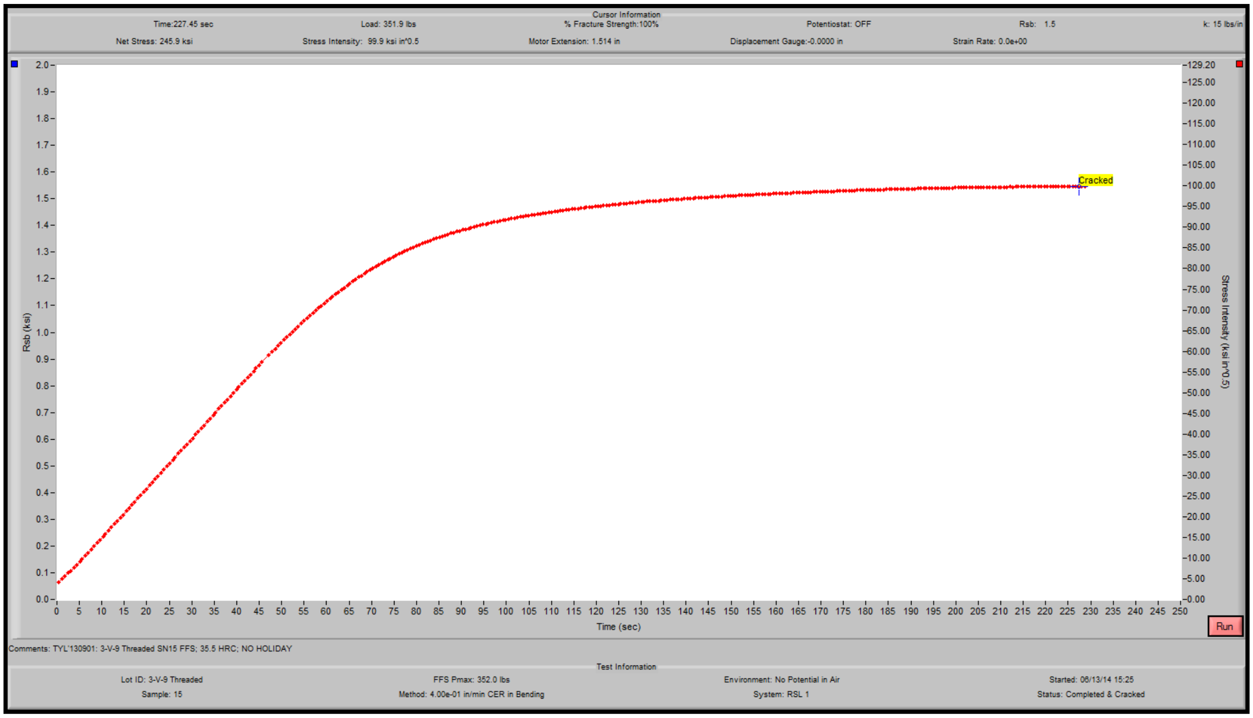


Figure F.7-1: Rod 3-V-9 Thd 15, Graphical FFS Results

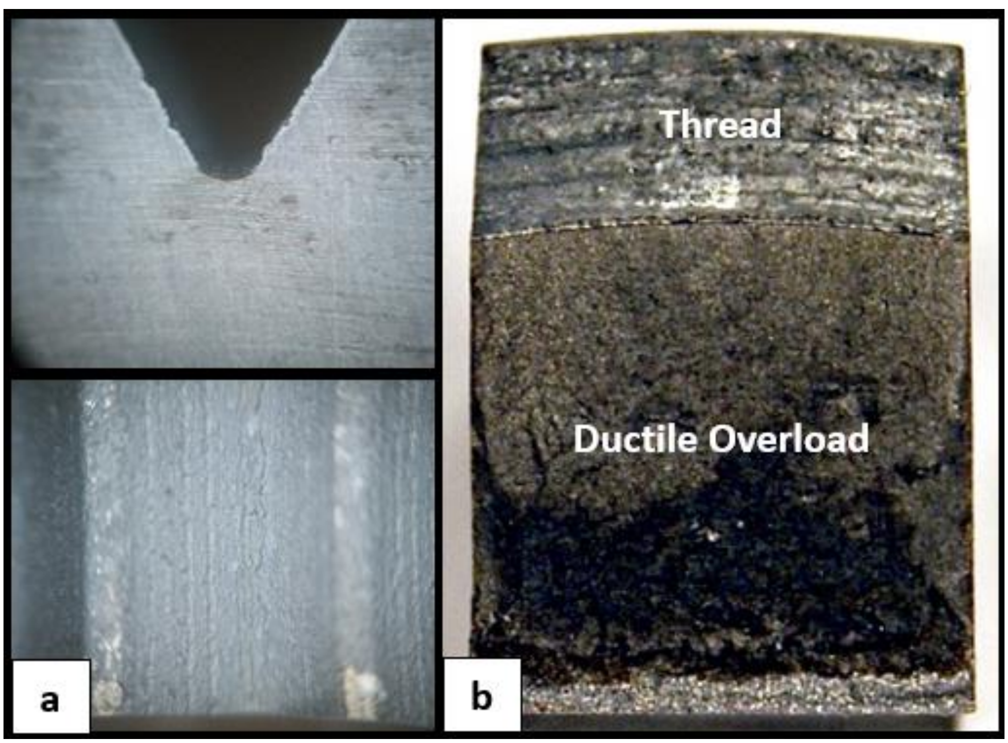


Figure F.7-2: Rod 3-V-9 Thd 15 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

F.7.2 Thd 3, IHE:

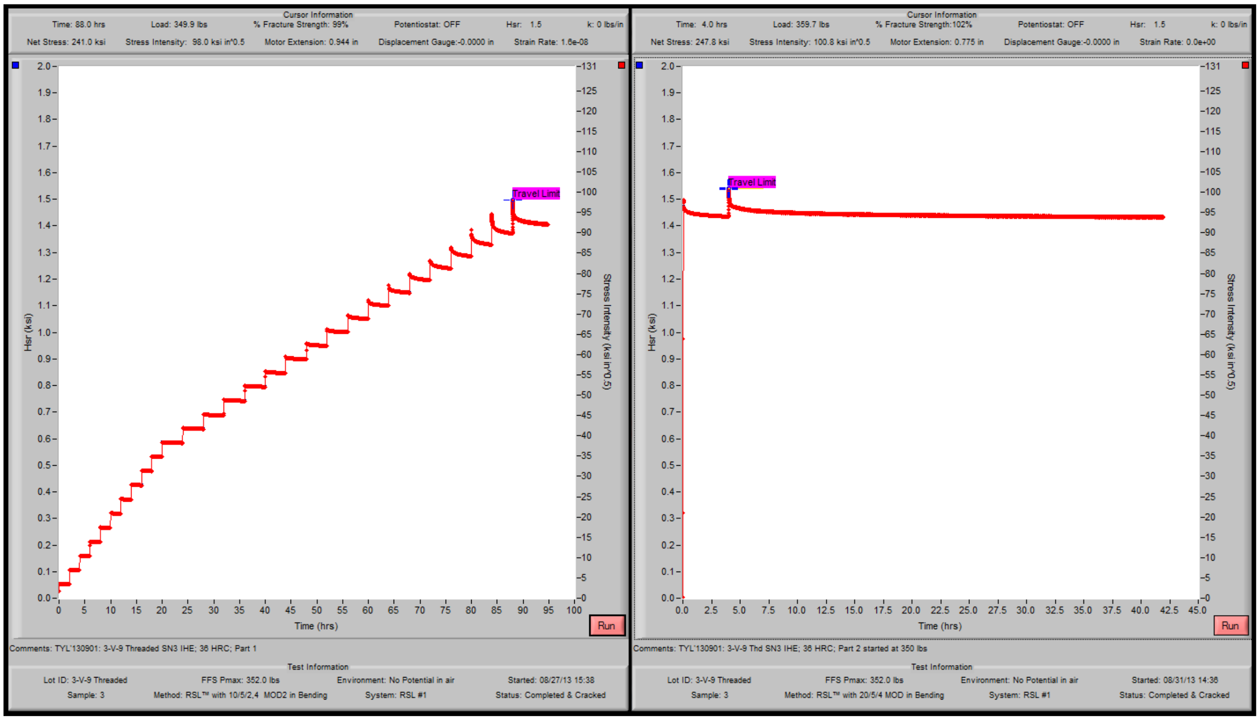


Figure F.7-3: Rod 3-V-9 Thd 3, Graphical IHE Results

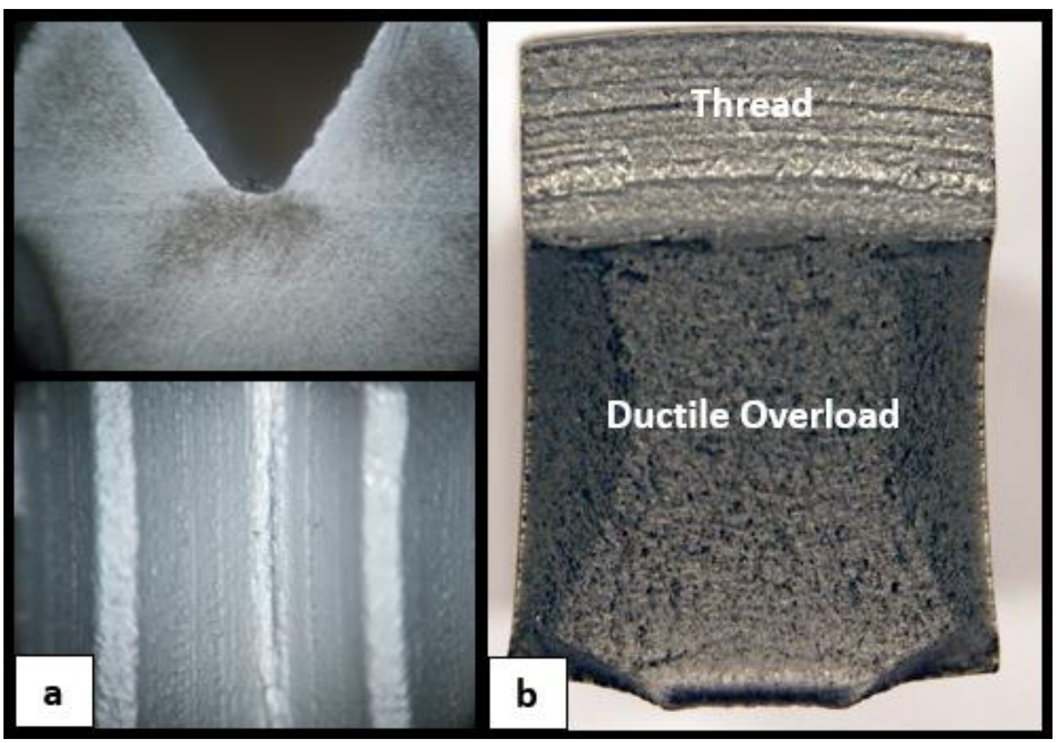


Figure F.7-4: Rod 3-V-9 Thd 3 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

F.7.3 Thd 2, EHE:

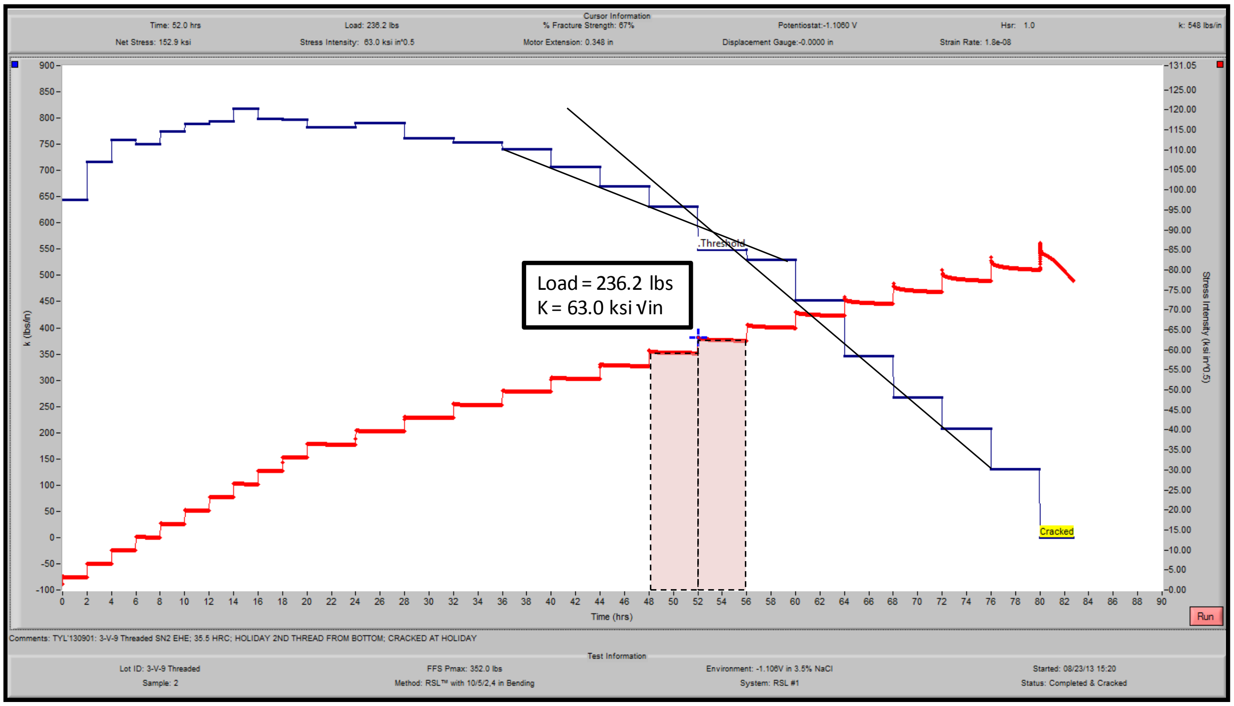


Figure F.7-5: Rod 3-V-9 Thd 2, Graphical EHE Results

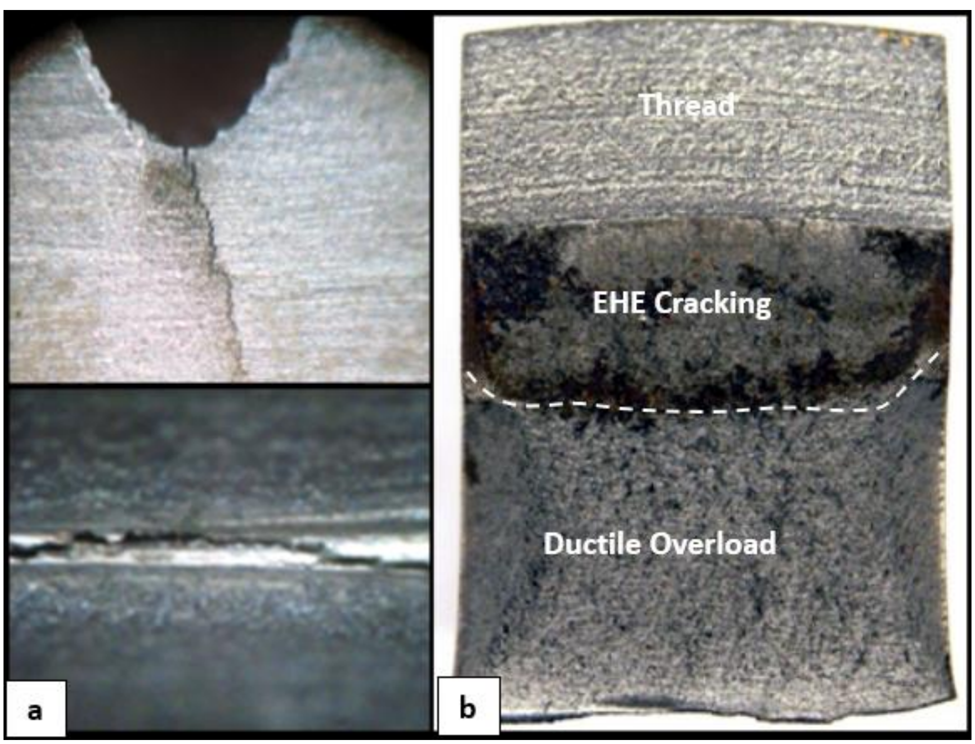


Figure F.7-6: Rod 3-V-9 Thd 2 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

F.7.4 Thd 4, EHE:

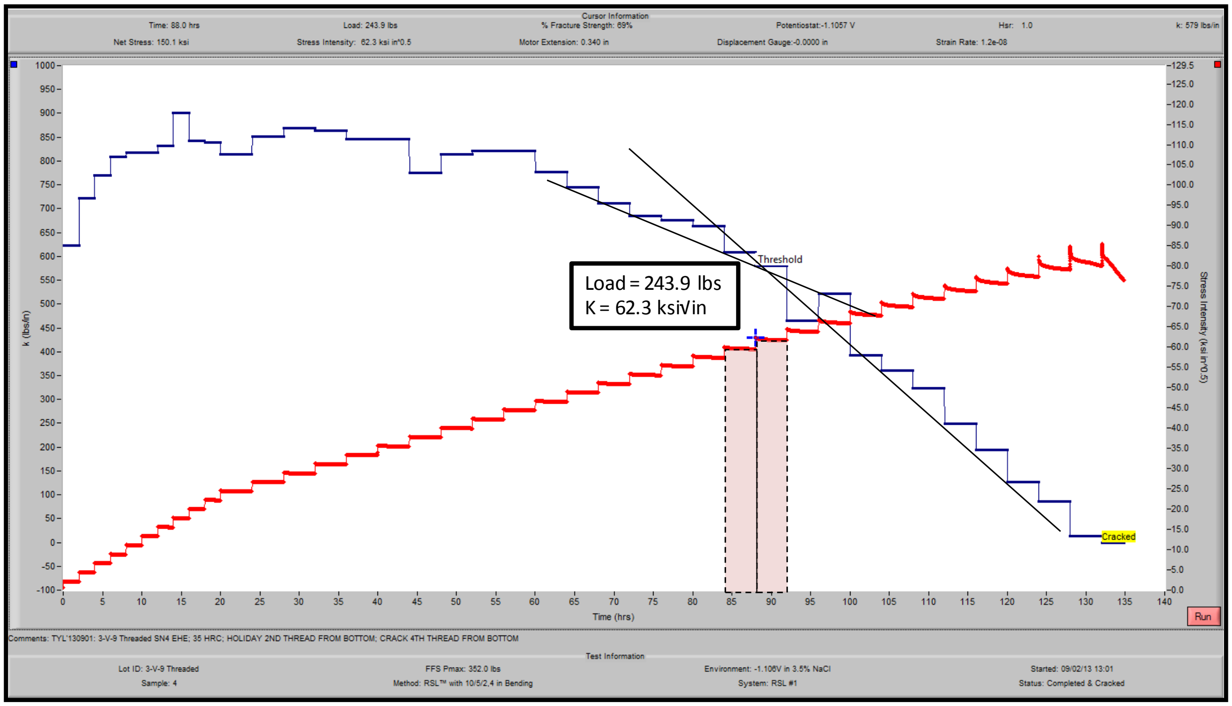


Figure F.7-7: Rod 3-V-9 Thd 4, Graphical EHE Results

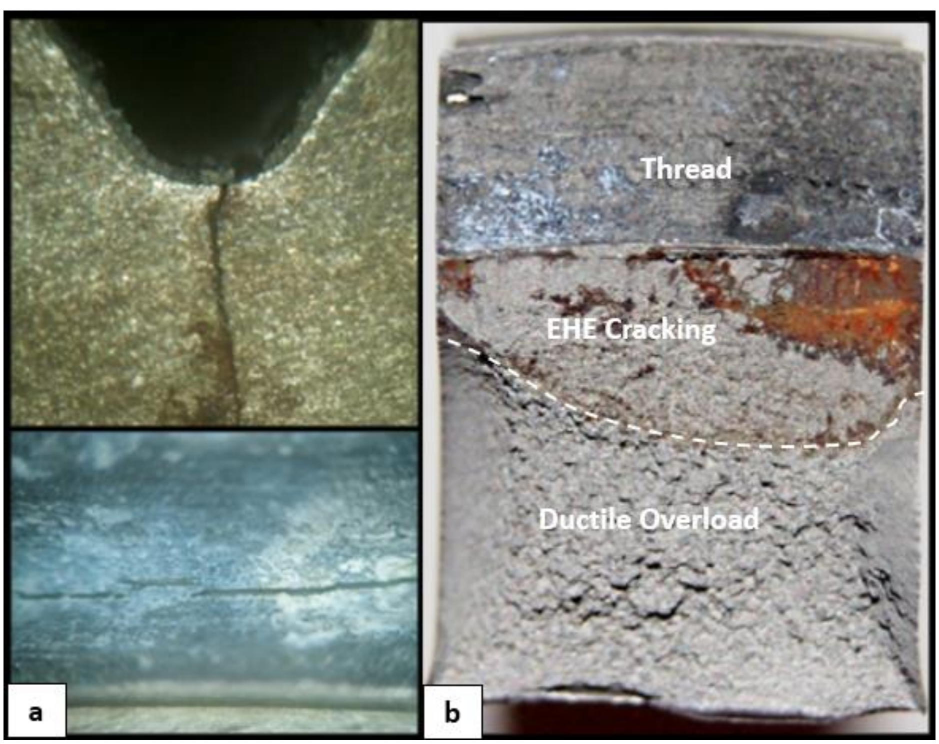
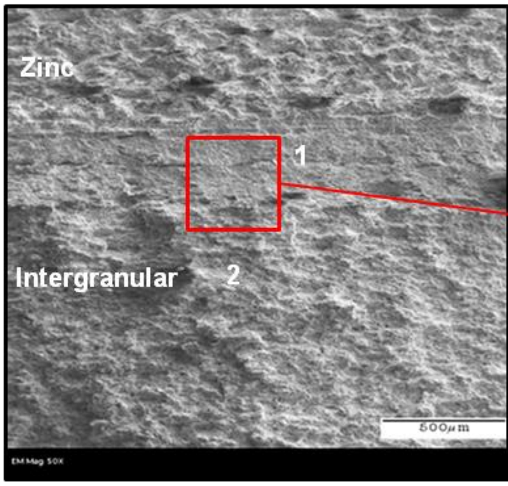
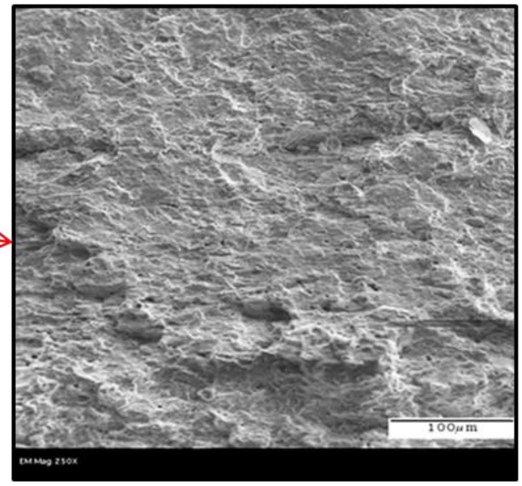


Figure F.7-8: Rod 3-V-9 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

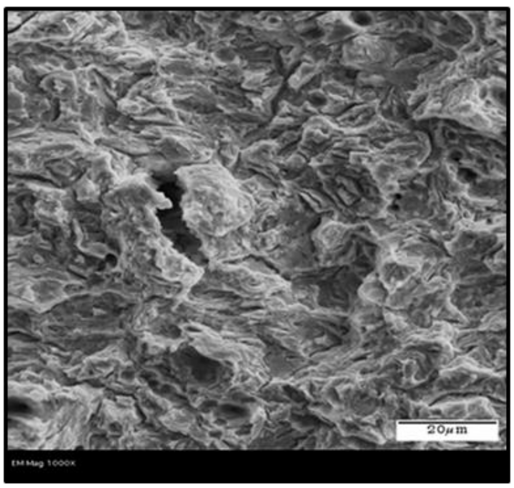
Figure F.7-9: SEM of Rod 3-V-9 Thd 4, EHE



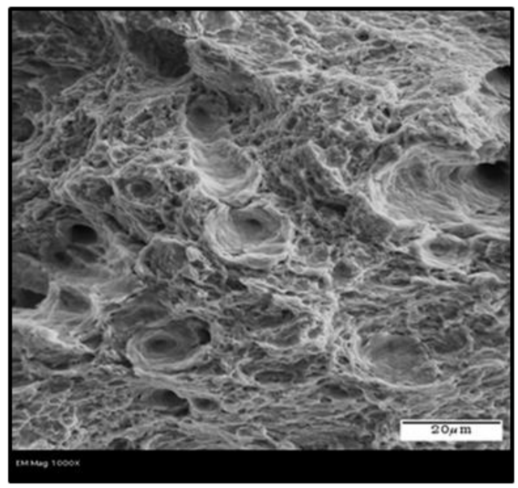
Thread Root 50X



1) Ductile Overload 250X



2) Mixed: Ductile Overload, Intergranular 1000X



Impact, Ductile Overload 1000X

Appendix G: Rod 3-V-10

G.1 Description of Sample

Rod 3-V-10 was a spare Shear Key Anchor Bolt at the top of Pier E2 (S1/S2) and is from a similar heat of material as was tested in Test Rigs 1, 2, 3 and 4 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 3 inches in diameter with machined threads. The segment from one of four spares from this rod provided to LRA is shown in **Figure G.1-1**.

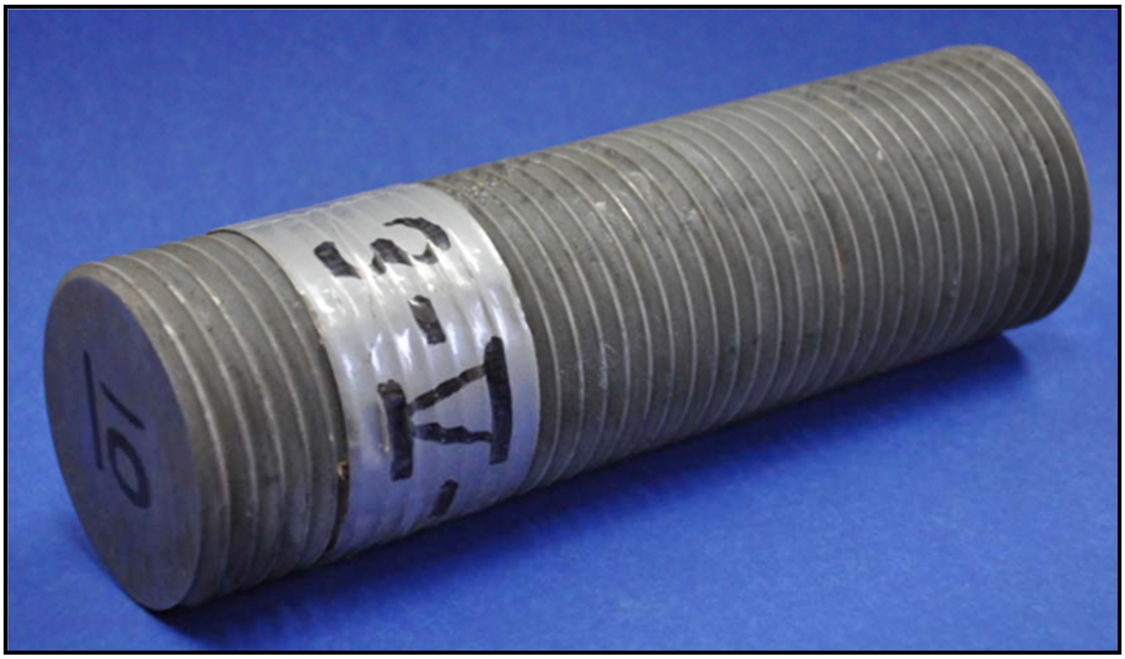


Figure G.1-1: Pier E2 Shear Key Anchor Bolt (Top), Rod 3-V-10

G.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 3-V-10 can be seen in **Figure G.2-1** where the black portion of the Shadowgraph represents the rod material. As can be seen from **Figure G.2-1**, these machined thread roots are non-uniform and exhibit a sharp radius.

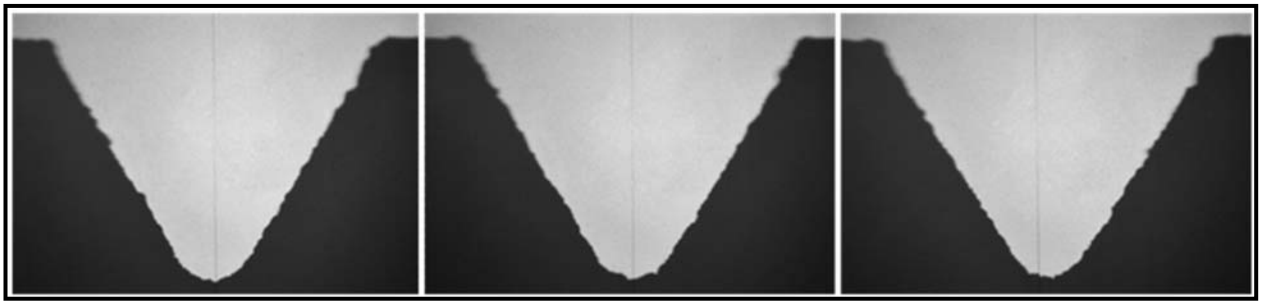


Figure G.2-1: Thread Comparison of Three Threads of Rod 3-V-10

G.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 3-V-10 and can be seen versus time in **Figure G**.3-1. The final OCP recorded for Rod 3-V-10 was Vsce=-1.052 V.

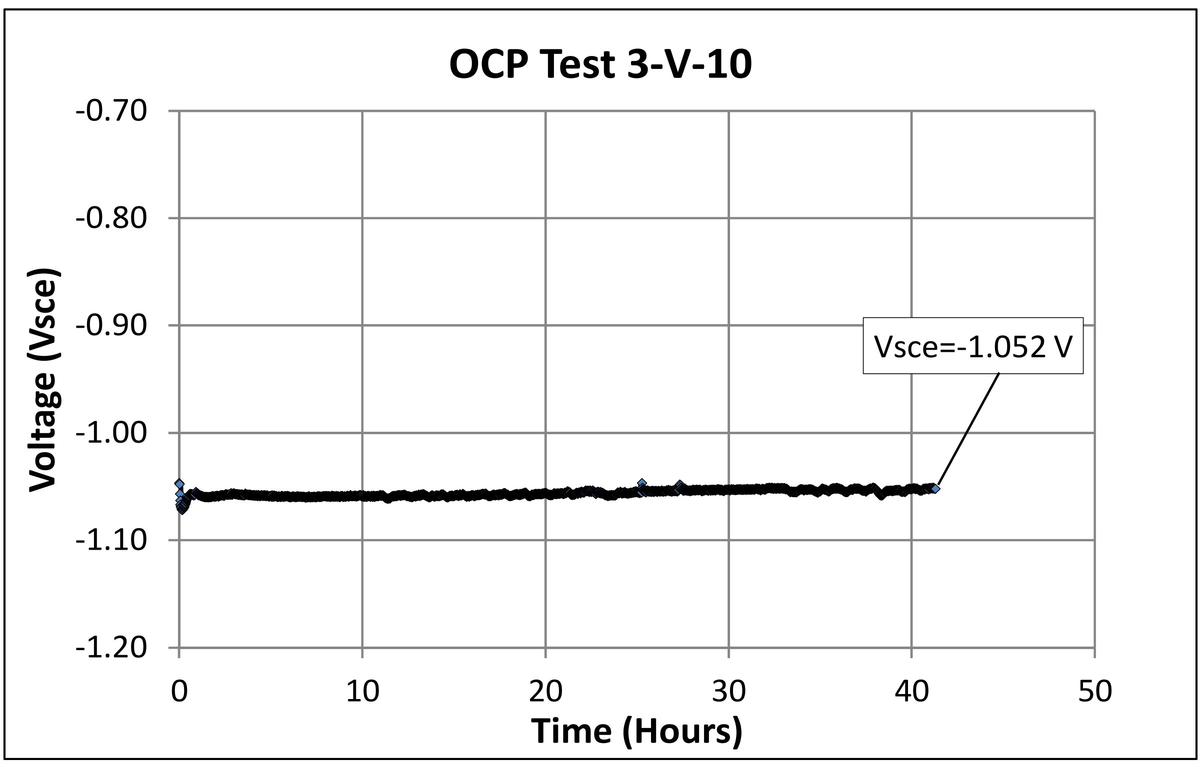


Figure G.3-1: Open Circuit Potential for Rod 3-V-10

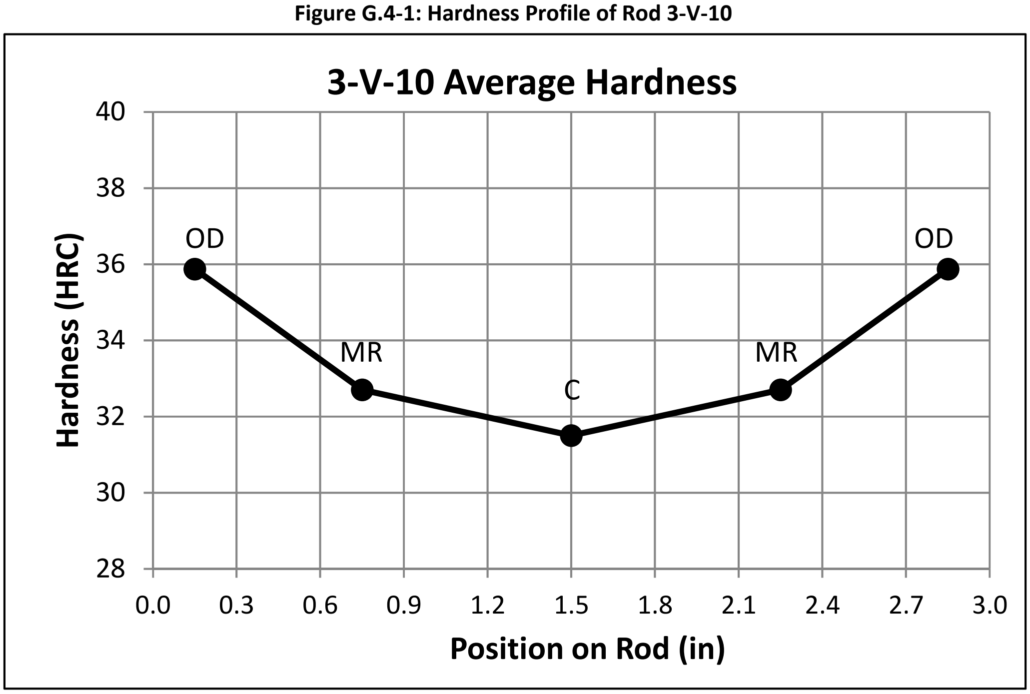
G.4 Hardness

The hardness data and profile for sample 3-V-10 are shown in **Table G.4-1** and **Figure G.4-1**.

Table G.4-1: Hardness Data of Rod 3-V-10 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 2, FFS	31.5	31.5
MR 7, FFS	31.5	32.7
MR 2, IHE	33.0	
MR 3, EHE	33.0	
MR 4, EHE	33.0	
MR 8, EHE	33.0	
OD 1, FFS	36.0	35.9
OD 2, IHE	35.5	
OD 3, EHE	35.5	
OD 4, EHE	36.0	
Thd 1, FFS	36.0	
Thd 2, IHE	36.0	
Thd 3, IHE	36.0	
Thd 4, EHE	36.0	

Figure G.4-1: Hardness Profile of Rod 3-V-10



G.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

G.5.1 Fatigue Pre-crack Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-10						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-10**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**36.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	85.3 0.53 0.96 7900		
	OD 2, IHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		85.2 0.53 0.96 2.1	
	OD 3, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			26.5 0.16 0.30 4.0
	OD 4, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			29.4 0.18 0.33 0.9
	MR 7, FFS	**31.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	79.4 0.56 0.90 8800		

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-10						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-10**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 2, IHE**	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		92.1 0.62 1.04 2.2	
	MR 3, EHE	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			52.1 0.35 0.59 2.0
	MR 4, EHE	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			35.0 0.24 0.40 1.5
	MR 8, EHE	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			36.4 0.24 0.41 1.3
	Center 2, FFS	**31.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	77.2 0.54 0.87 8500		

G.5.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-10						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-10**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**36.0**	Pmax* (lbs)	339.2		
			Fu	1.12		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	5400		
	Thd 2, IHE	**36.0**	$P_{threshold}$* (lbs)		339.5	
			Fu		1.12	
			Hsr		1.5	
			Strain Rate ($x10^{-8}$ in/in/sec)		1.7	
	Thd 3, EHE	**35.0**	$P_{threshold}$* (lbs)			227.4
			Fu			0.75
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			2.0
	Thd 4, EHE	**36.0**	$P_{threshold}$* (lbs)			235.3
			Fu			0.78
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			1.4

G.5.4 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 3-V-10
RSL™ (B) 4-pt Bend Test

LRA Job No.:	TYL130901
Rod #:	3-V-10
Product Form:	1e
Rod OD:	3"

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, KIp_{-EHE} (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	36.0	162	99.4	99.4	99.4	100.0%	85.3	0.53	286.3	1.8	7900	0.2043	147.2	50 lbs/min		0.96	
	OD 2, IHE	Air	35.5	159	2154.0	3448.2	3320.1	99.9%	85.2	0.53	282.6	1.8	2.1	0.1993		10/5/2,4		0.96	Tensile Frame
	OD 3, EHE	3.5% NaCl @ -1.106V	36.0	162	67.0	40.2	30.1	31.1%	26.5	0.16	89.7	0.6	4.0	0.2103		10/5/2,4		0.30	
	OD 4, EHE	3.5% NaCl @ -1.106V	36.0	162	24.0	37.2	32.3	34.5%	29.4	0.18	100.7	0.6	0.9	0.2121		10/5/2,4		0.33	
	MR 7, FFS	Air	31.5	143	84.7	84.7	84.7	100.0%	79.4	0.56	273.5	1.9	8800	0.2140	138.8	50 lbs/min		0.90	
	MR 2, IHE	Air	33.0	149	1910.0	3153.3	3153.3	116.0%	92.1	0.62	317.4	2.1	2.2	0.2204		10/5/2,4		1.04	Tensile Frame
	MR 3, EHE	3.5% NaCl @ -1.106V	33.0	149	59.7	71.4	59.4	65.6%	52.1	0.35	176.1	1.2	2.0	0.2119		10/5/2,4		0.59	
	MR 4, EHE	3.5% NaCl @ -1.106V	33.0	149	45.0	54.1	40.4	44.1%	35.0	0.24	117.6	0.8	1.5	0.2102		10/5/2,4		0.40	
	MR 8, EHE	3.5% NaCl @ -1.106V	33.0	149	35.0	47.3	38.4	45.8%	36.4	0.24	125.7	0.8	1.3	0.2151		10/5/2,4		0.41	
	Center 2, FFS	Air	31.5	143	84.9	84.9	84.9	100.0%	77.2	0.54	263.8	1.8	8500	0.2145	159.1	50 lbs/min		0.87	
Threaded	Thd 1, FFS	Air	36.0	162	327.9	327.9	327.9	100.0%	98.9	0.61	248.2	1.5	5400			150 lbs/min	339.2	1.12	
	Thd 2, IHE	Air	36.0	162	257.0	374.3	374.3	100.1%	99.0	0.61	241.9	1.5	1.7			10/5/2,4	339.5	1.12	
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.0	157	256.6	335.2	242.7	67.0%	66.3	0.42	162.7	1.0	2.0			10/5/2,4	227.4	0.75	No Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	36.0	162	180.0	324.1	241.8	69.4%	68.6	0.42	169.0	1.0	1.4			10/5/1,4	235.3	0.78	No Holiday

G.6 Fatigue Pre-cracked Specimen Test Results

G.6.1 OD 1, FFS:

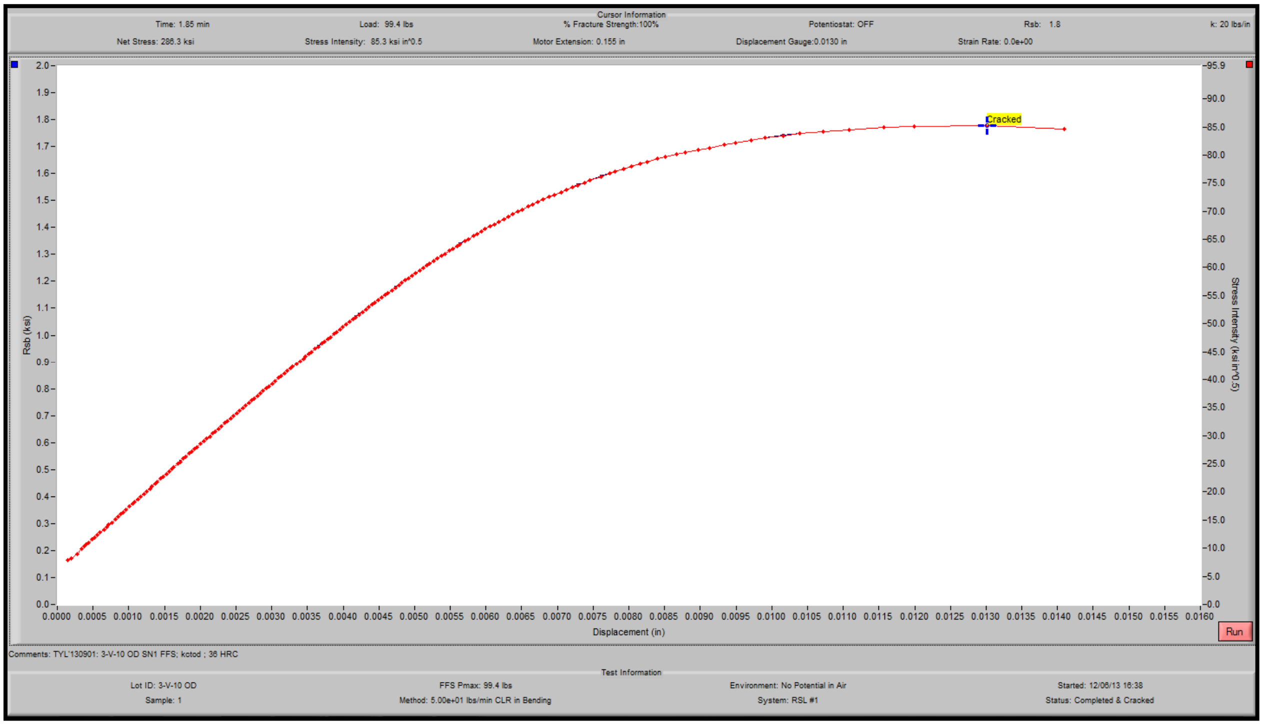


Figure G.6-1: Rod 3-V-10 OD 1, Graphical FFS Results

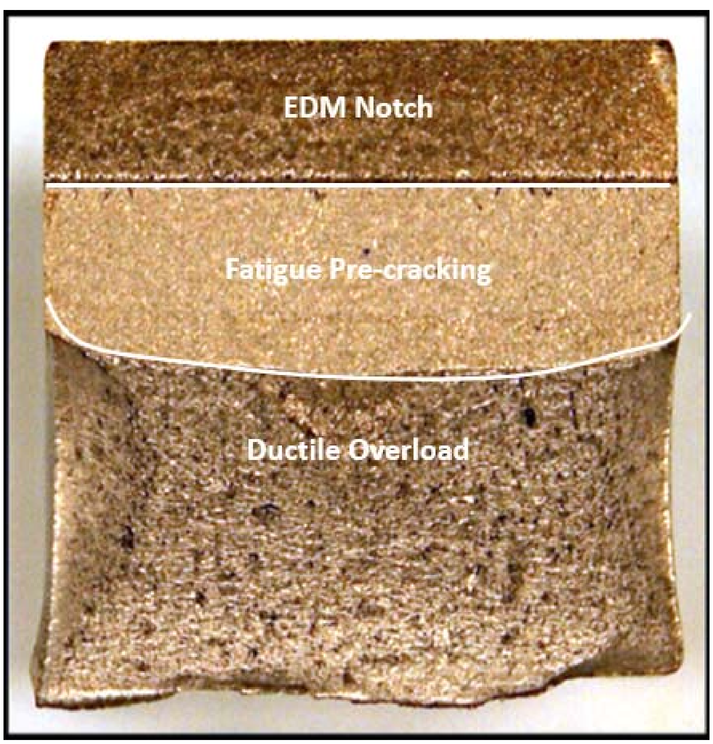


Figure G.6-2: Fracture Face of Rod 3-V-10 OD 1, FFS

G.6.2 OD 2, IHE:

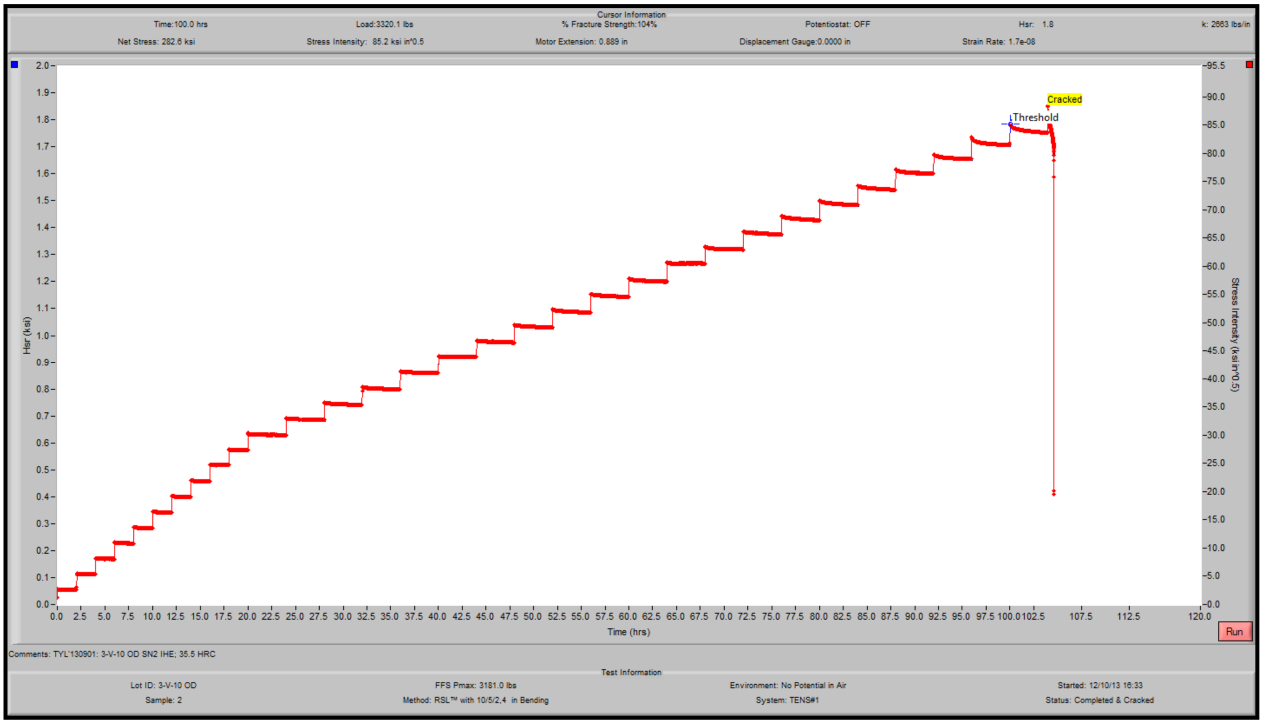


Figure G.6-3: Rod 3-V-10 OD 2, Graphical IHE Results

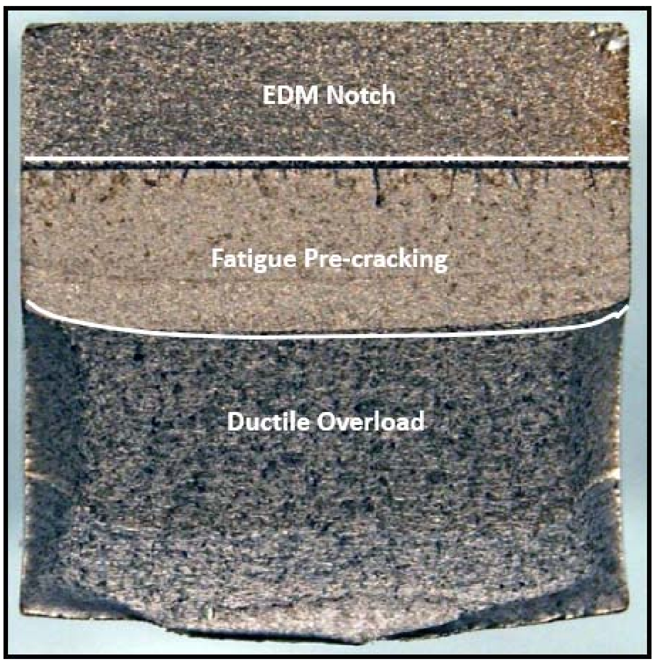


Figure G.6-4: Fracture Face of Rod 3-V-10 OD 2, IHE

G.6.3 OD 3, EHE:

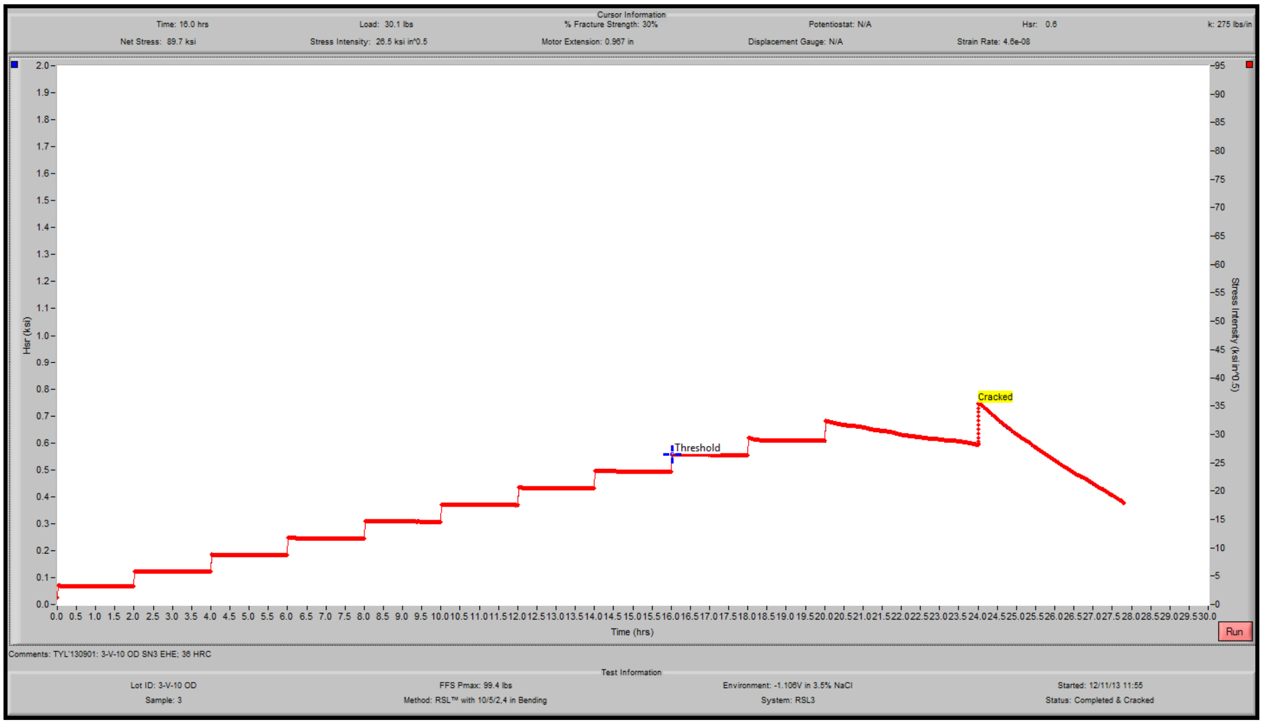


Figure G.6-5: Rod 3-V-10 OD 3, Graphical EHE Results

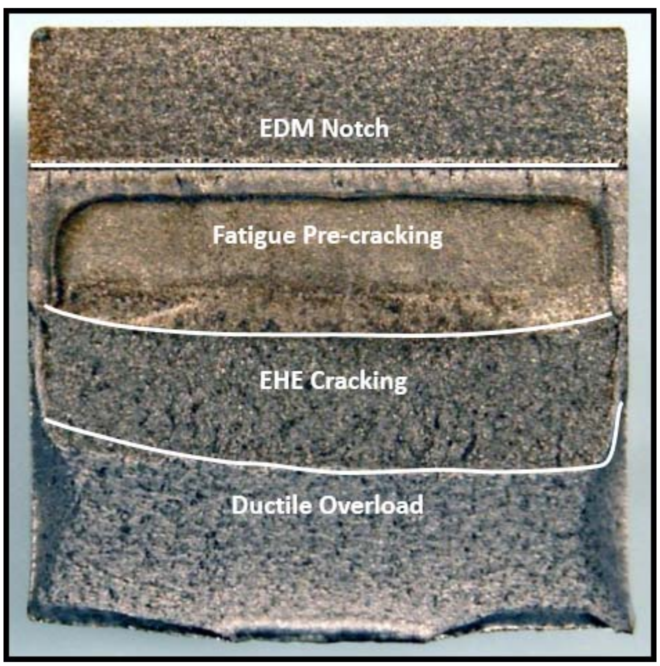


Figure G.6-6: Fracture Face of Rod 3-V-10 OD 3, EHE

G.6.4 OD 4, EHE:

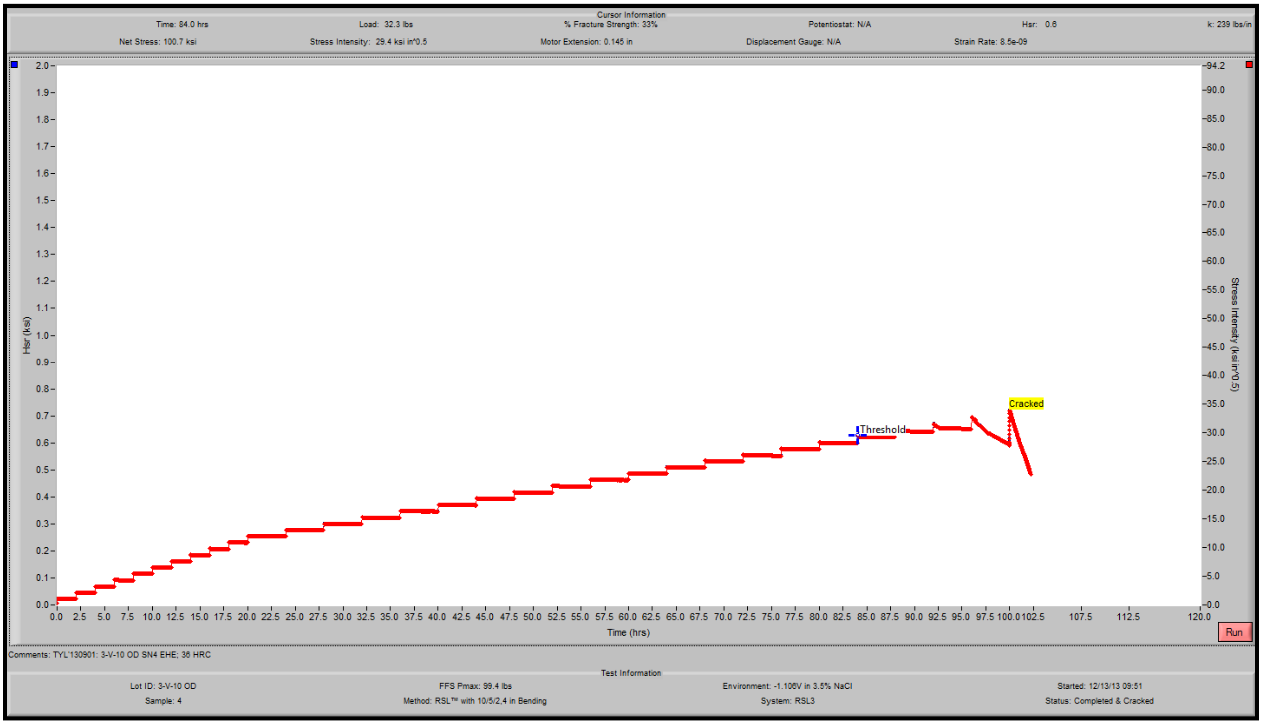


Figure G.6-7: Rod 3-V-10 OD 4, Graphical EHE Results

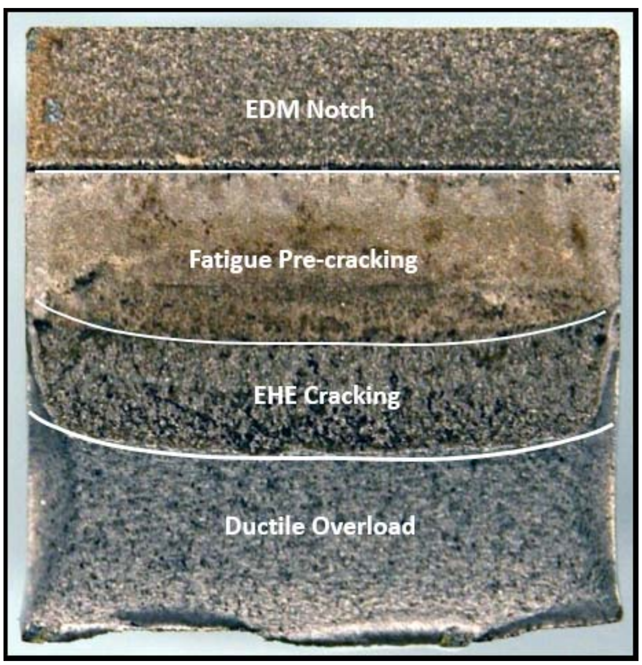


Figure G.6-8: Fracture Face of Rod 3-V-10 OD 4, EHE

G.6.5 MR 7, FFS:

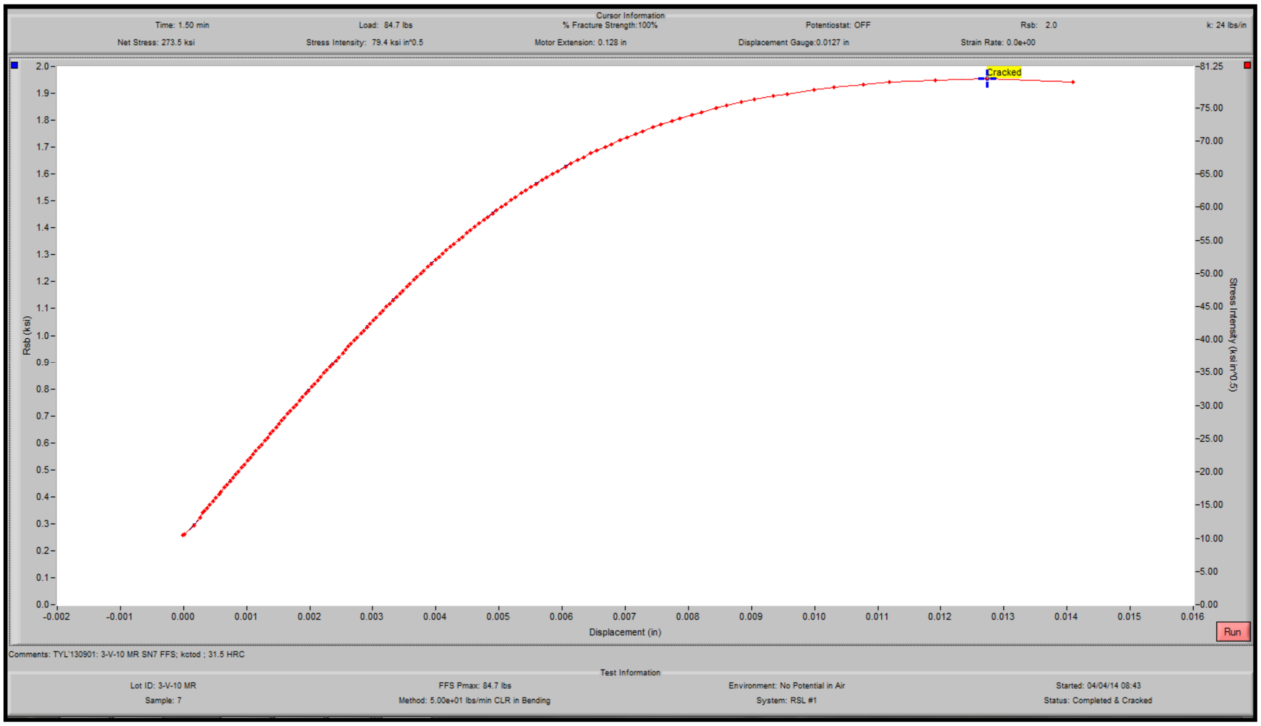


Figure G.6-9: Rod 3-V-10 MR 7, Graphical FFS Results

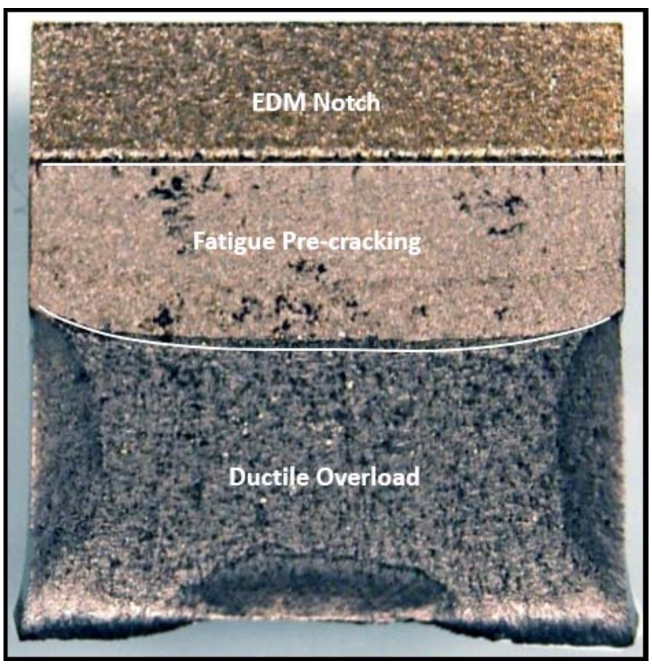


Figure G.6-10: Fracture Face of Rod 3-V-10 MR 7, FFS

G.6.6 MR 2, IHE:

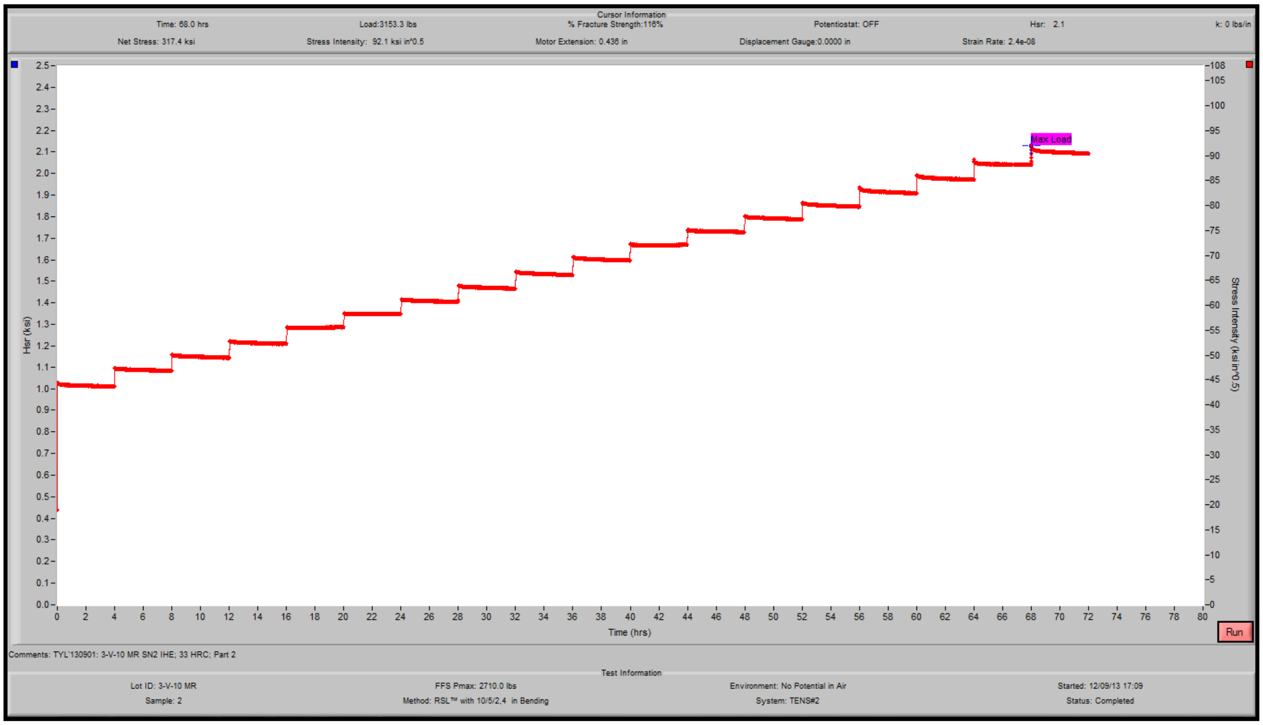


Figure G.6-11: Rod 3-V-10 MR 2, Graphical IHE Results

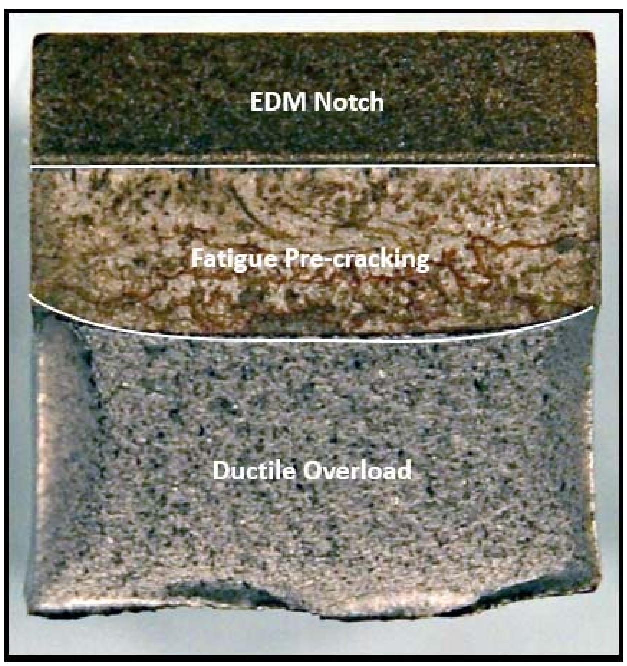


Figure G.6-12: Fracture Face of Rod 3-V-10 MR 2, IHE

G.6.7 MR 3, EHE:

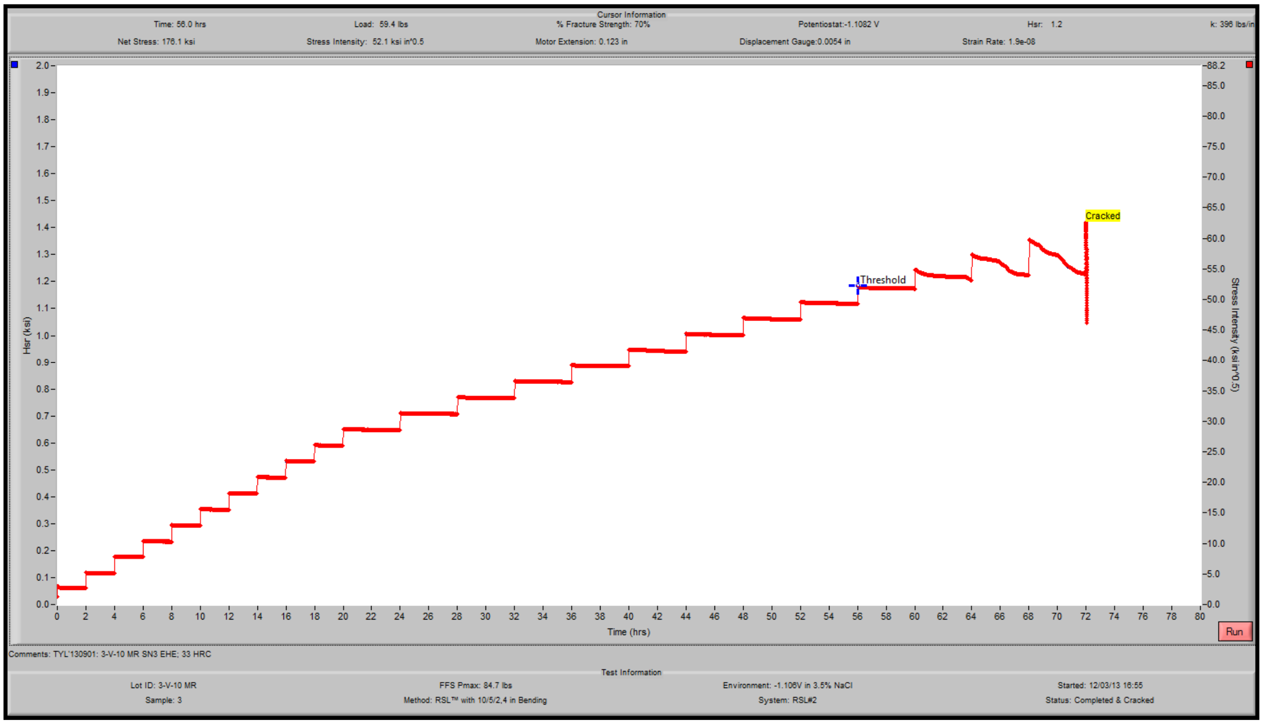


Figure G.6-13: Rod 3-V-10 MR 3, Graphical EHE Results

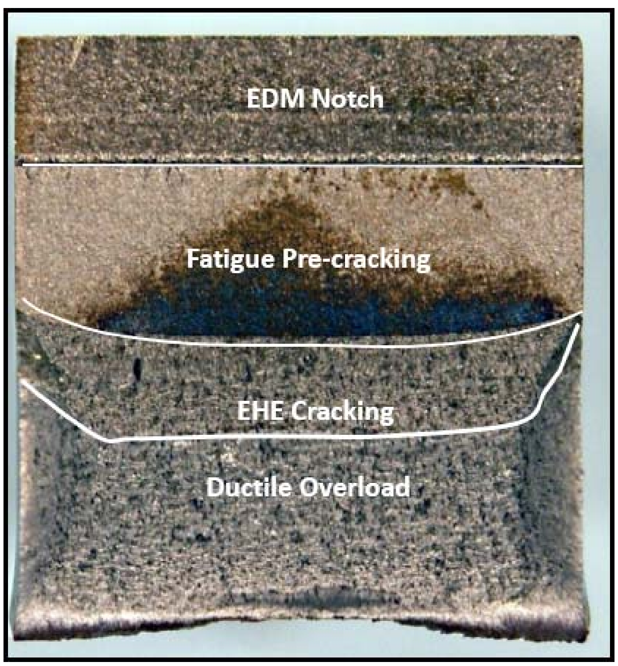


Figure G.6-14: Fracture Face of Rod 3-V-10 MR 3, EHE

G.6.8 MR 4, EHE:

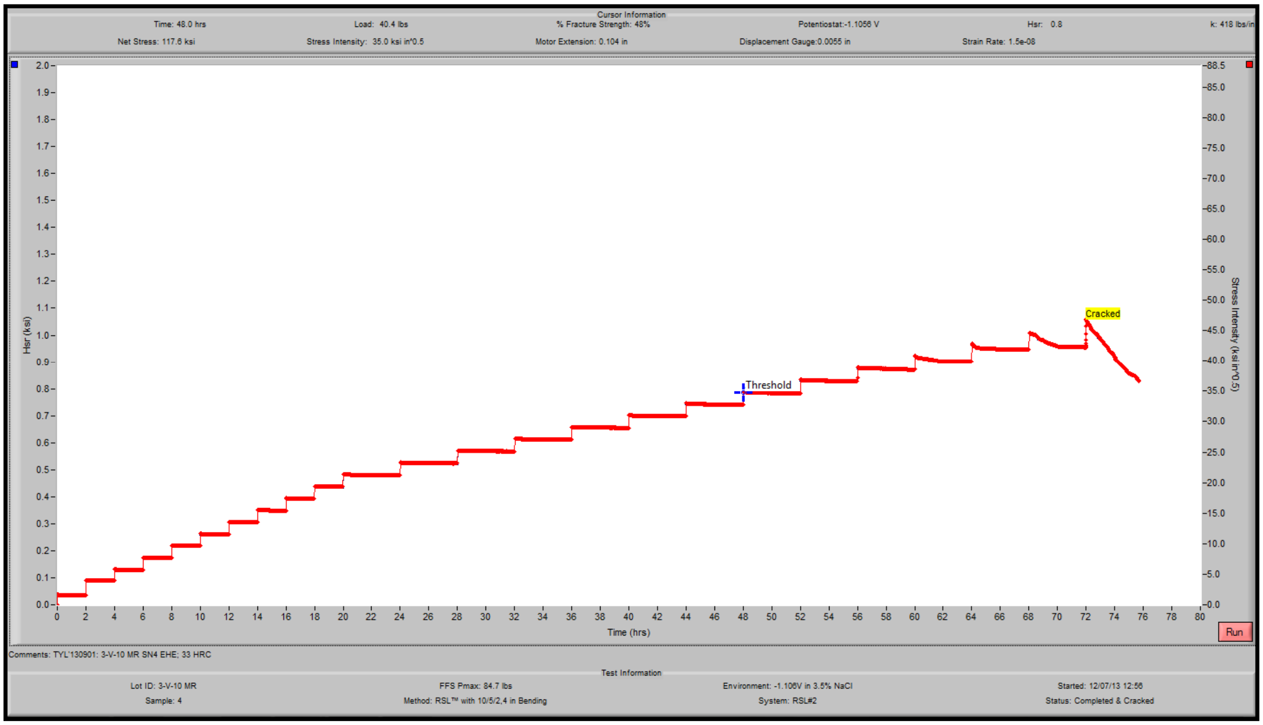


Figure G.6-15: Rod 3-V-10 MR 4, Graphical EHE Results

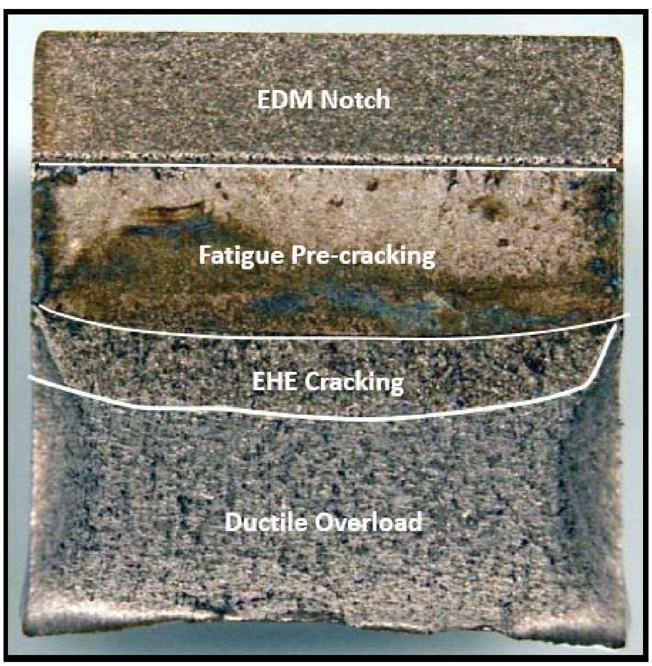


Figure G.6-16: Fracture Face of Rod 3-V-10 MR 4, EHE

G.6.9 MR 8, EHE:

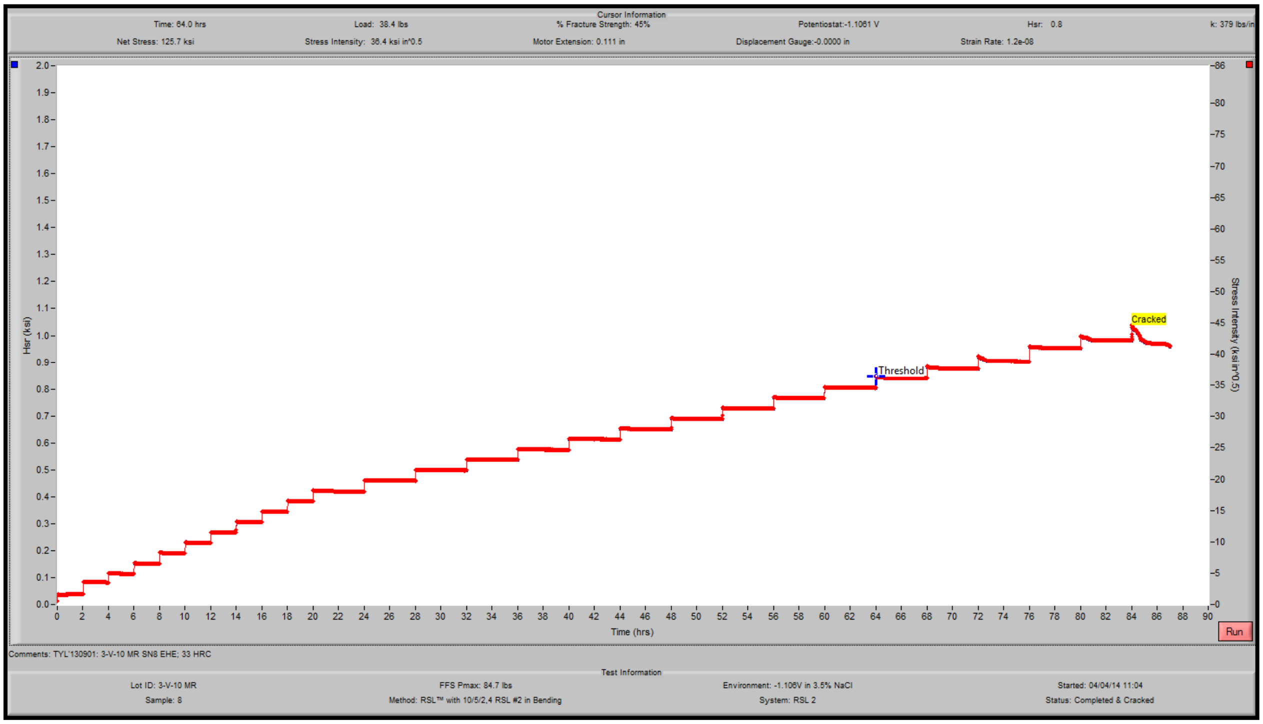


Figure G.6-17: Rod 3-V-10 MR 8, Graphical EHE Results

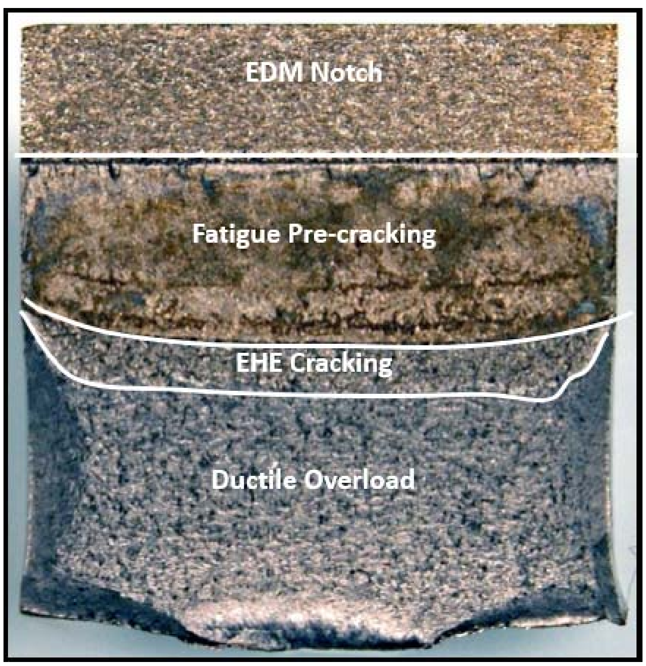


Figure G.6-18: Fracture Face of Rod 3-V-10 MR 8, EHE

G.6.10 Center 2, FFS:

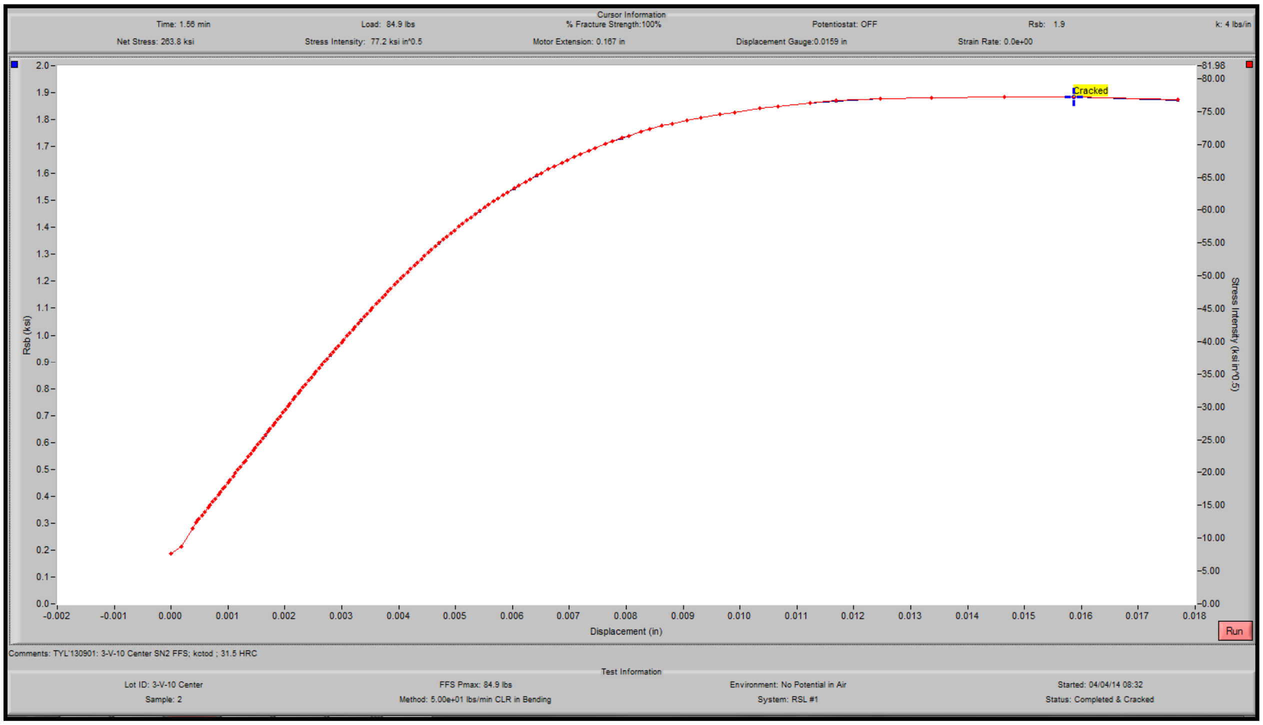


Figure G.6-19: Rod 3-V-10 Center 2, Graphical FFS Results

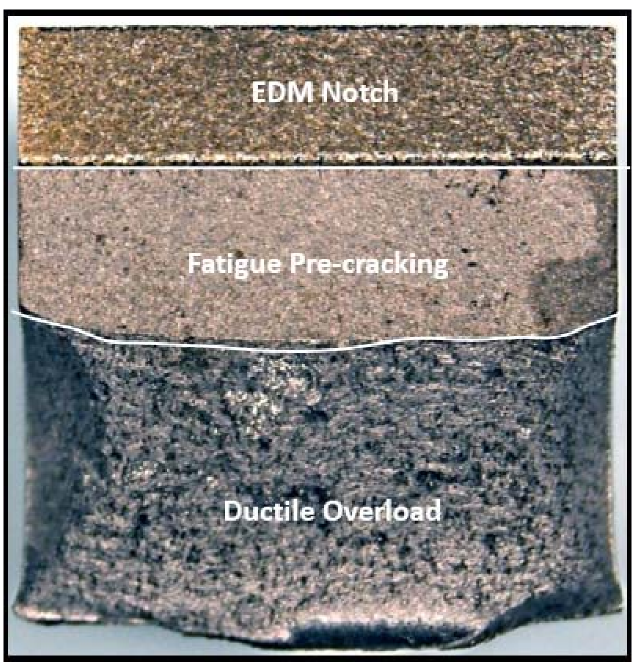


Figure G.6-20: Fracture Face of Rod 3-V-10 Center 2, FFS

G.7 Threaded Specimen Test Results

G.7.1 Thd 1, FFS:

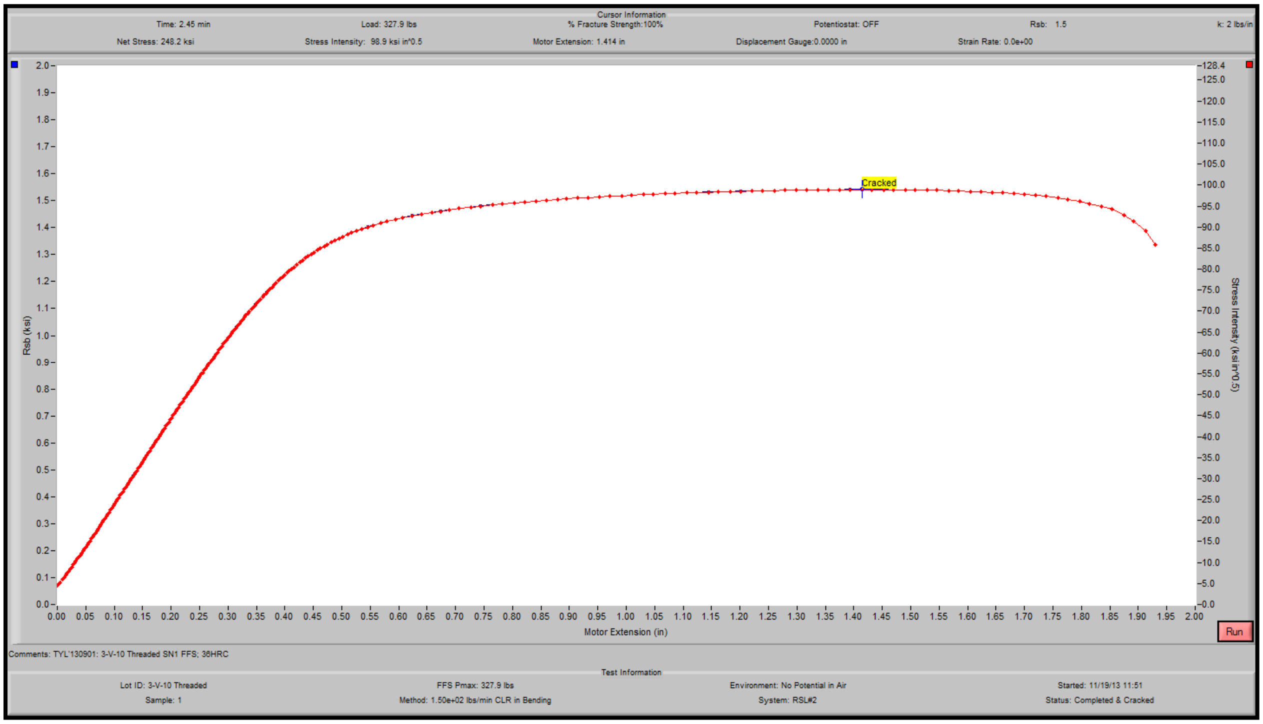


Figure G.7-1: Rod 3-V-10 Thd 1, Graphical FFS Results

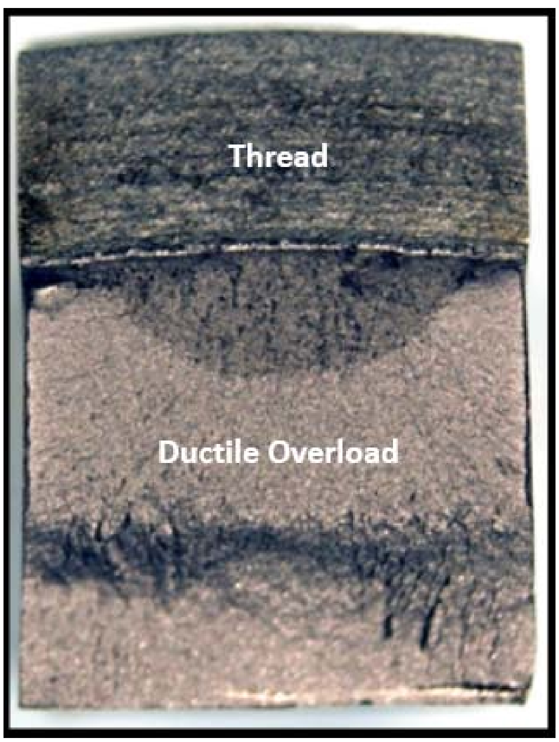
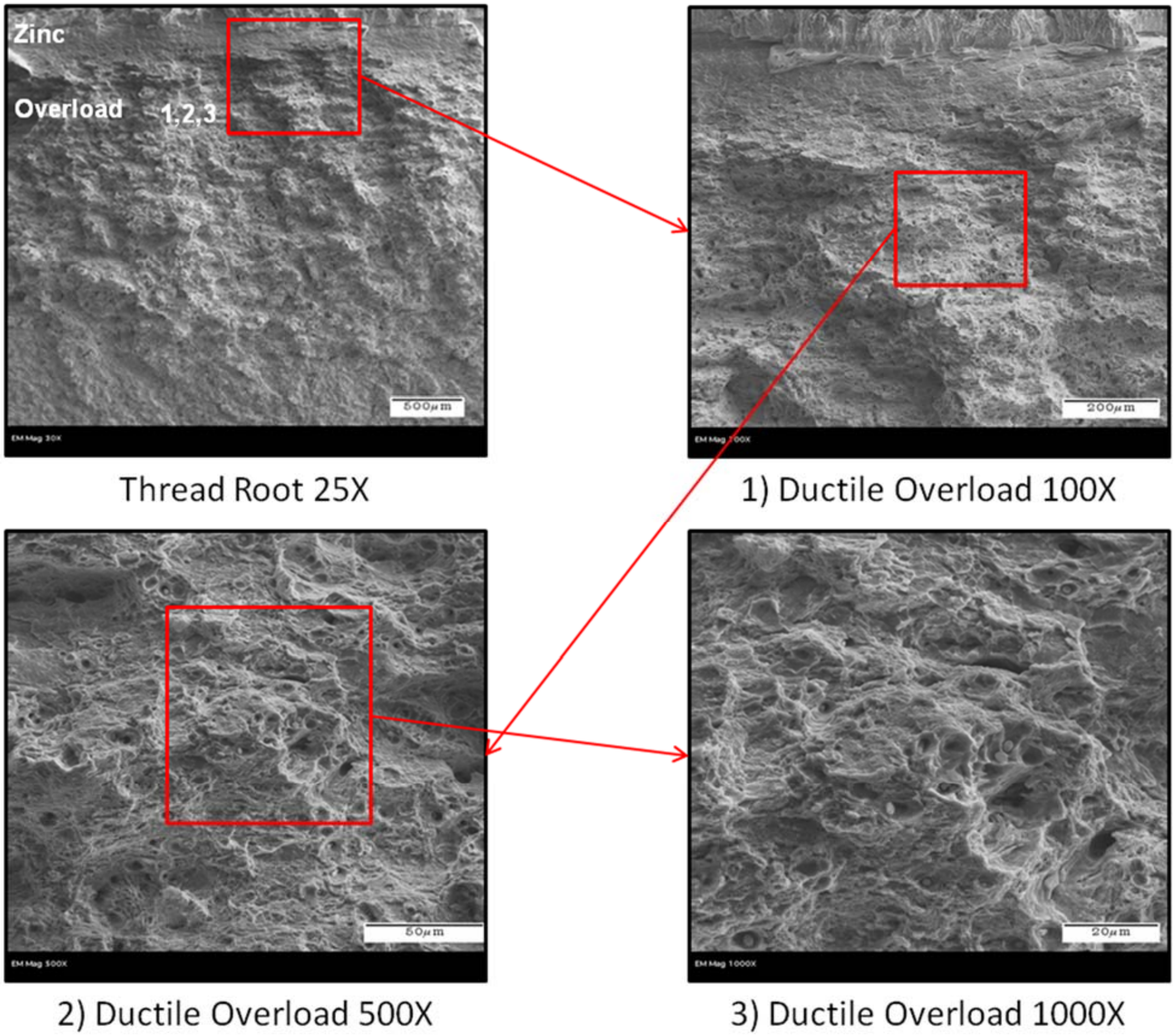


Figure G.7-2: Rod 3-V-10 Thd 1 FFS Fracture Face

Figure G.7-3: SEM of Rod 3-V-10 Thd 1, FFS



G.7.2 Thd 2, IHE:

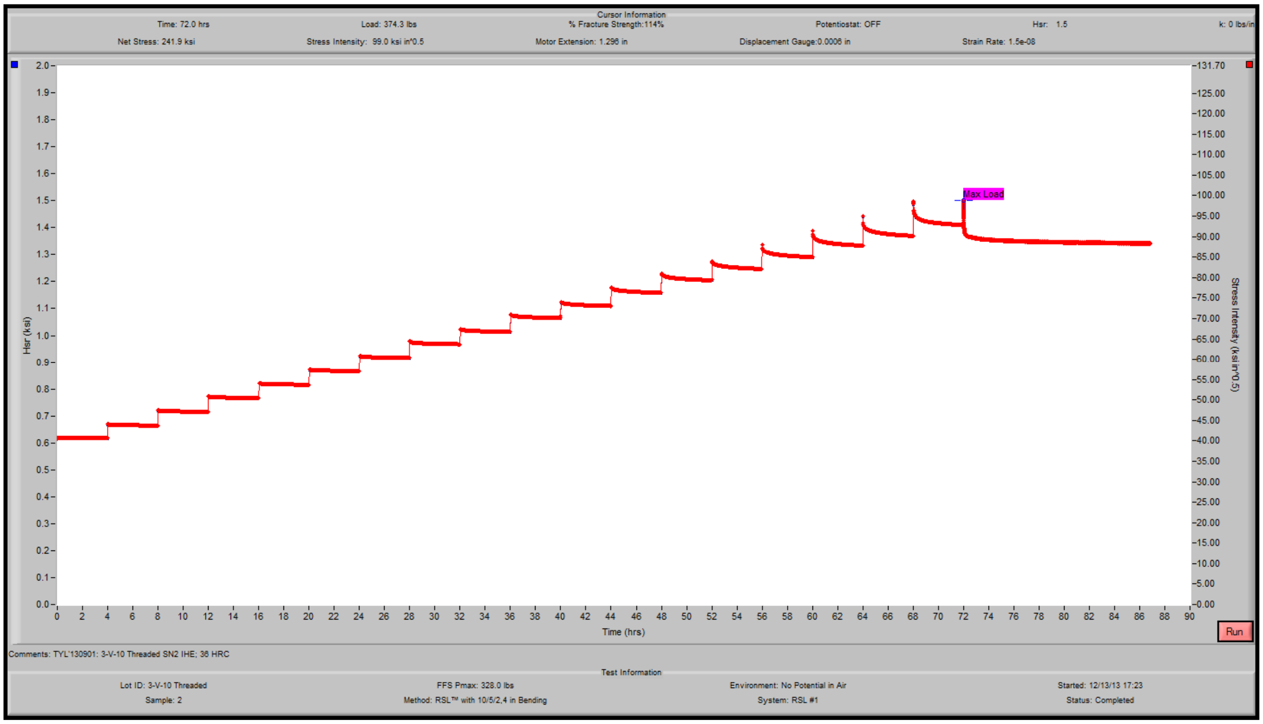


Figure G.7-4: Rod 3-V-10 Thd 2, Graphical IHE Results

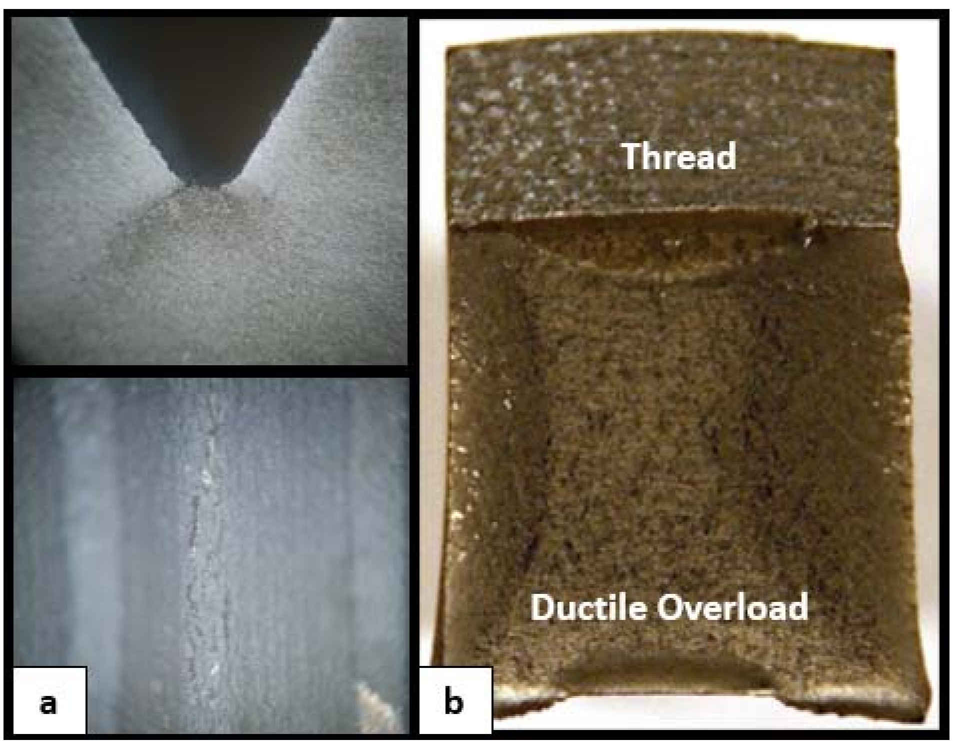


Figure G.7-5: Rod 3-V-10 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

G.7.3 Thd 3, EHE:

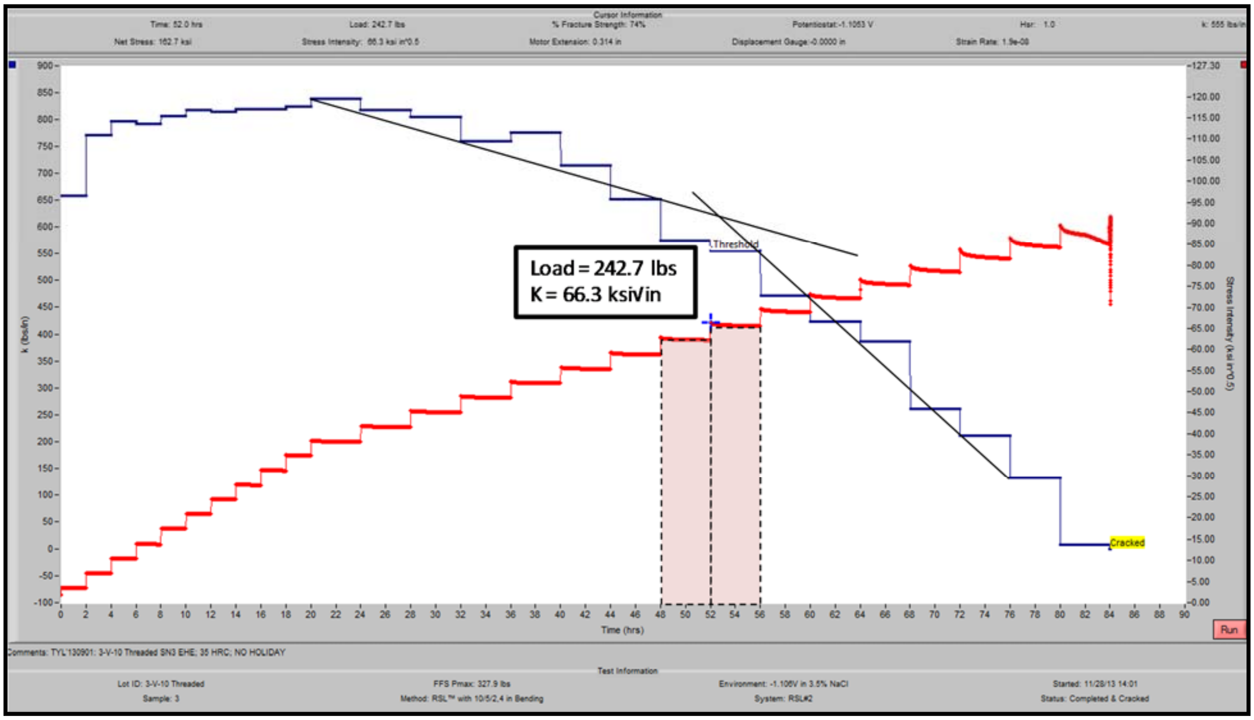


Figure G.7-6: Rod 3-V-10 Thd 3, Graphical EHE Results

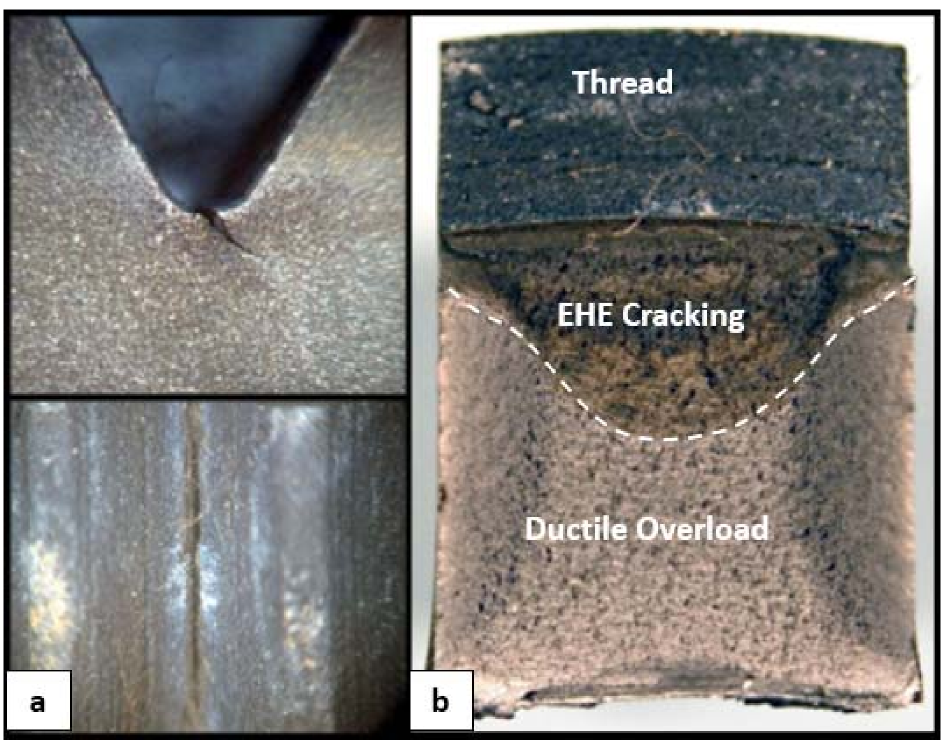
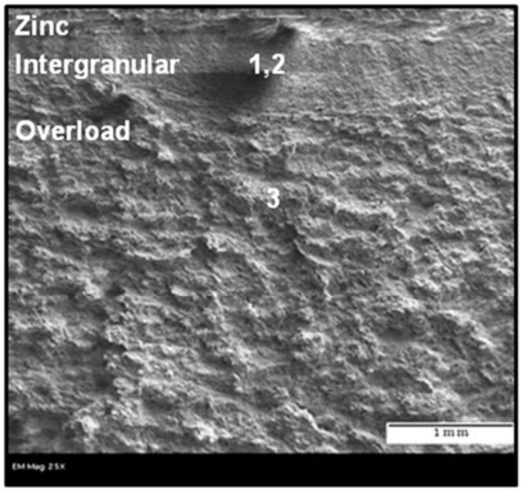
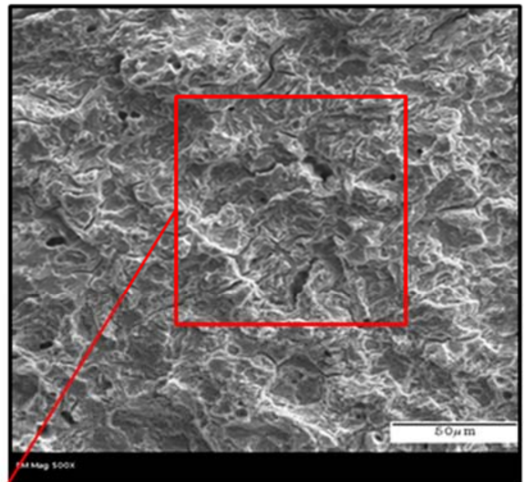


Figure G.7-7: Rod 3-V-10 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

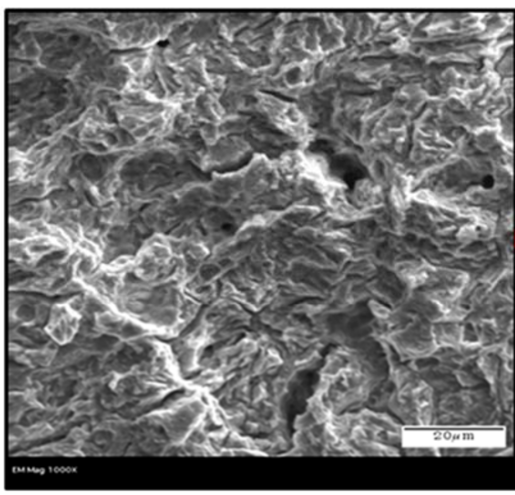
Figure G.7-8: SEM of Rod 3-V-10 Thd 3, EHE



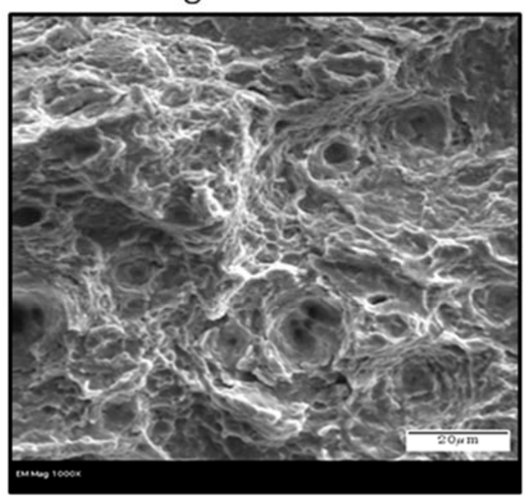
Thread Root 25X



1) Mixed: Ductile Overload, Intergranular 500X



2) Mixed: Ductile Overload, Intergranular 1000X



3) Ductile Overload 1000X

G.7.4 Thd 4, EHE:

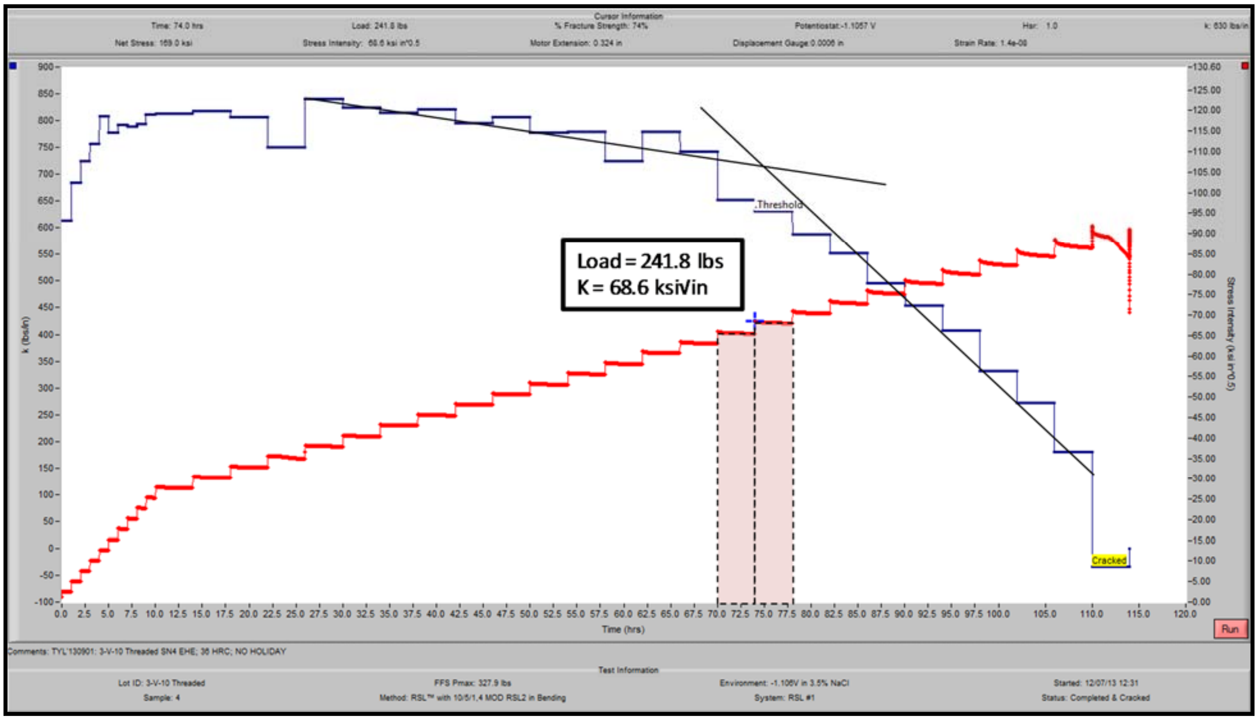


Figure G.7-9: Rod 3-V-10 Thd 4, Graphical EHE Results

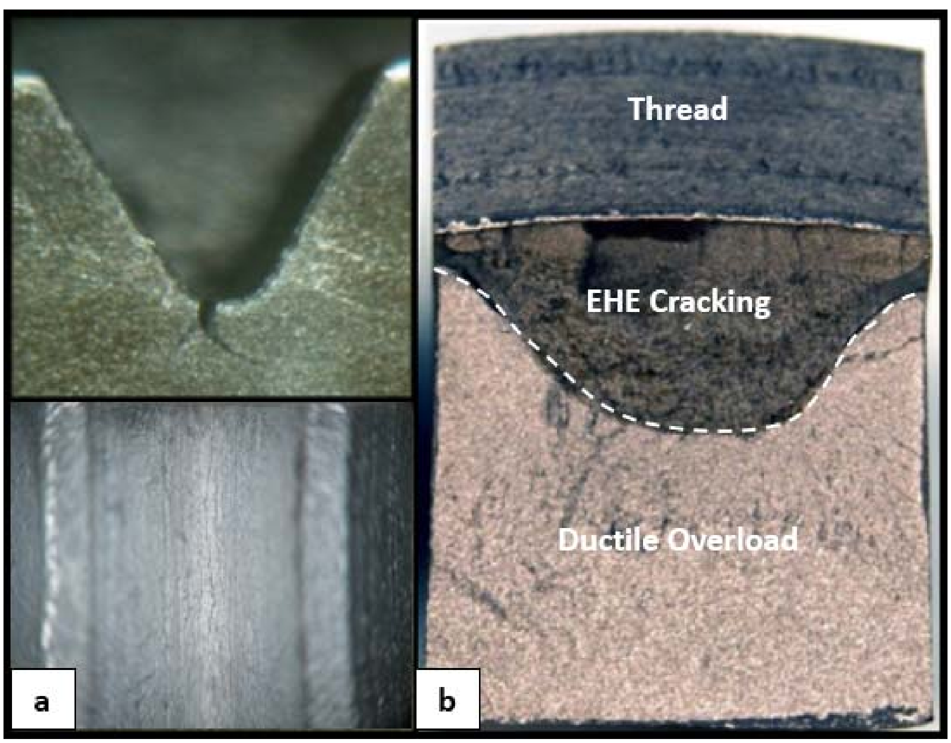
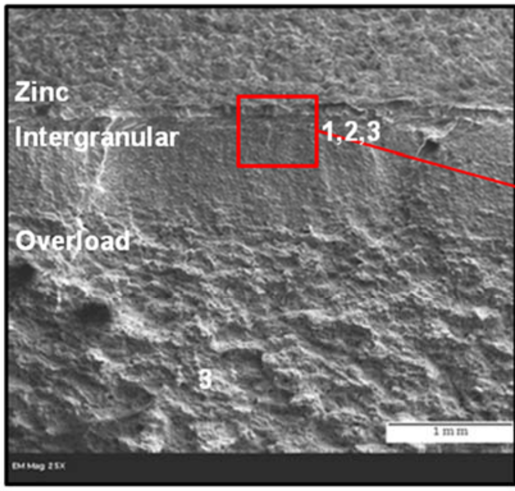
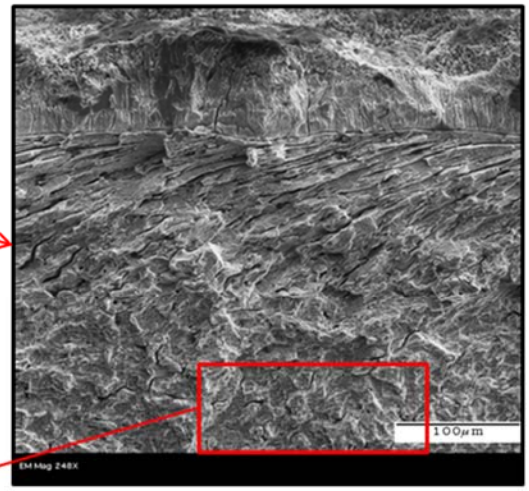


Figure G.7-10: Rod 3-V-10 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

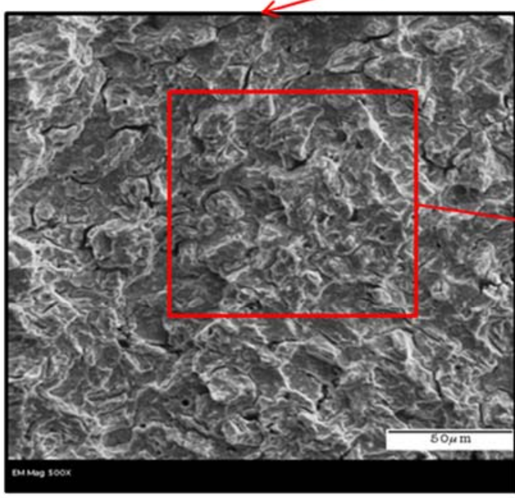
Figure G.7-11: SEM of Rod 3-V-10 Thd 4, EHE



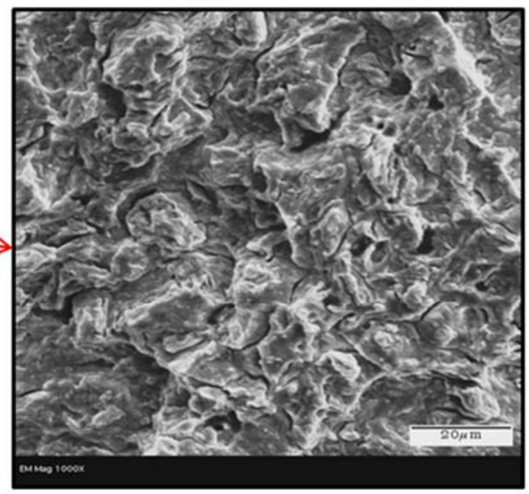
Thread Root 25X



1) Mixed: Ductile Overload, Intergranular 250X



2) Mixed: Ductile Overload, Intergranular 500X



3) Mixed: Ductile Overload, Intergranular 1000X

Appendix H: Rod 3-V-11

H.1 Description of Sample

Rod 3-V-11 was a spare Shear Key Anchor Bolt at the top of Pier E2 (S1/S2) and is from a similar heat of material as was tested in Test Rigs 1, 2, 3 and 4 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. These bolts are 3 inches in diameter with machined threads. The segment from one of four spares from this rod provided to LRA is shown in **Figure H.1-1**.

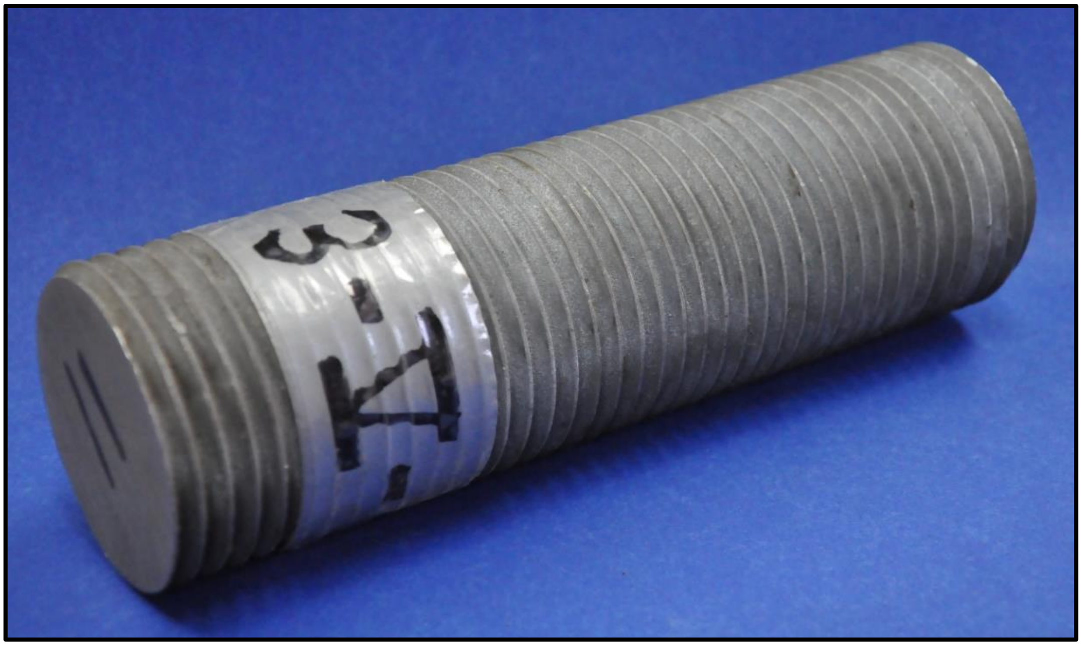


Figure H.1-1: Pier E2 Shear Key Anchor Bolt (Top), Rod 3-V-11

H.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 3-V-11 can be seen in **Figure H.2-1** where the black portion of the Shadowgraph represents the rod material. As can be seen from **Figure H.2-1**, these machined thread roots show non-uniformity.

Figure H.2-1: Thread Comparison of Three Threads of Rod 3-V-11

H.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 3-V-11 and can be seen versus time in **Figure H**.3-1. The final OCP recorded for Rod 3-V-11 was Vsce=-0.965 V.

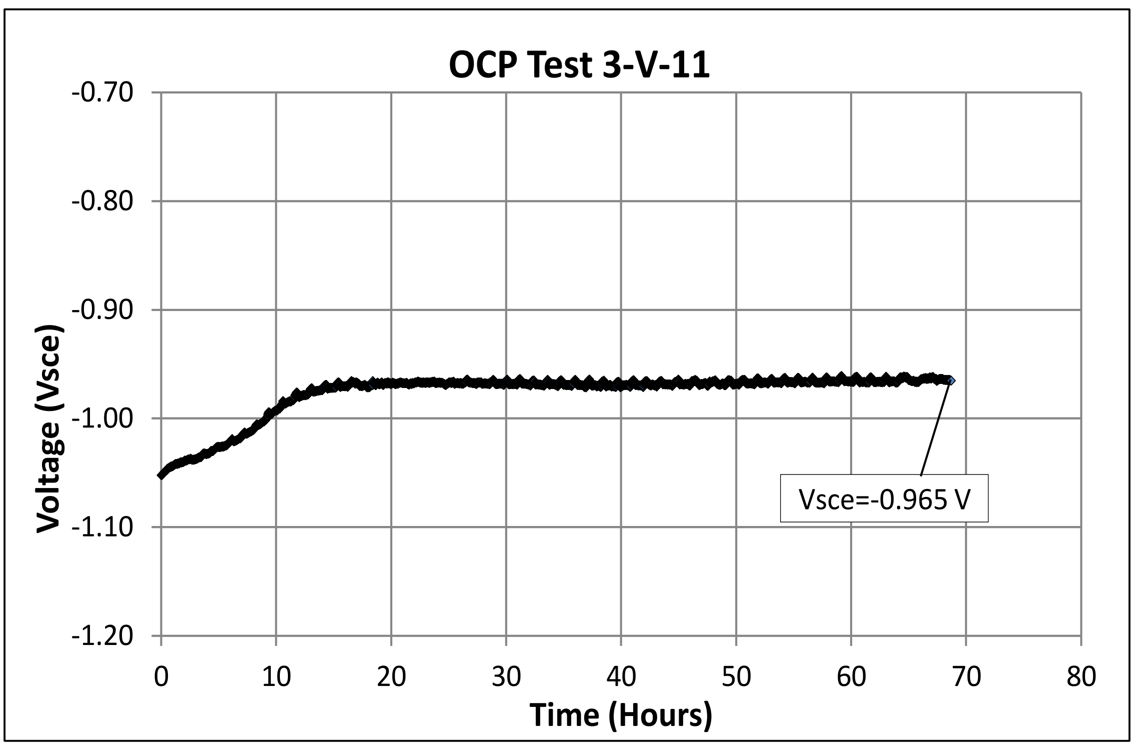


Figure H.3-1: Open Circuit Potential for Rod 3-V-11

H.4 Hardness

The hardness data and profile for sample 3-V-11 are shown in **Table H.4-1** and **Figure H.4-1**.

Table H.4-1: Hardness Data of Rod 3-V-11 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	28.0	28.0
MR 1, FFS	33.0	32.9
MR 2, IHE	32.5	
MR 3, EHE	33.0	
MR 4, EHE	33.0	
OD 1, FFS	35.0	35.8
OD 2, IHE	36.0	
OD 5, EHE	37.0	
OD 6, EHE	34.5	
OD 7, EHE	35.5	
OD 8, EHE	36.0	
Thd 1, FFS	35.5	
Thd 2, IHE	36.0	
Thd 3, EHE	36.0	
Thd 4, EHE	37.0	
Thd 7, EHE	35.0	

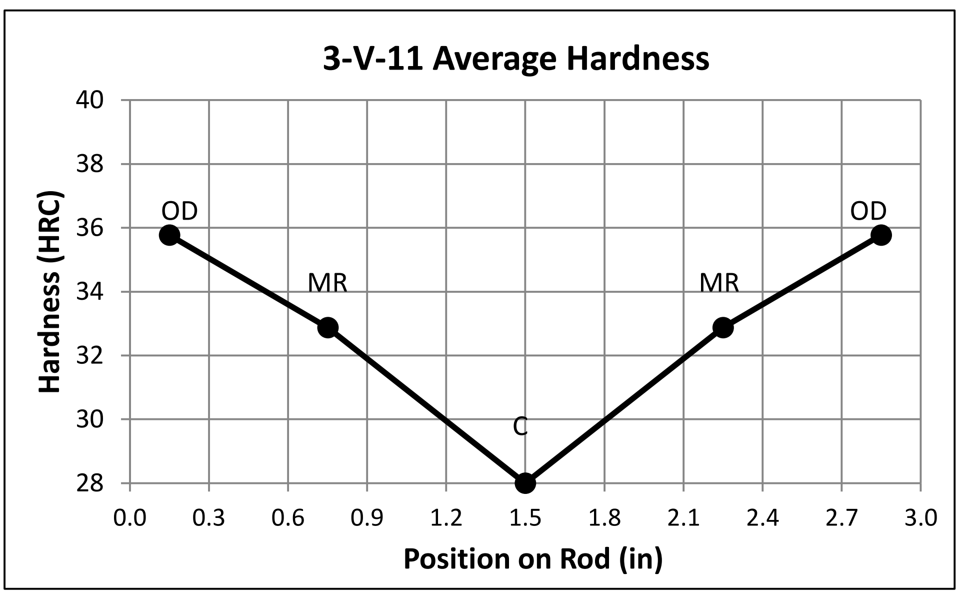


Figure H.4-1: Hardness Profile of Rod 3-V-11

H.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following “checker board” tables.

H.5.1 Fatigue Pre-crack Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-11						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top				
Rod#:	**3-V-11**					
Product Form:	**1e**	**Comments**: 2010 Machined Threads				
Rod OD:	**3"**	Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**35.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	86.2 0.55 0.97 8600		
	OD 2, IHE	**36.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		84.4 0.52 0.95 2.0	
	OD 5, EHE	**37.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			53.2 0.32 0.60 1.0
	OD 6, EHE	**34.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			32.1 0.21 0.36 2.0
	OD 7, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			38.5 0.24 0.43 1.5
	OD 8, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			33.4 0.21 0.38 1.5

<table>
<tr><td colspan="7">Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 3-V-11</td></tr>
<tr><td>LRA Job No.:</td><td>TYL130901</td><td colspan="5" rowspan="4">Structural Component: Shear Key Anchor Bolts-Top

Comments: 2010 Machined Threads
Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)</td></tr>
<tr><td>Rod#:</td><td>3-V-11</td></tr>
<tr><td>Product Form:</td><td>1e</td></tr>
<tr><td>Rod OD:</td><td>3"</td></tr>
<tr><td></td><td>Sample #/ID</td><td>HRC</td><td></td><td>K-FFS</td><td>K-IHE</td><td>K-EHE</td></tr>
<tr><td rowspan="5">Fatigue Pre-cracked</td><td>MR 1, FFS</td><td>33.0</td><td>K_{max}
DTI_{th}
Fu
Strain Rate
($x10^{-8}$ in/in/sec)</td><td>80.9
0.54
0.91
8100</td><td></td><td></td></tr>
<tr><td>MR 2, IHE</td><td>32.5</td><td>K_{max}
DTI_{th}
Fu
Strain Rate
($x10^{-8}$ in/in/sec)</td><td></td><td>86.4
0.59
0.98
2.0</td><td></td></tr>
<tr><td>MR 3, EHE</td><td>33.0</td><td>$K_{threshold}$
DTI_{th}
Fu
Strain Rate
($x10^{-8}$ in/in/sec)</td><td></td><td></td><td>39.8
0.27
0.45
2.2</td></tr>
<tr><td>MR 4, EHE</td><td>33.0</td><td>$K_{threshold}$
DTI_{th}
Fu
Strain Rate
($x10^{-8}$ in/in/sec)</td><td></td><td></td><td>36.9
0.25
0.42
1.5</td></tr>
<tr><td>Center 1, FFS</td><td>28.0</td><td>K_{max}
DTI_{th}
Fu
Strain Rate
($x10^{-8}$ in/in/sec)</td><td>72.2
0.55
0.82
7200</td><td></td><td></td></tr>
</table>

H.5.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-11						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top (S1/S2) **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-11**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.5**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	342.3 1.13 1.5 4900		
	Thd 2, IHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		333.7 1.10 1.5 2.2	
	Thd 3, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			239.7 0.79 1.1 2.2
	Thd 4, EHE	**37.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			240.1 0.79 1.0 2.4
	Thd 7, EHE	**35.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			248.6 0.82 1.1 1.1

H.5.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 3-V-11
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**3-V-11**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, KIp_{-EHE} (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	35.0	157	93.8	93.8	93.8	100.0%	86.2	0.55	296.0	1.9	8600	0.2156	132.7	50 lbs/min		0.97	
	OD 2, IHE	Air	36.0	162	1891.2	3122.2	3122.2	97.9%	84.4	0.52	284.6	1.8	2.0	0.2079		10/5/2,4		0.95	Tensile Frame
	OD 5, EHE	3.5% NaCl @ -1.106V	37.0	167	30.0	67.5	62.9	61.7%	53.2	0.32	177.9	1.1	1.0	0.2054		1/110/3-10/5/4		0.60	Test interrupted for 10 minutes.
	OD 6, EHE	3.5% NaCl @ -1.106V	34.5	155	60.0	42.0	35.9	37.2%	32.1	0.21	108.4	0.7	2.0	0.2096		10/5/2,4		0.36	
	OD 7, EHE	3.5% NaCl @ -1.106V	35.5	159	40.0	48.0	41.9	44.7%	38.5	0.24	132.1	0.8	1.5	0.2168		10/5/2,4		0.43	
	OD 8, EHE	3.5% NaCl @ -1.106V	36.0	162	40.0	38.1	35.9	38.7%	33.4	0.21	114.6	0.7	1.5	0.2157		10/5/2,4		0.38	
	MR 1, FFS	Air	33.0	149	91.5	91.5	91.5	100.0%	80.9	0.54	274.4	1.8	8100	0.2113	147.8	50 lbs/min		0.91	
	MR 2, IHE	Air	32.5	147	1910.4	3155.0	3155.0	106.8%	86.4	0.59	292.1	2.0	2.0	0.2094		10/5/2,4		0.98	Tensile Frame
	MR 3, EHE	3.5% NaCl @ -1.106V	33.0	149	59.7	50.8	41.7	49.2%	39.8	0.27	138.1	0.9	2.2	0.2202		10/5/2,4		0.45	
	MR 4, EHE	3.5% NaCl @ -1.106V	33.0	149	41.7	50.0	41.6	45.6%	36.9	0.25	125.5	0.8	1.5	0.2113		10/5/2,4		0.42	
	Center 1, FFS	Air	28.0	131	84.7	84.7	84.7	100.0%	72.2	0.55	241.9	1.8	7200	0.2068	148.4	50 lbs/min		0.82	
Threaded	Thd 1, FFS	Air	35.5	159	362.0	362.0	362.0	100.0%	99.8	0.63	245.5	1.5	4900			150 lbs/min	342.3	1.13	
	Thd 2, IHE	Air	36.0	162	284.6	359.0	352.6	97.5%	97.3	0.60	239.6	1.5	2.2			10/5/2,4	333.7	1.10	
	Thd 3, EHE	3.5% NaCl @ -1.106V	36.0	162	284.6	312.7	254.1	70.0%	69.9	0.43	171.9	1.1	2.2			10/5/2,4	239.7	0.79	Did not crack in Holiday.
	Thd 4, EHE	3.5% NaCl @ -1.106V	37.0	167	320.0	348.6	254.2	70.1%	70.0	0.42	172.0	1.0	2.4			10/5/2,4	240.1	0.79	No Holiday
	Thd 7, EHE	3.5% NaCl @ -1.106V	35.0	157	285.0	299.5	268.8	72.6%	72.5	0.46	177.6	1.1	1.1			10/5/1,8	248.6	0.82	Same strain rate as SN6 Did not crack in Holiday.

H.6 Fatigue Pre-cracked Specimen Test Results

H.6.1 OD 1, FFS:

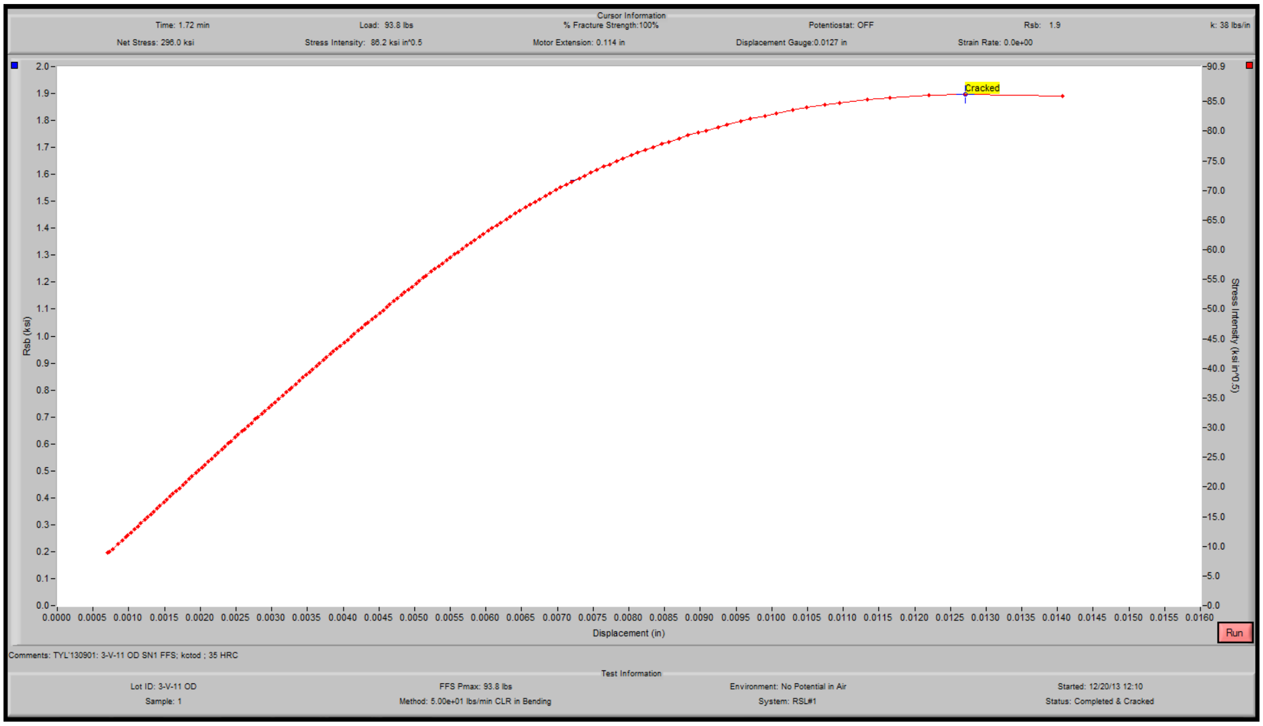


Figure H.6-1: Rod 3-V-11 OD 1, Graphical FFS Results

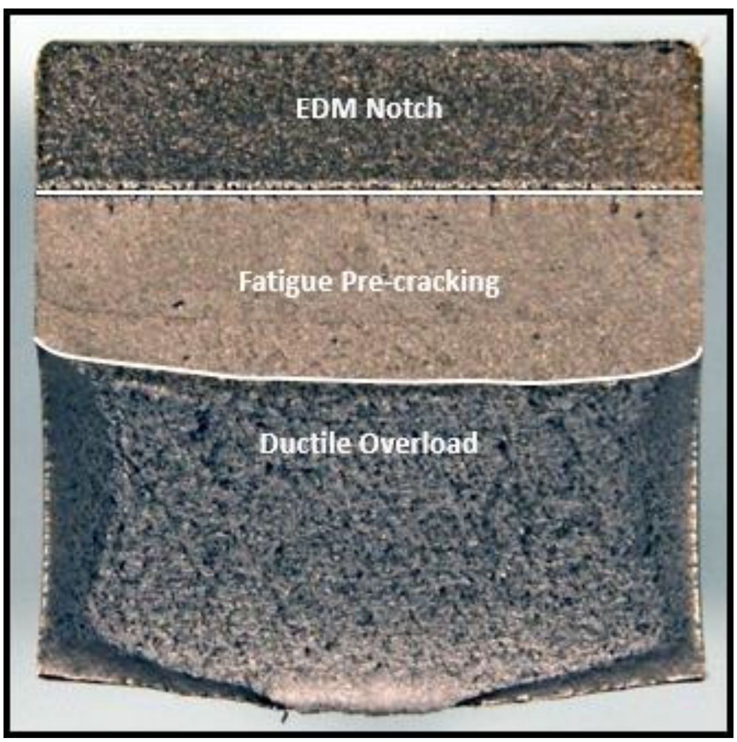


Figure H.6-2: Fracture Face of Rod 3-V-11 OD 1, FFS

H.6.2 OD 2, IHE:

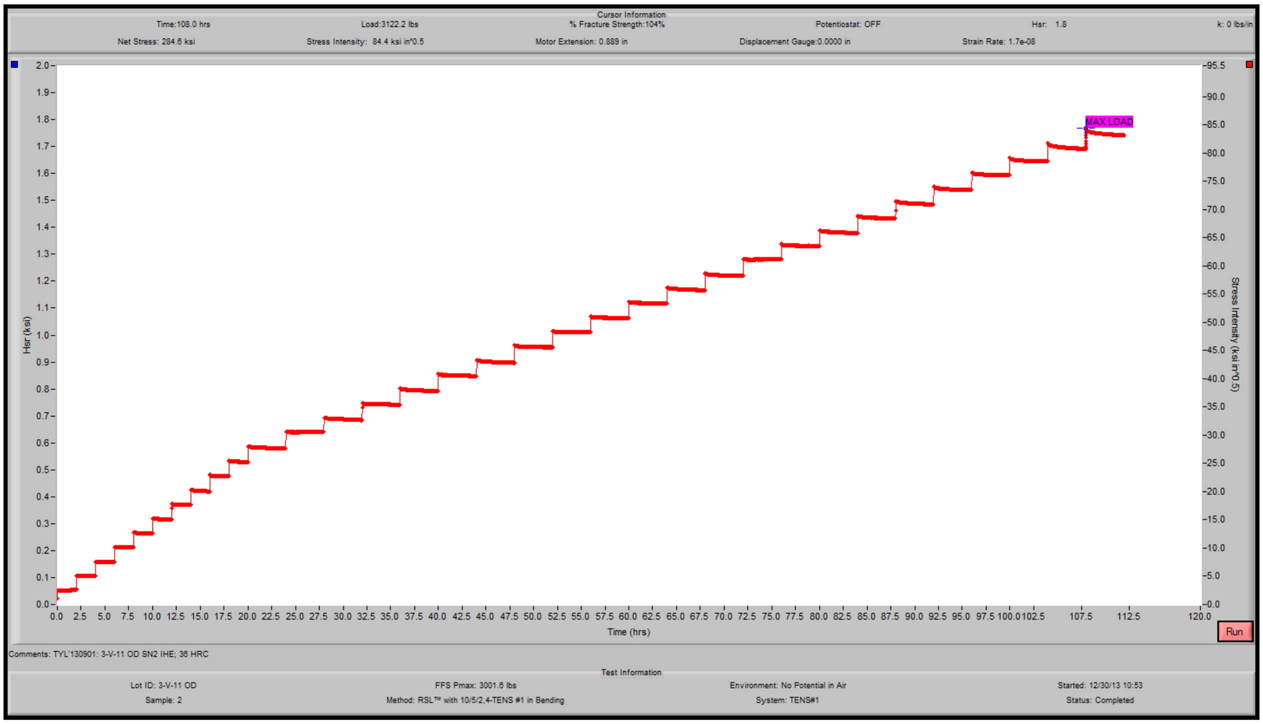


Figure H.6-3: Rod 3-V-11 OD 2, Graphical IHE Results

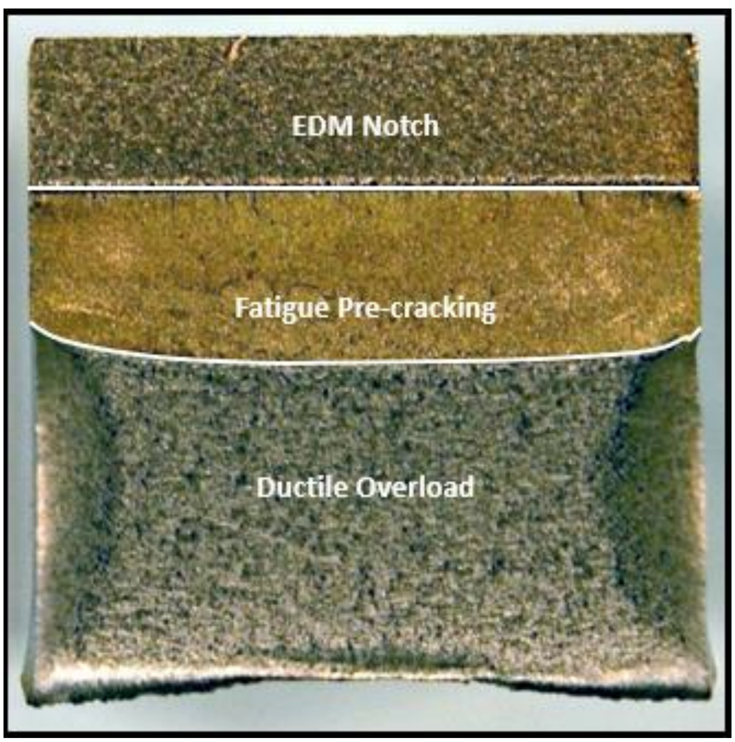


Figure H.6-4: Fracture Face of Rod 3-V-11 OD 2, IHE

H.6.3 OD 5, EHE:

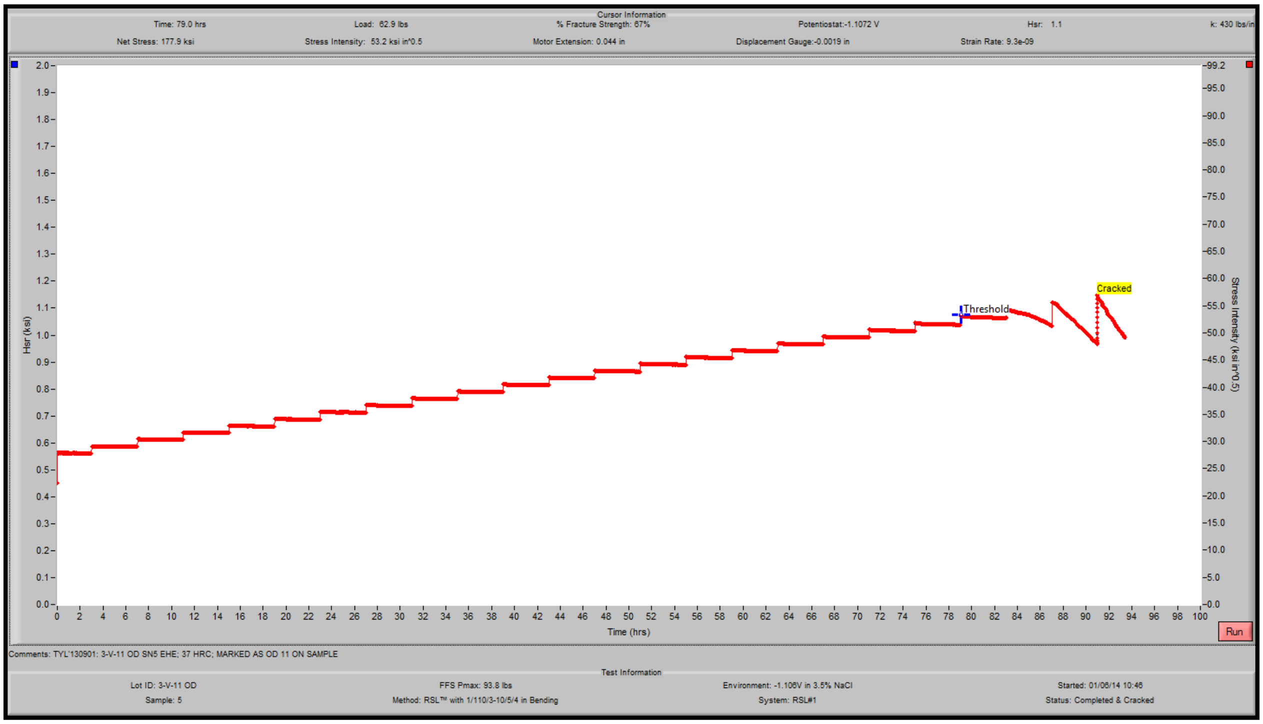


Figure H.6-5: Rod 3-V-11 OD 5, Graphical EHE Results

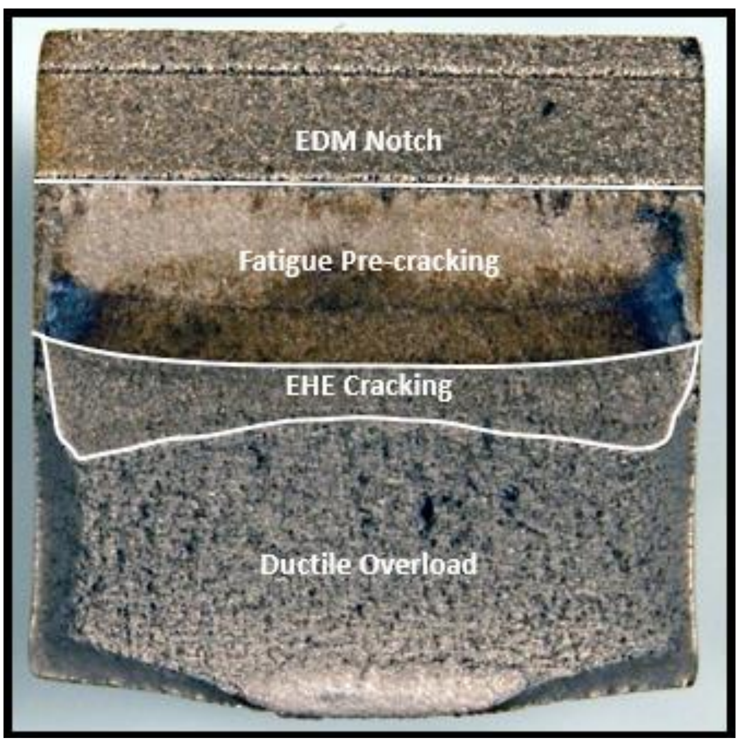


Figure H.6-6: Fracture Face of Rod 3-V-11 OD 5, EHE

H.6.4 OD 6, EHE:

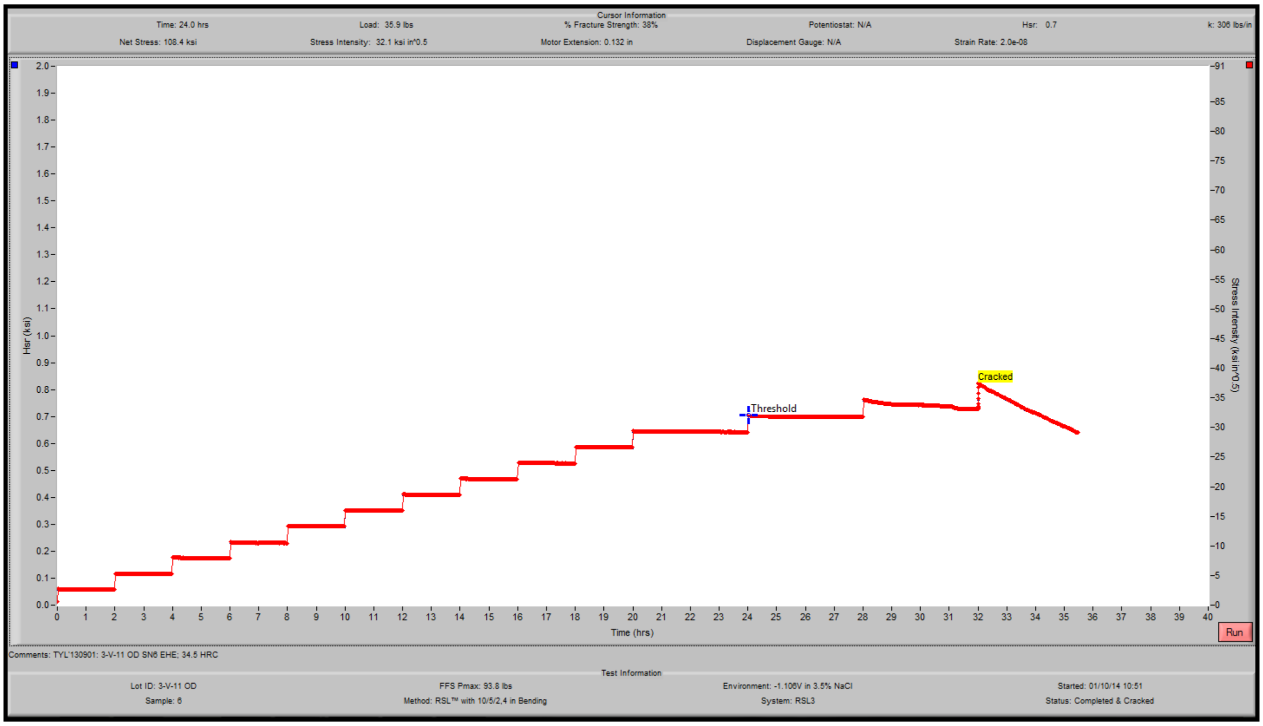


Figure H.6-7: Rod 3-V-11 OD 6, Graphical EHE Results

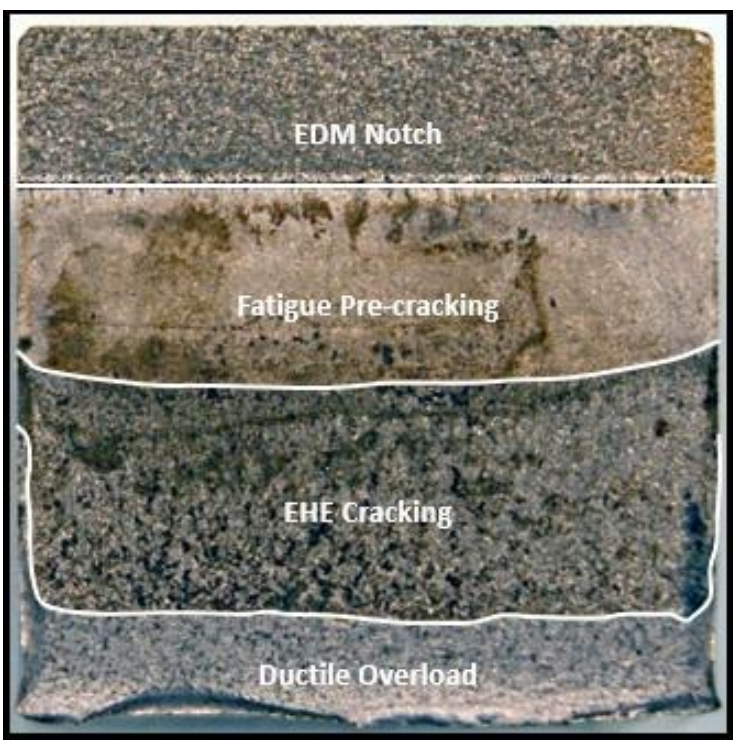


Figure H.6-8: Fracture Face of Rod 3-V-11 OD 6, EHE

H.6.5 OD 7, EHE:

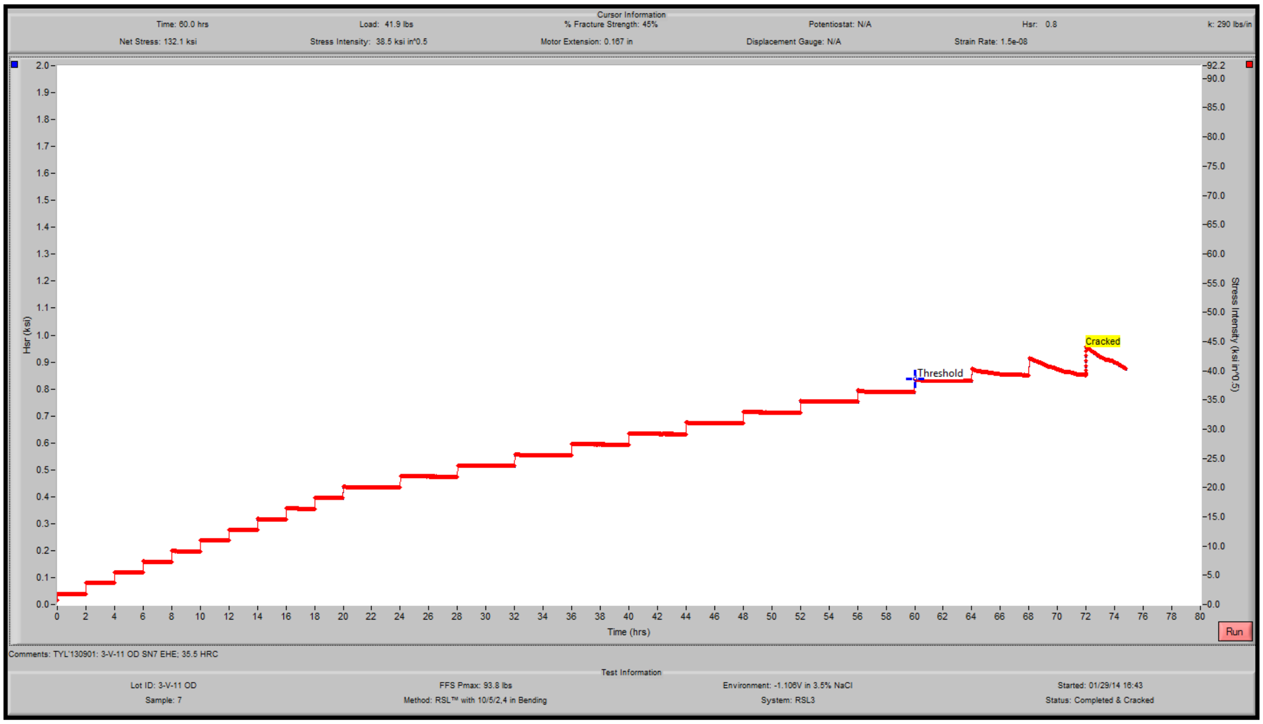


Figure H.6-9: Rod 3-V-11 OD 7, Graphical EHE Results

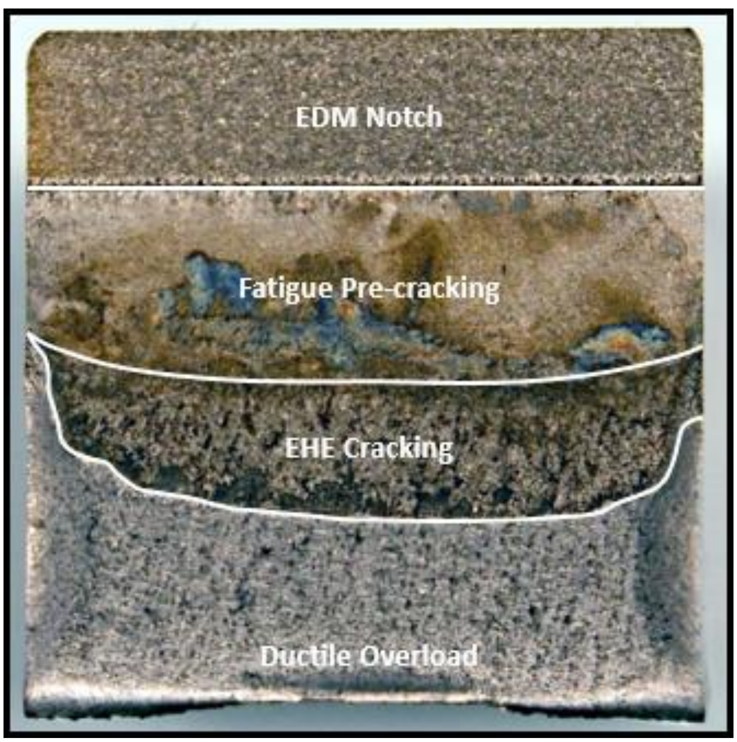


Figure H.6-10: Fracture Face of Rod 3-V-11 OD 7, EHE

H.6.6 OD 8, EHE:

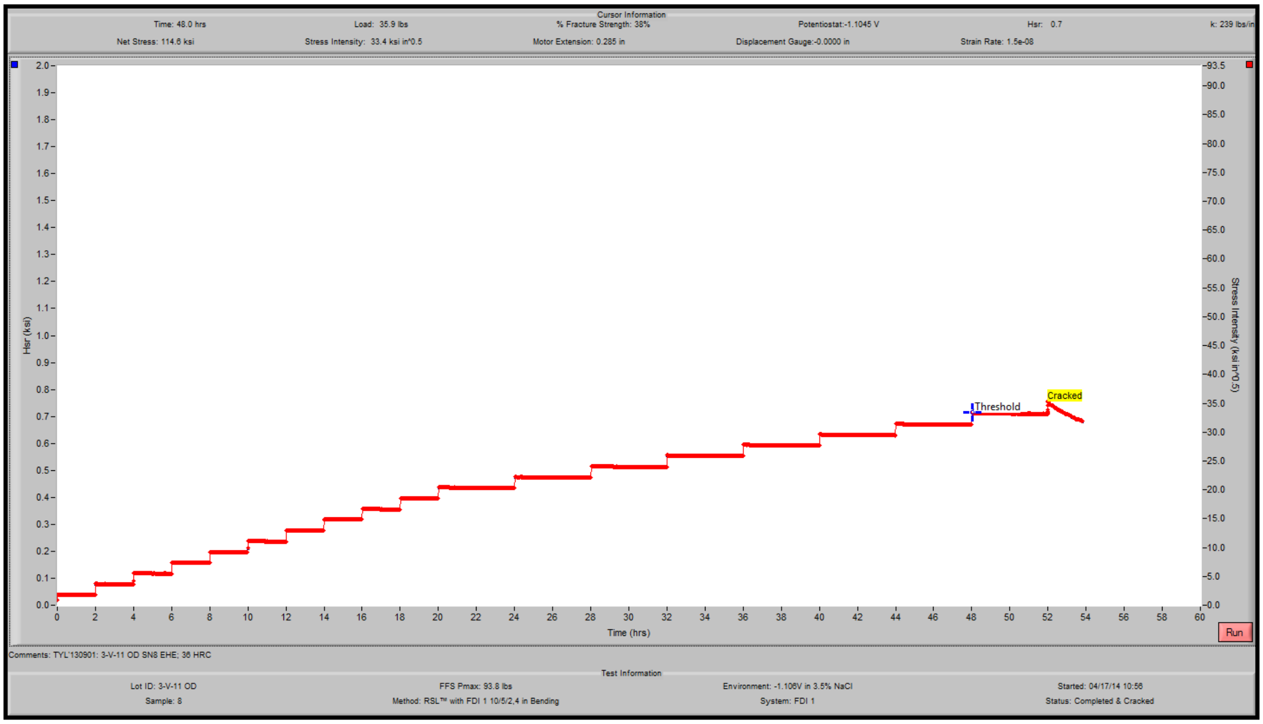


Figure H.6-11: Rod 3-V-11 OD 8, Graphical EHE Results

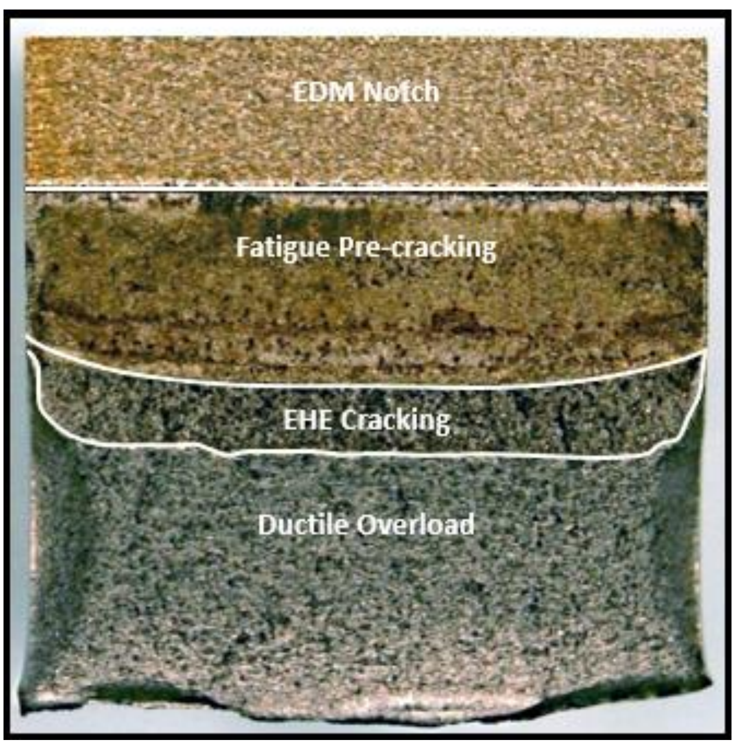


Figure H.6-12: Fracture Face of Rod 3-V-11 OD 8, EHE

H.6.7 MR 1, FFS:

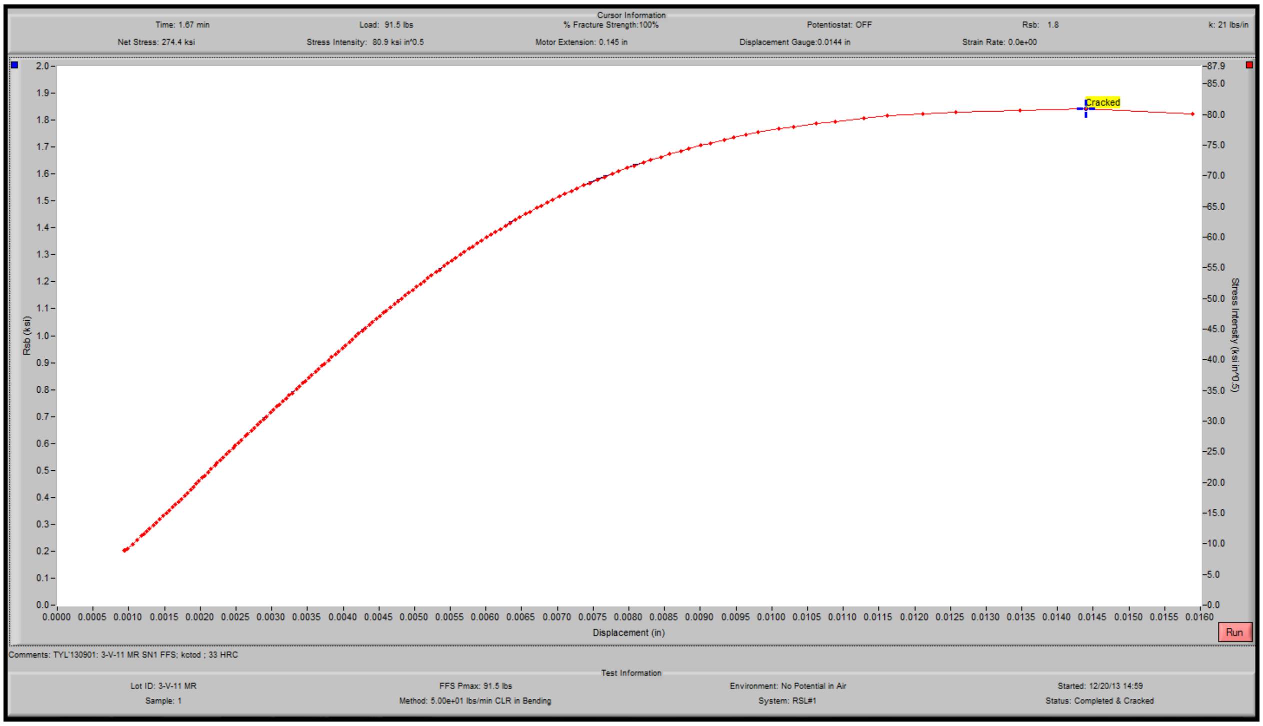


Figure H.6-13: Rod 3-V-11 MR 1, Graphical FFS Results

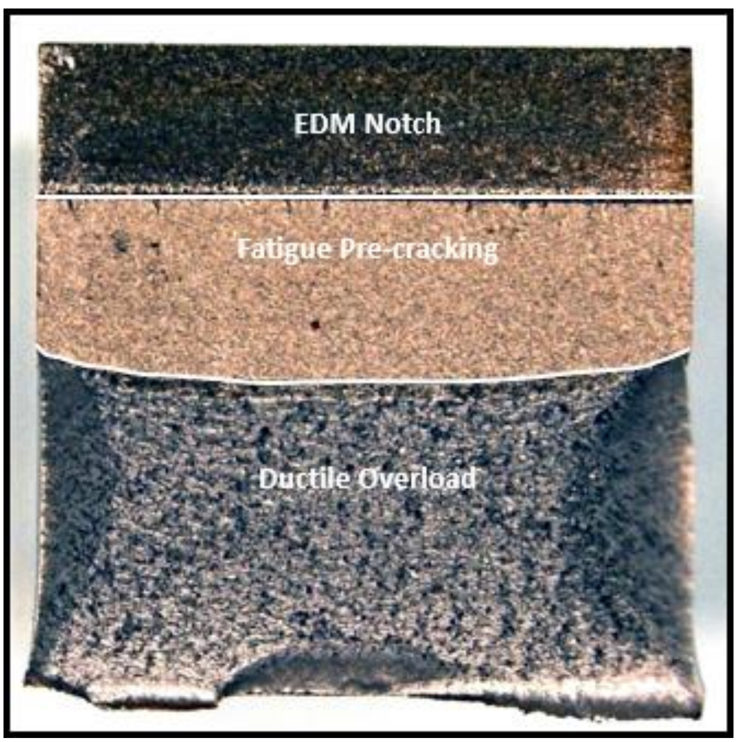


Figure H.6-14: Fracture Face of Rod 3-V-11 MR 1, FFS

H.6.8 MR 2, IHE:

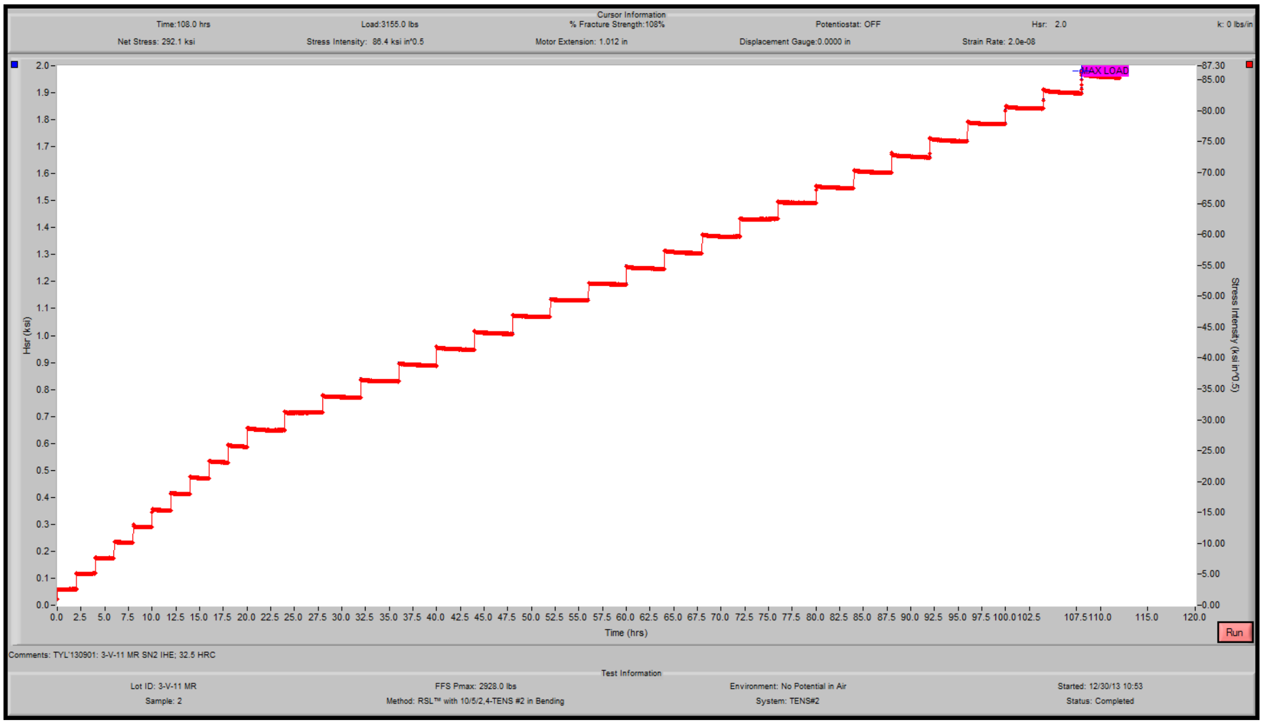


Figure H.6-15: Rod 3-V-11 MR 2, Graphical IHE Results

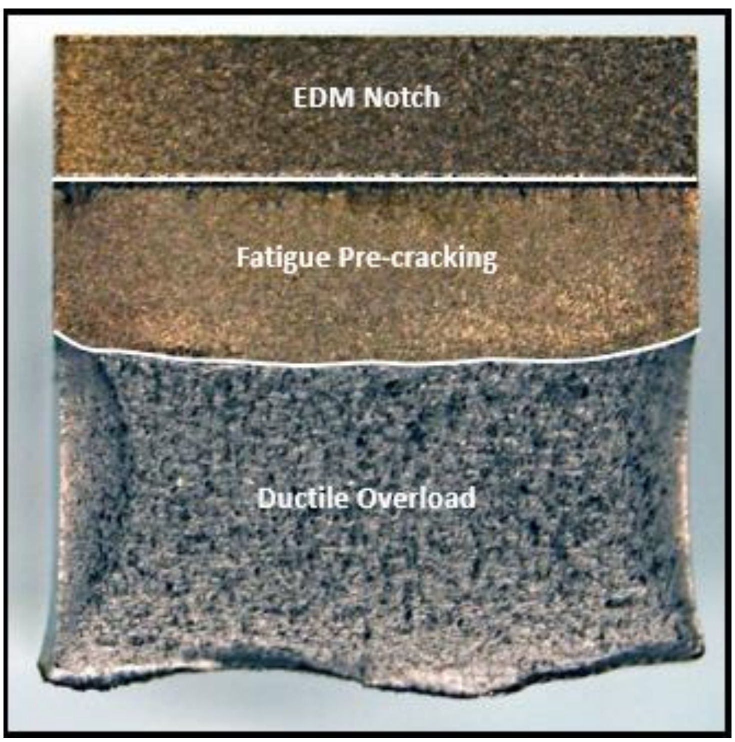


Figure H.6-16: Fracture Face of Rod 3-V-11 MR 2, IHE

H.6.9 MR 3, EHE:

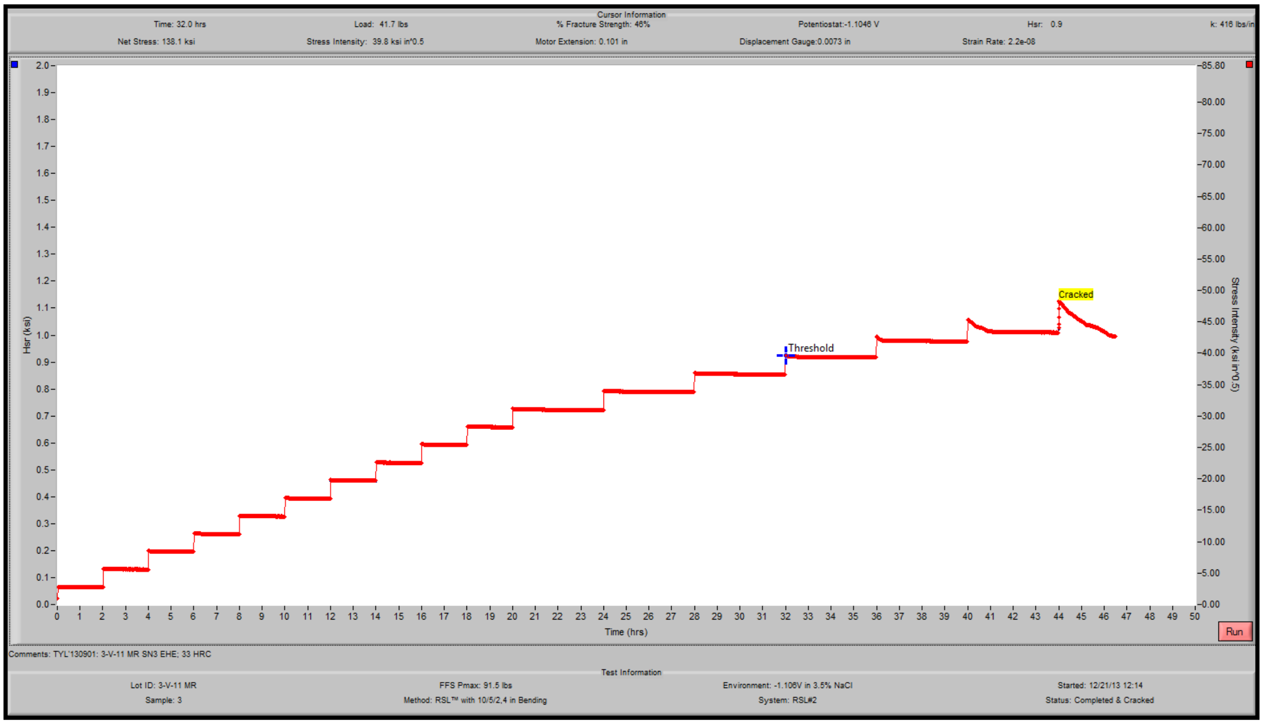


Figure H.6-17: Rod 3-V-11 MR 3, Graphical EHE Results

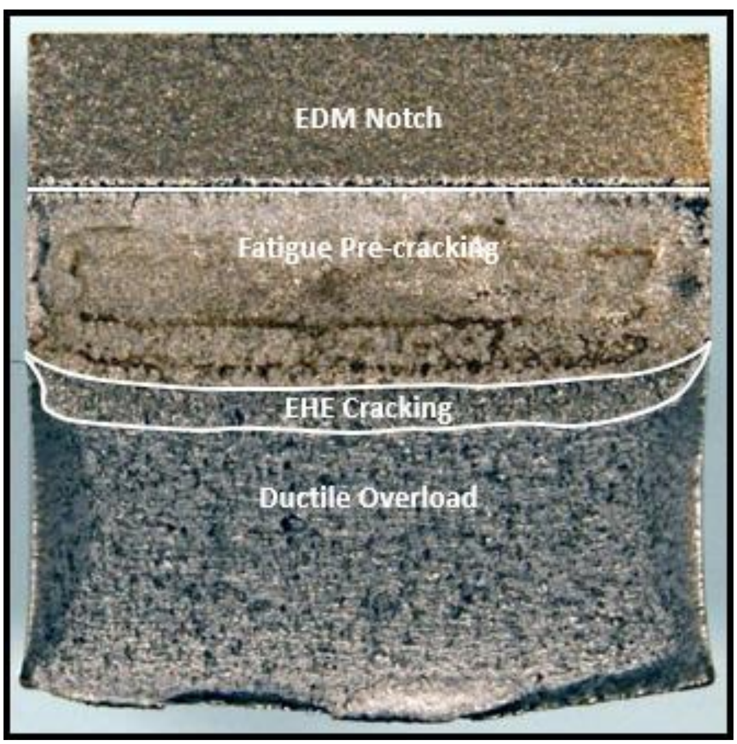
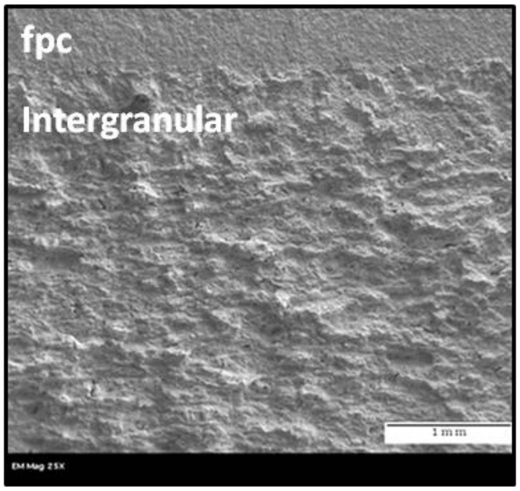
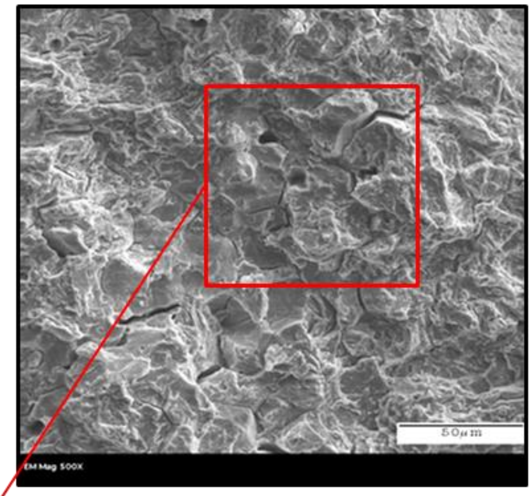


Figure H.6-18: Fracture Face of Rod 3-V-11 MR 3, EHE

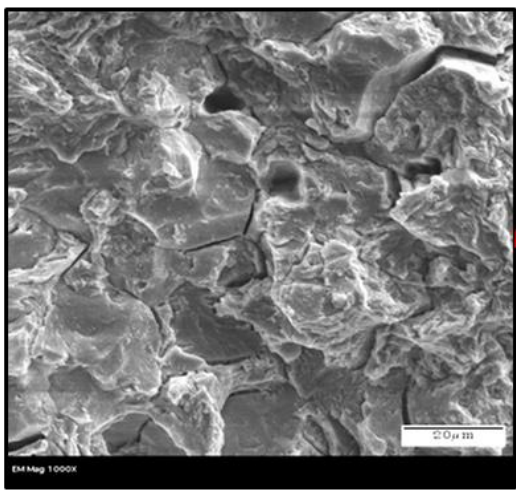
Figure H.6-19: SEM of Rod 3-V-11 MR 3, EHE



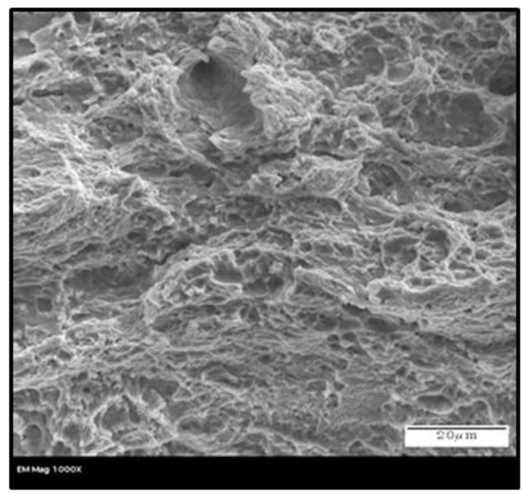
Macro 25X



Intergranular 500X



Intergranular 1000X



Overload 1000X

H.6.10 MR 4, EHE:

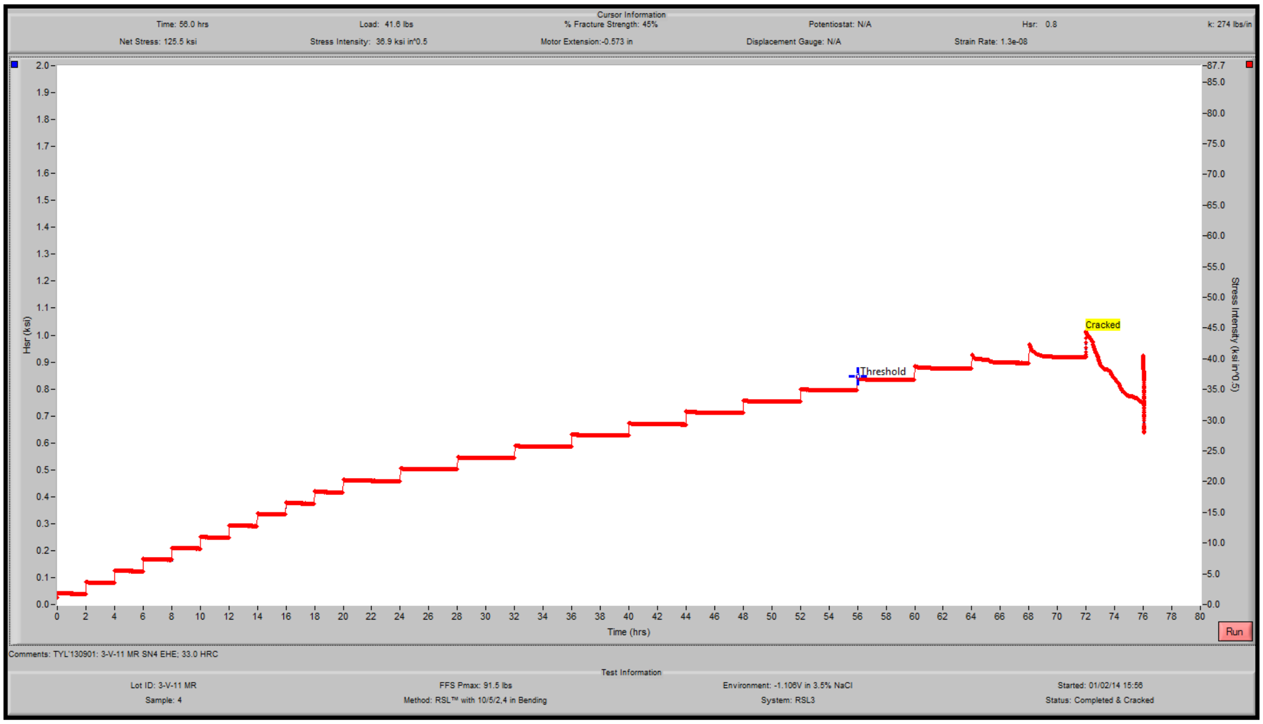


Figure H.6-20: Rod 3-V-11 MR 4, Graphical EHE Results

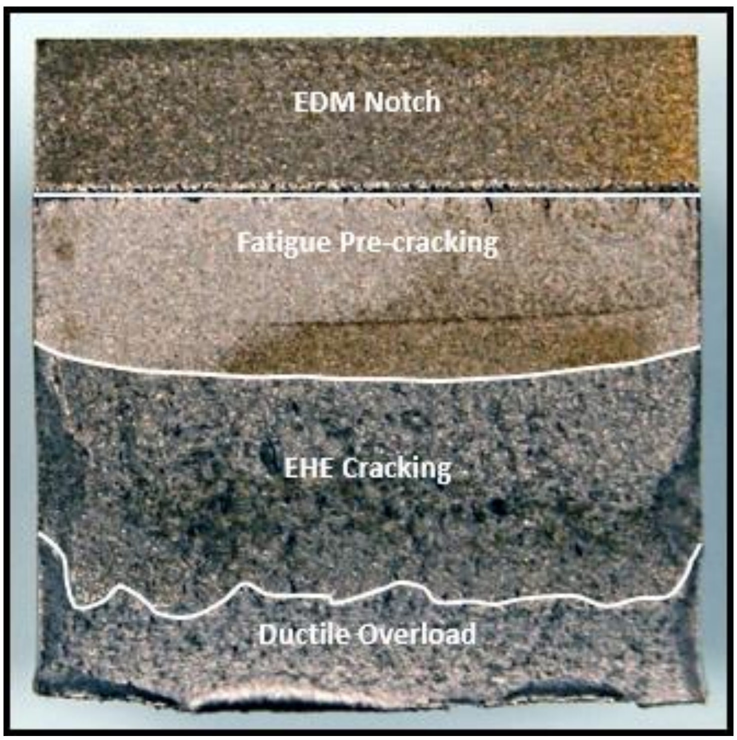


Figure H.6-21: Fracture Face of Rod 3-V-11 MR 4, EHE

H.6.11 Center 1, FFS:

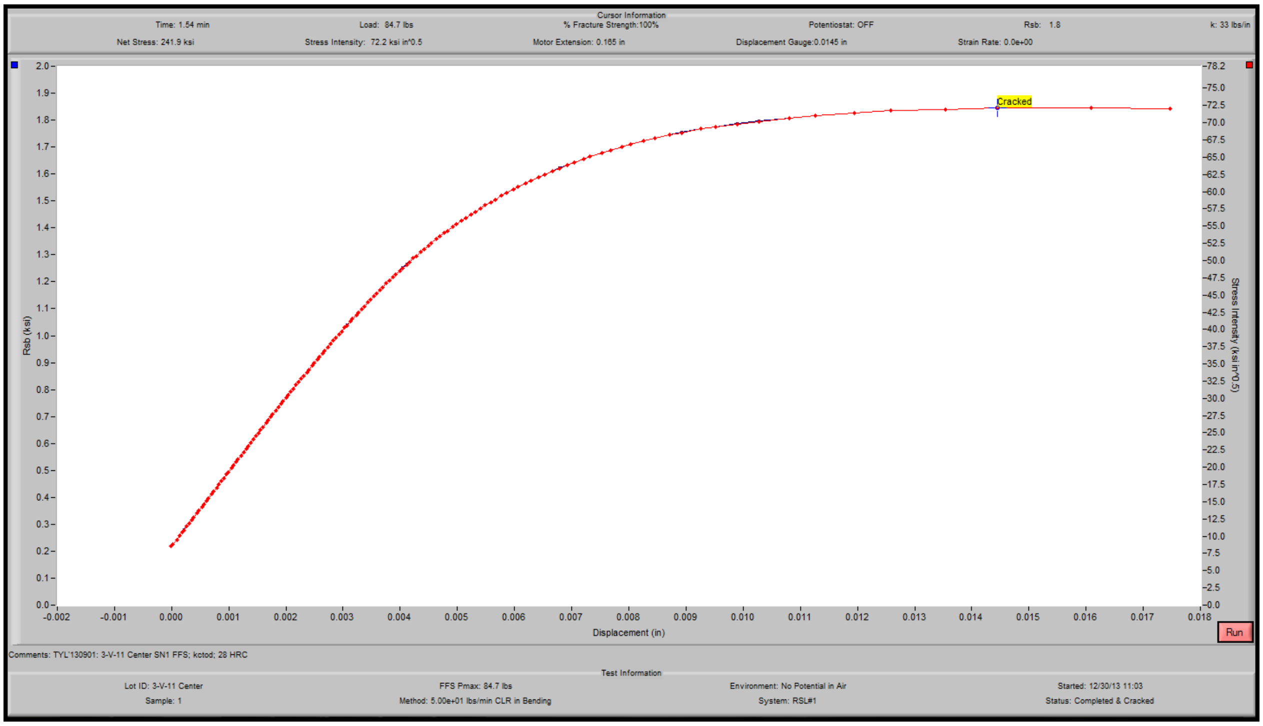


Figure H.6-22: Rod 3-V-11 Center 1, Graphical FFS Results

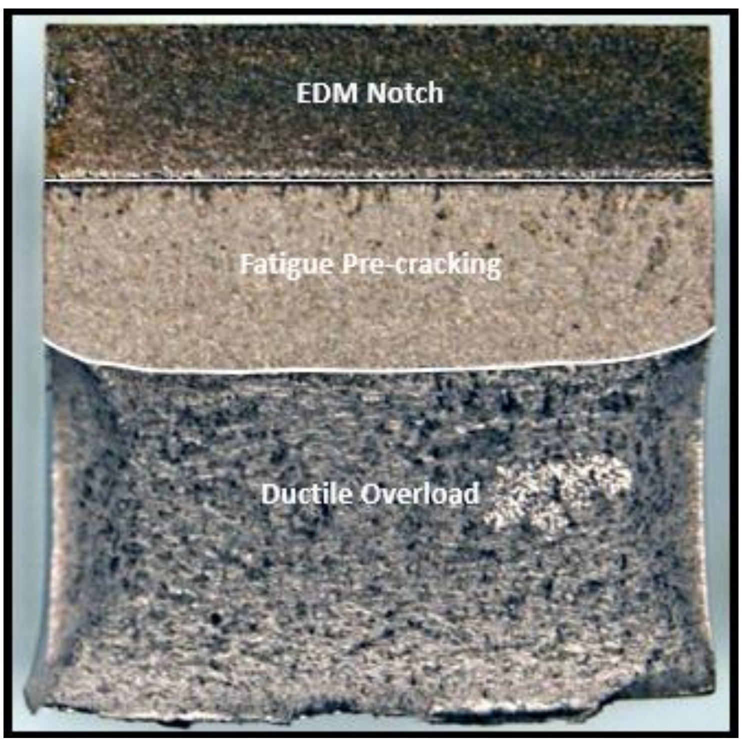


Figure H.6-23: Fracture Face of Rod 3-V-11 Center 1, FFS

H.7 Threaded Specimen Test Results

H.7.1 Thd 1, FFS:

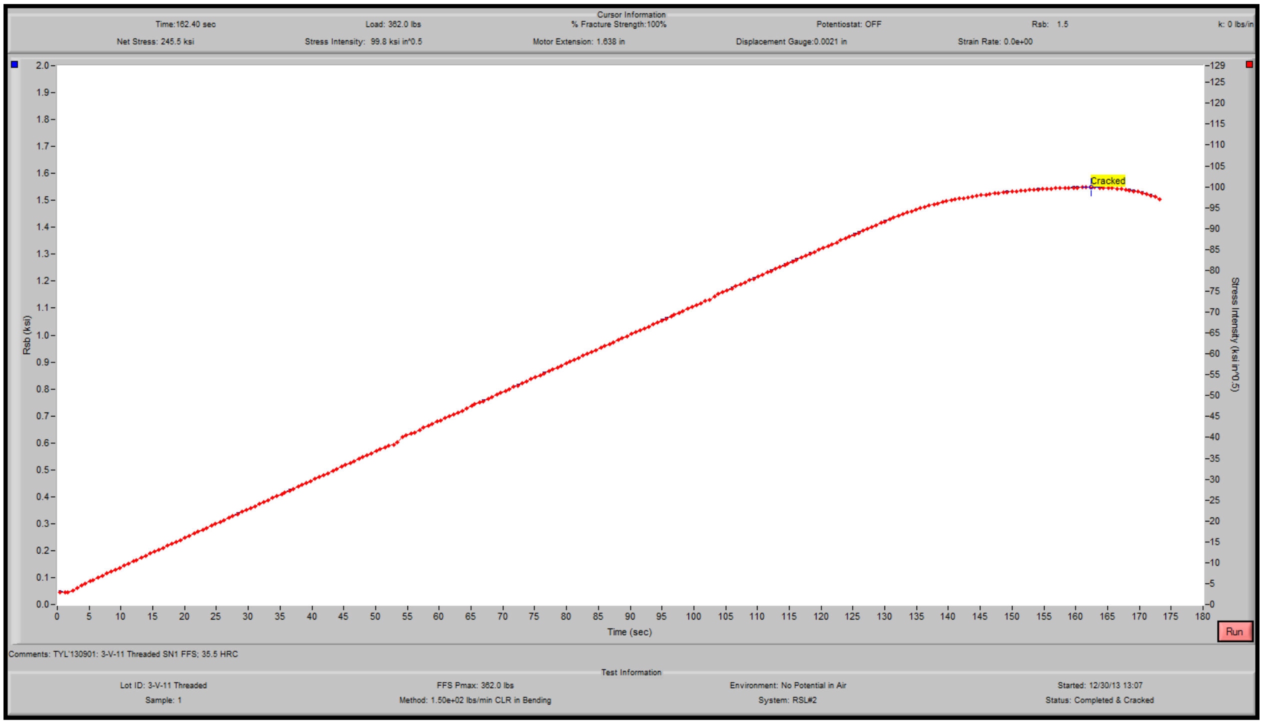


Figure H.7-1: Rod 3-V-11 Thd 1, Graphical FFS Results

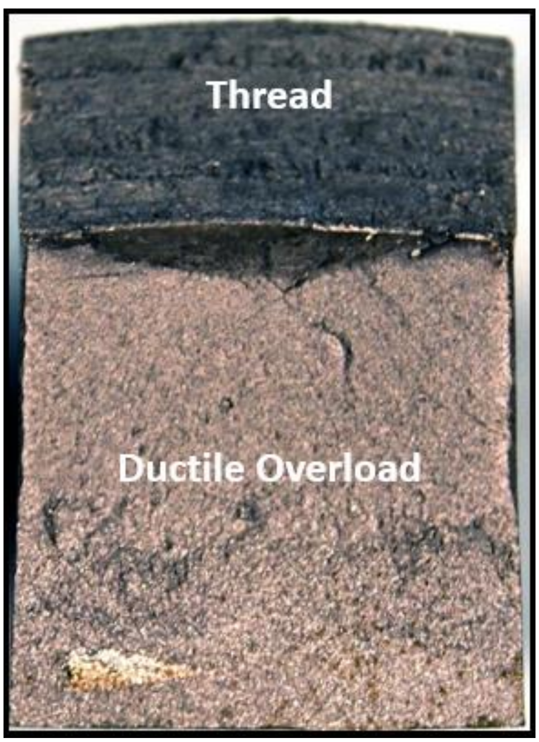


Figure H.7-2: Rod 3-V-11 Thd 1 FFS Fracture Face

H.7.2 Thd 2, IHE:

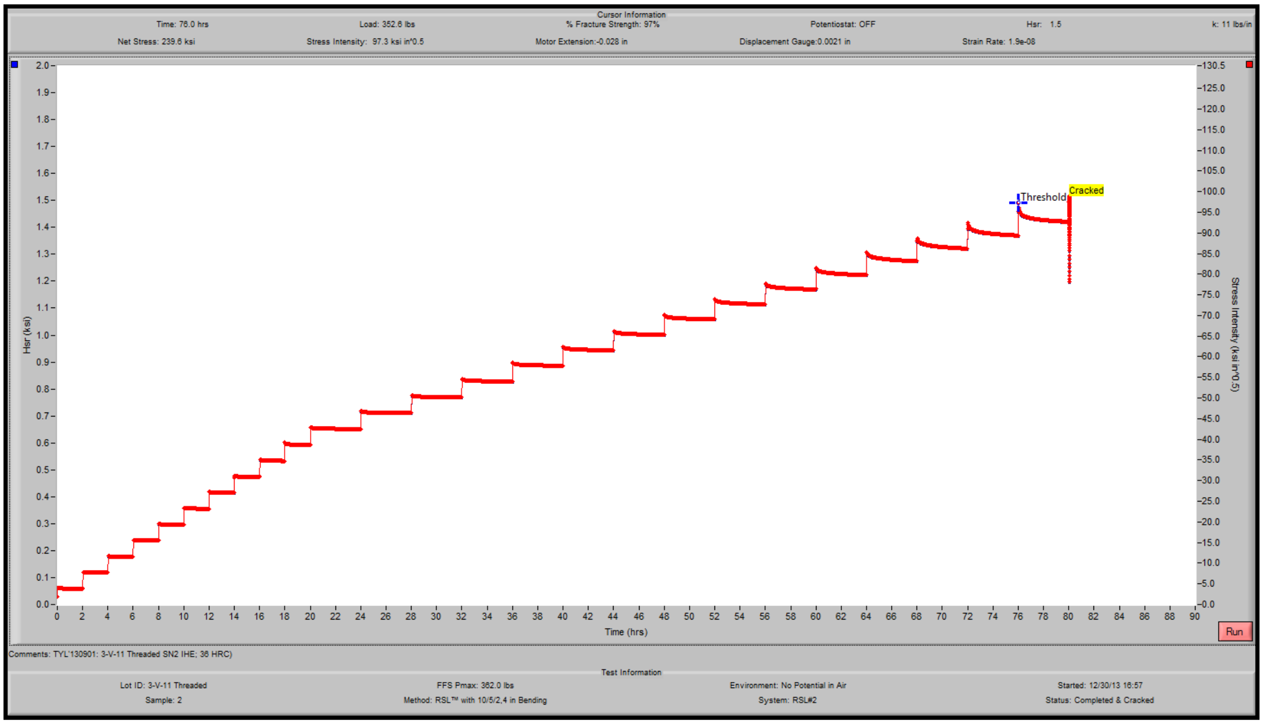


Figure H.7-3: Rod 3-V-11 Thd 2, Graphical IHE Results

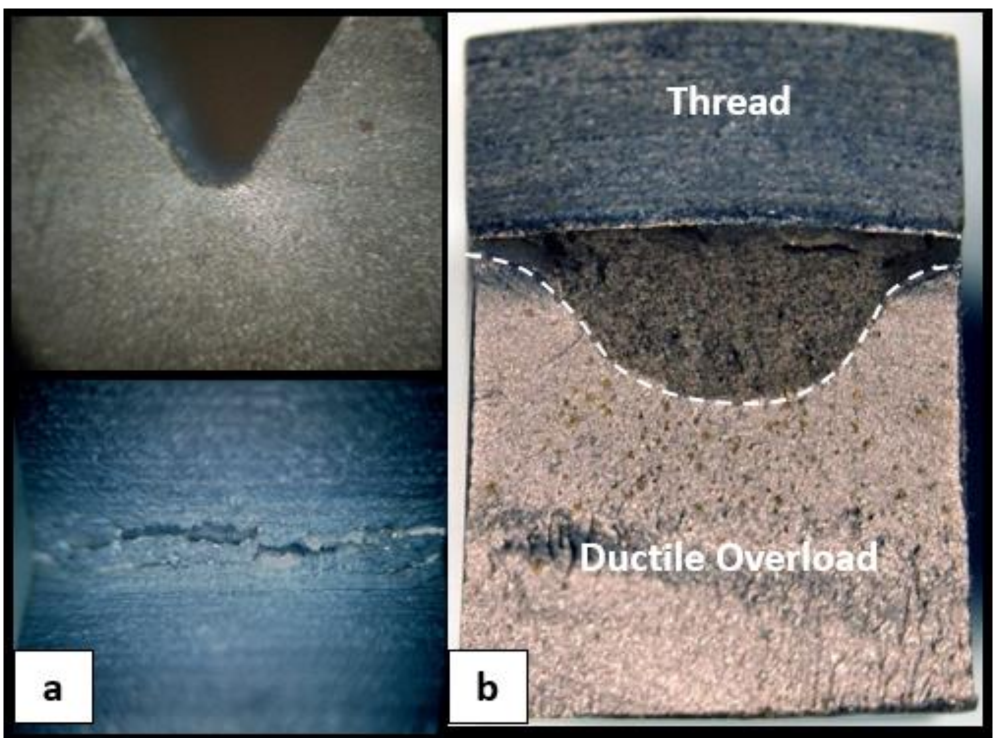


Figure H.7-4: Rod 3-V-11 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

H.7.3 Thd 3, EHE:

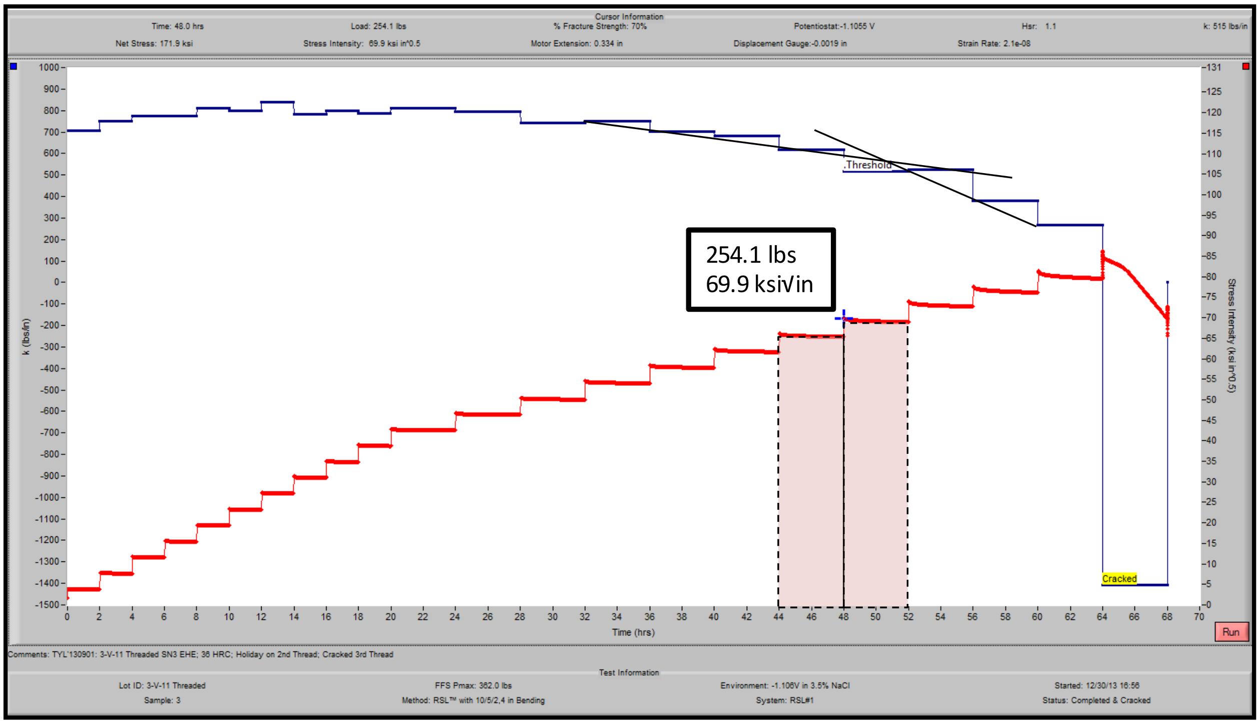


Figure H.7-5: Rod 3-V-11 Thd 3 Graphical EHE Results

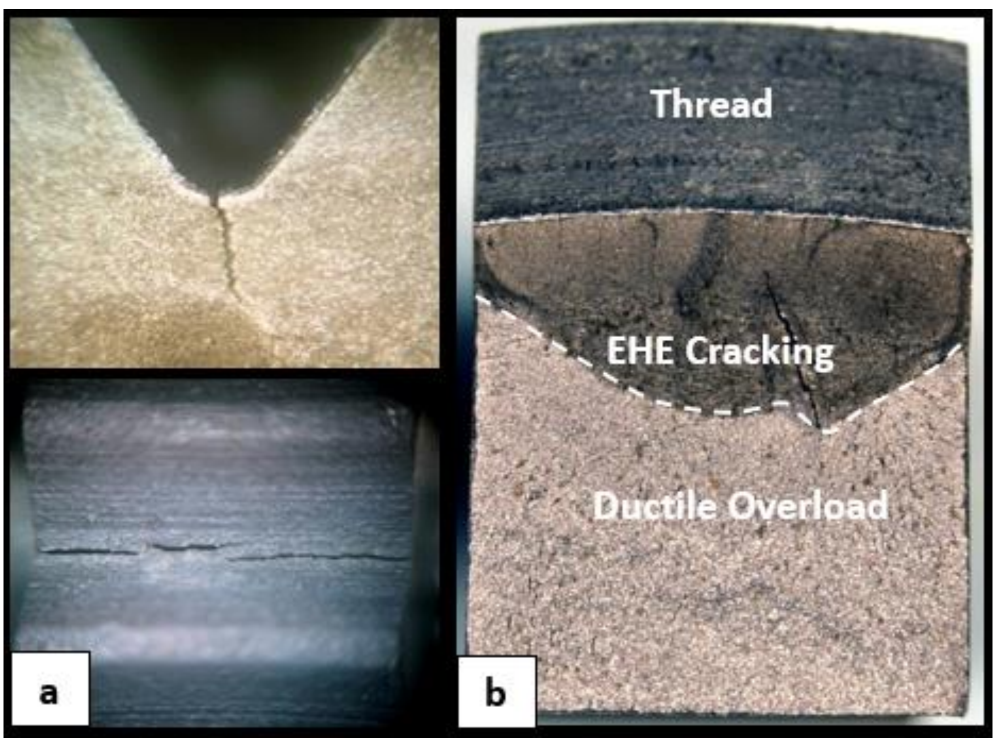
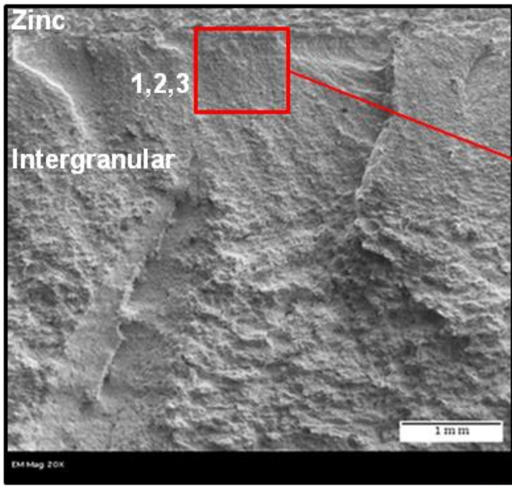
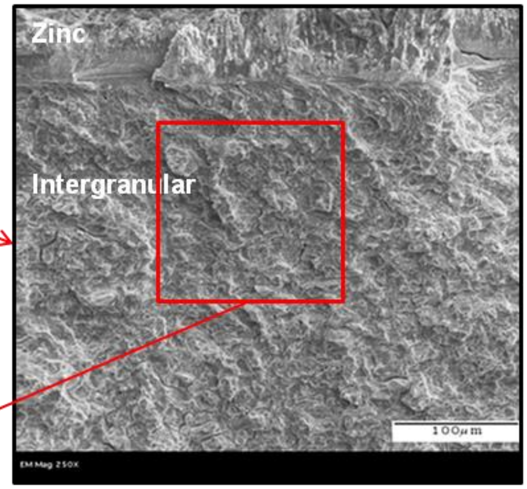


Figure H.7-6: Rod 3-V-11 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

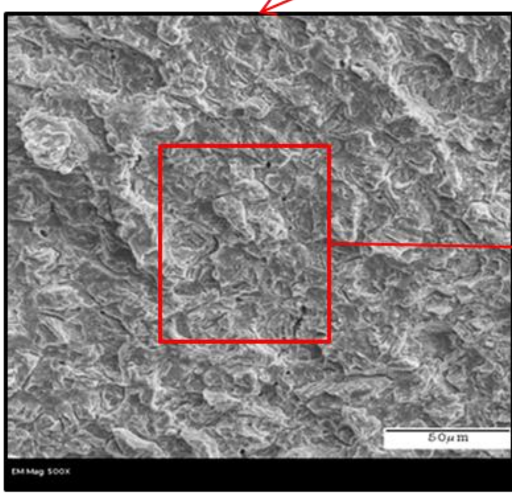
Figure H.7-7: SEM of Rod 3-V-11 Thd 3, EHE



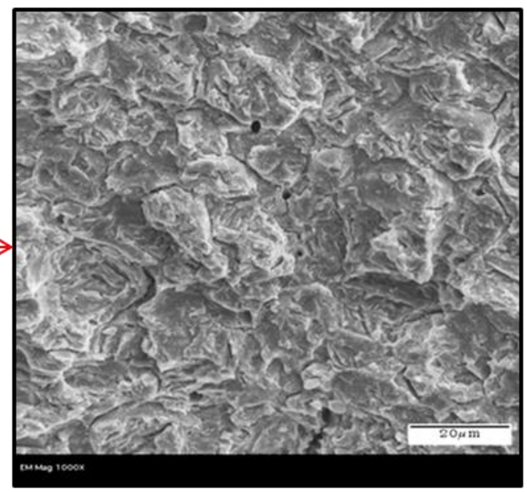
Thread Root 20X



1) Mixed: Ductile Overload, Intergranular 250X



2) Mixed: Ductile Overload, Intergranular 500X



3) Mixed: Ductile Overload, Intergranular 1000X

H.7.4 Thd 4, EHE:

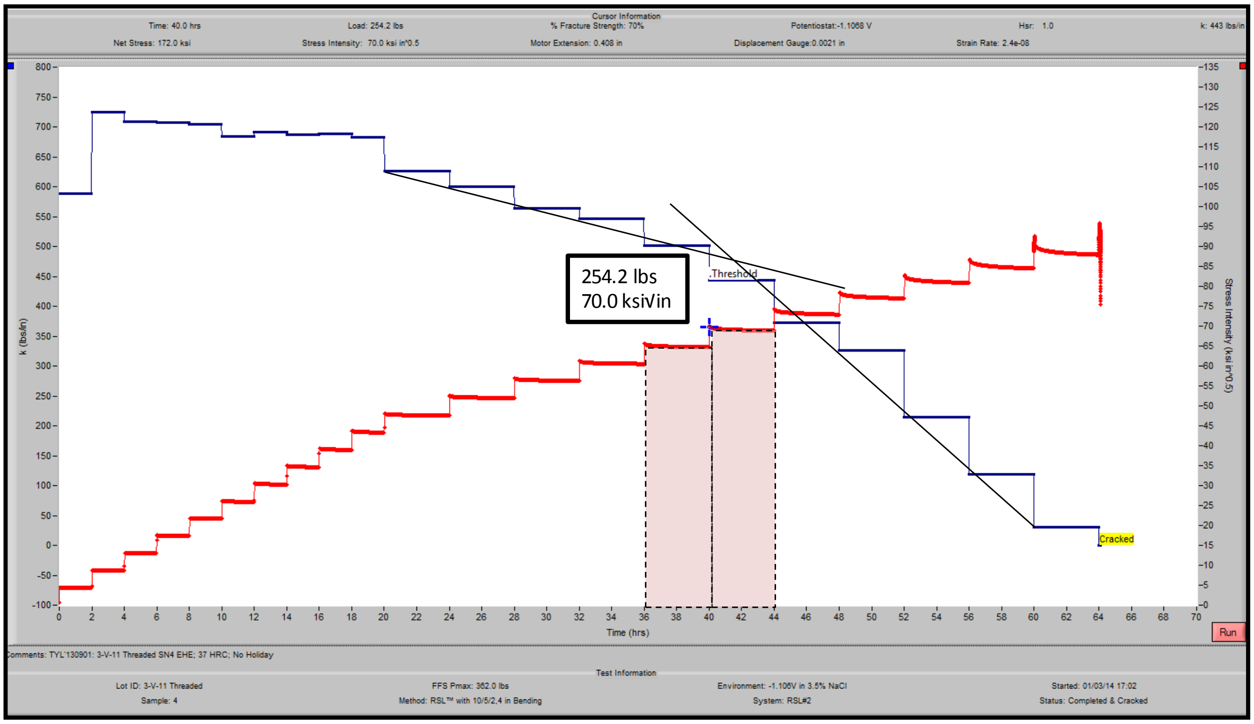


Figure H.7-8: Rod 3-V-11 Thd 4 Graphical EHE Results

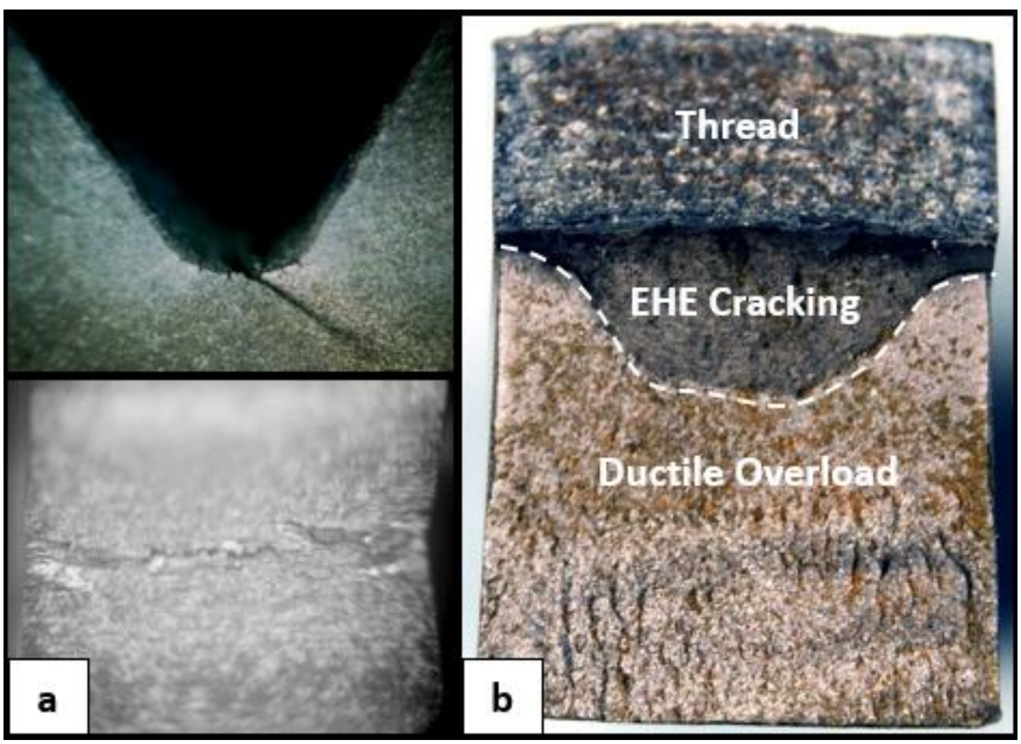
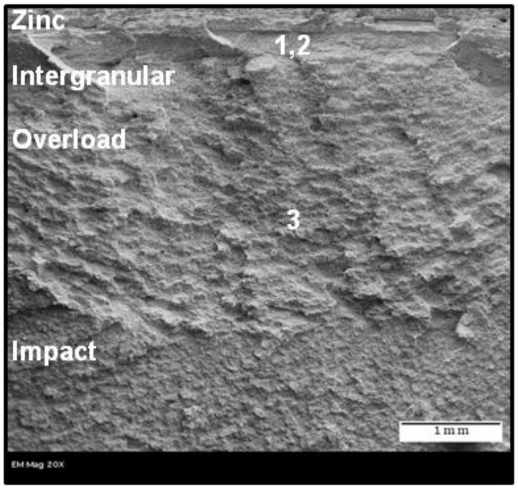
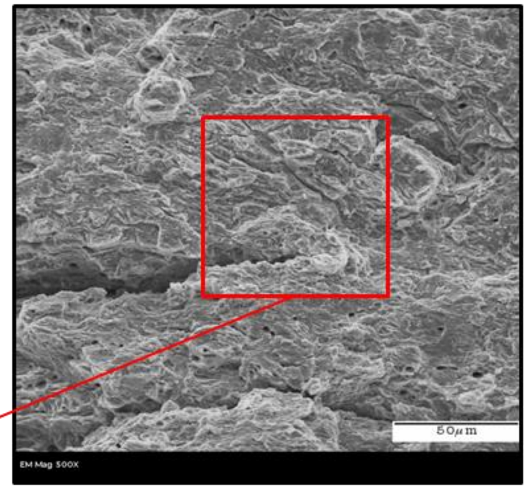


Figure H.7-9: Rod 3-V-11 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

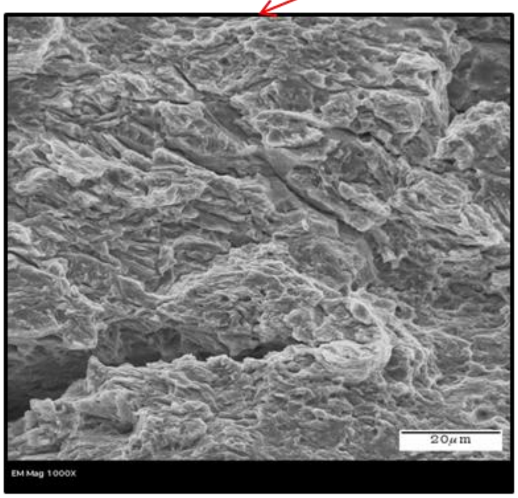
Figure H.7-10: SEM of Rod 3-V-11 Thd 4, EHE



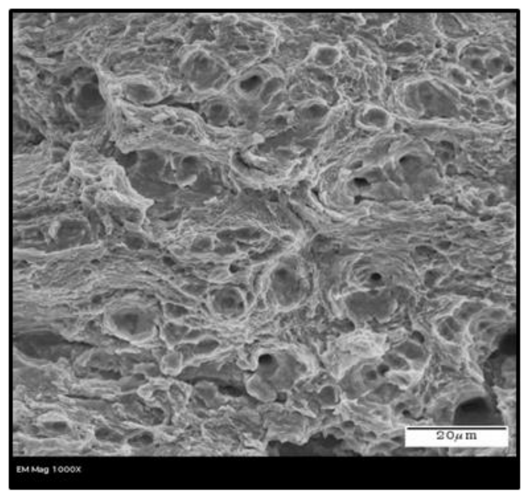
Thread Root 20X



1) Mixed: Ductile Overload, Intergranular 500X



2) Mixed: Ductile Overload, Intergranular 1000X



3) Ductile Overload 1000X

H.7.5 Thd 7, EHE:

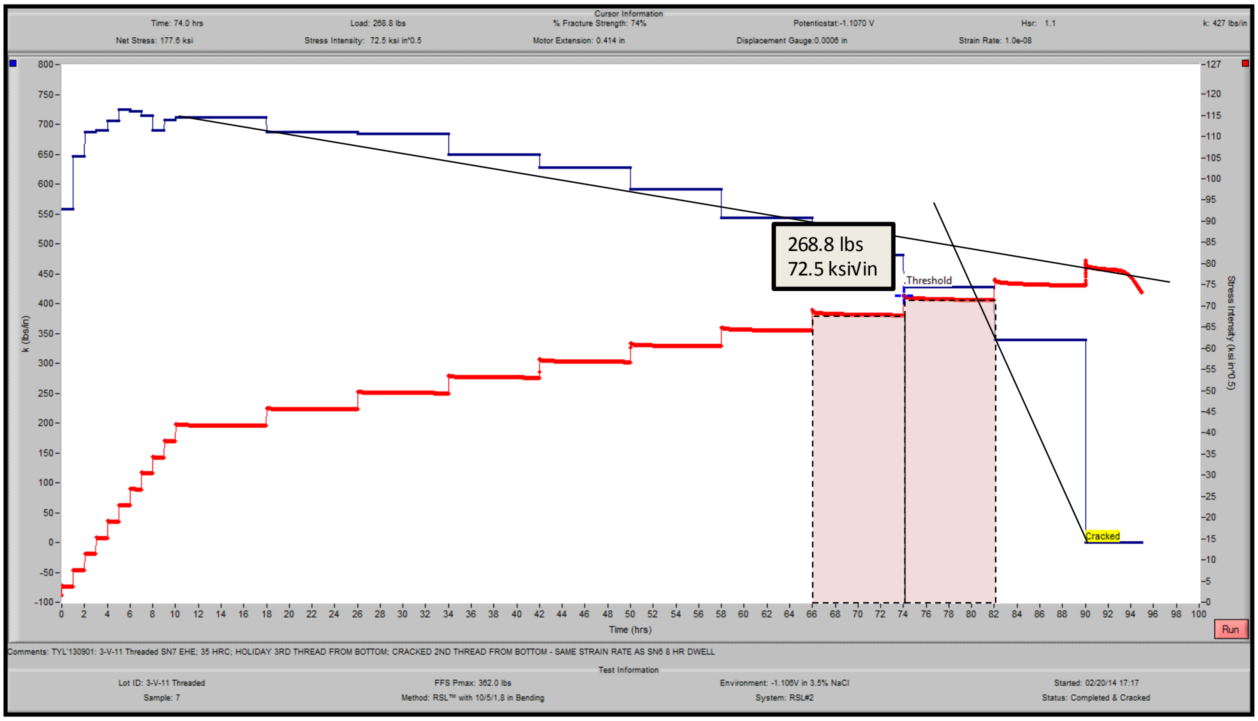


Figure H.7-11: Rod 3-V-11 Thd 7 Graphical EHE Results

Figure H.7-12: Rod 3-V-11 Thd 7 EHE Fracture Face

Appendix I: Rod 3-V-12

I.1 Description of Sample

Rod 3-V-12 was a spare Shear Key Anchor Bolt at the top of Pier E2 (S1/S2) and is from a similar heat of material as was tested in Test Rigs 1, 2, 3 and 4 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. The bolts are 3 inches in diameter with machined threads. The segment from one of four spares from this rod provided to LRA is shown in Figure I.1-1.

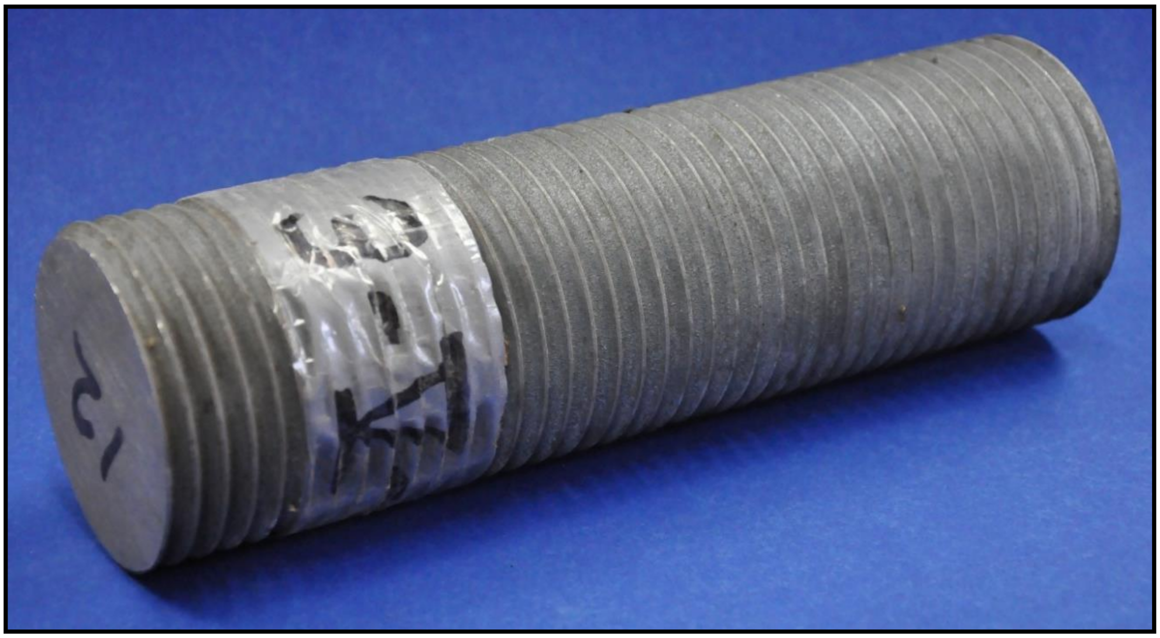


Figure I.1-1: Pier E2 Shear Key Anchor Bolt (Top), Rod 3-V-12

I.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 3-V-12 can be seen in Figure I.2-1 where the black portion of the Shadowgraph represents the rod material. As can be seen from Figure I.2-1, these cut thread roots show non-uniformity and exhibit a sharp radius.

Figure I.2-1: Thread Comparison of Three Threads of Rod 3-V-12

I.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 3-V-12 and can be seen versus time in **Figure I**.3-1. The final OCP recorded for Rod 3-V-12 was Vsce=-1.003 V.

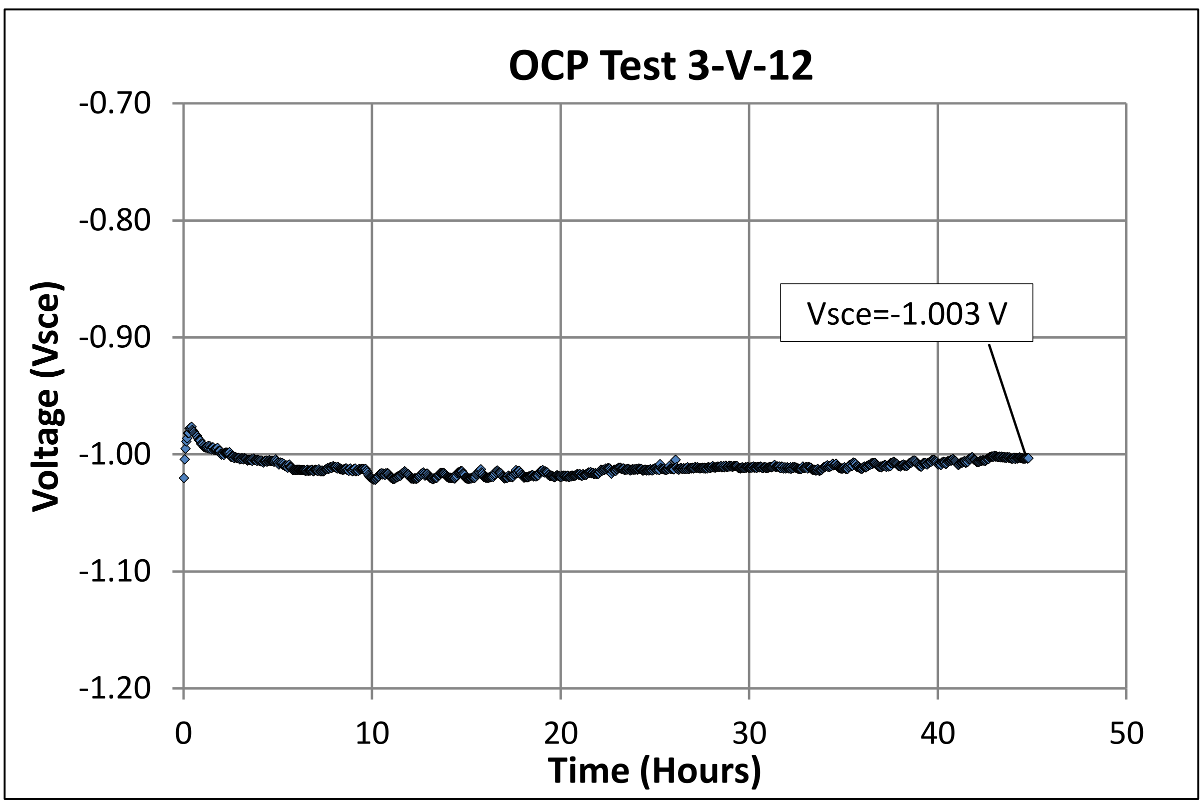


Figure I.3-1: Open Circuit Potential for Rod 3-V-12

I.4 Hardness

The hardness data and profile for sample 3-V-12 are shown in Table I.4-1 and Figure I.4-1.

Table I.4-1: Hardness Data of Rod 3-V-12 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 2, FFS	31.0	31.0
MR 2, IHE	33.0	33.1
MR 3, EHE	33.0	
MR 4, EHE	32.5	
MR 10, FFS	34.0	
OD 2, IHE	35.5	35.6
OD 6, EHE	35.5	
OD 10, FFS	36.0	
Thd 2, IHE	35.0	
Thd 3, EHE	35.5	
Thd 4, EHE	35.5	
Thd 5, FFS	36.0	
Thd 6, EHE	36.0	

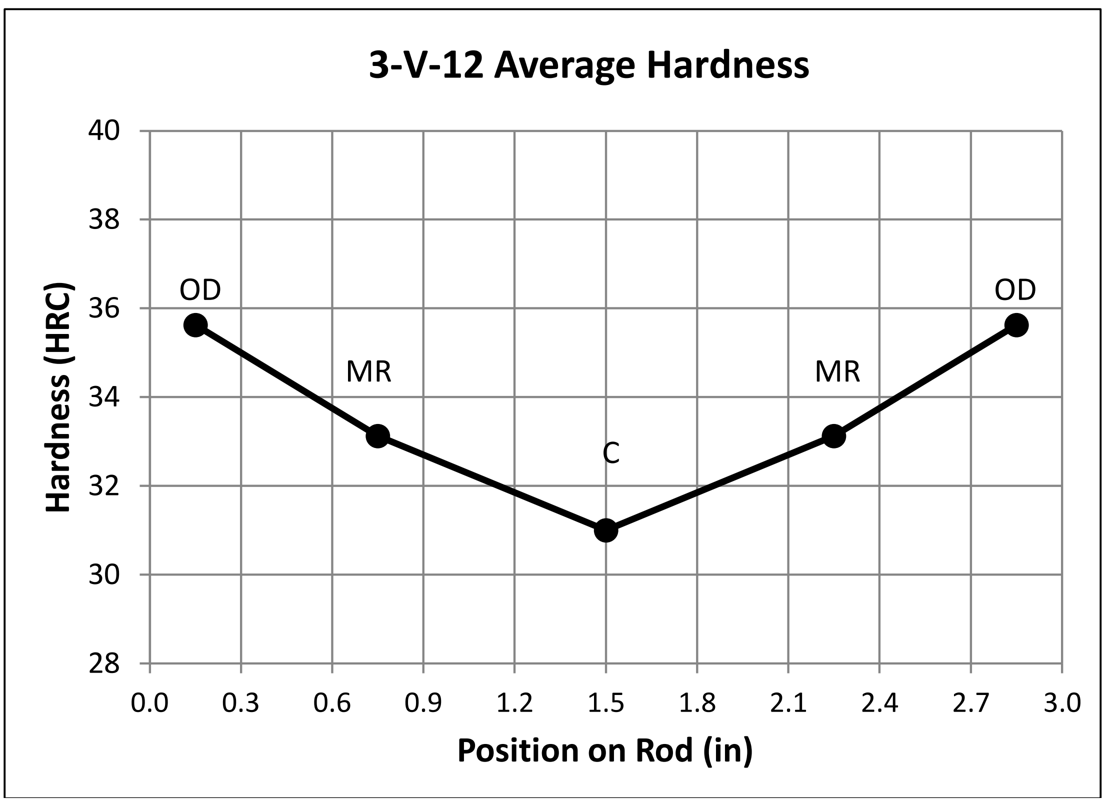


Figure I.4-1: Hardness Profile of Rod 3-V-12

I.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

I.5.1 Fatigue Pre-crack Results

Threaded Rod ID # 3-V-12						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top				
Rod#:	**3-V-12**					
Product Form:	**1e**	**Comments**: 2010 Machined Threads				
Rod OD:	**3"**	Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 10, FFS**	**36.0**	K_{max}	85.3		
			DTI_{th}	0.53		
			Fu	0.96		
			Strain Rate ($x10^{-8}$ in/in/sec)	7600		
	OD 2, IHE	**35.5**	$K_{threshold}$		88.7	
			DTI_{th}		0.56	
			Fu		1.00	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.3	
	OD 6, EHE	**35.5**	$K_{threshold}$			23.1
			DTI_{th}			0.14
			Fu			0.26
			Strain Rate ($x10^{-8}$ in/in/sec)			1.2
	MR 10, FFS	**34.0**	K_{max}	79.2		
			DTI_{th}	0.52		
			Fu	0.89		
			Strain Rate ($x10^{-8}$ in/in/sec)	8400		

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-12						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-12**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 2, IHE**	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		92.1 0.62 1.04 2.3	
	MR 3, EHE	**33.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			33.6 0.23 0.38 2.1
	MR 4, EHE	**32.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			35.8 0.24 0.40 1.6
	Center 2, FFS	**31.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	77.1 0.55 0.87 8200		

I.5.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 3-V-12						
LRA Job No.:	**TYL130901**	**Structural Component:** Shear Key Anchor Bolts-Top **Comments**: 2010 Machined Threads Same Heat as ID 2 Rods (Test Rigs #1 through #4 Test IV)				
Rod#:	**3-V-12**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 5, FFS**	**36.0**	Pmax* (lbs)	340.9		
			Fu	1.12		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	2800		
	Thd 2, IHE	**35.0**	$P_{threshold}$* (lbs)		328.6	
			Fu		1.08	
			Hsr		1.5	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.0	
	Thd 3, EHE	**35.5**	$P_{threshold}$* (lbs)			227.4
			Fu			0.75
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			2.1
	Thd 4, EHE	**35.5**	$P_{threshold}$* (lbs)			245.9
			Fu			0.81
			Hsr			1.1
			Strain Rate ($x10^{-8}$ in/in/sec)			1.9
	Thd 6, EHE	**36.0**	$P_{threshold}$* (lbs)			240.1
			Fu			0.79
			Hsr			1.1
			Strain Rate ($x10^{-8}$ in/in/sec)			1.6

I.5.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 3-V-12
RSL™ (B) 4-pt Bend Test

LRA Job No.:	TYL130901
Rod #:	3-V-12
Product Form:	1e
Rod OD:	3"

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, $KI_{p\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 10, FFS	Air	36.0	162	99.4	99.4	99.4	100.0%	85.3	0.53	286.7	1.8	7600	0.20496	143.1	50lbs/min		0.96	
	OD 2, IHE	Air	35.5	159	2073.6	3215.1	3089.5	104.0%	88.7	0.56	304.4	1.9	2.3	0.2151		10/5/2,4		1.00	Tensile Frame
	OD 6, EHE	3.5% NaCl @ -1.106V	35.5	159	35.0	33.3	26.2	27.1%	23.1	0.14	78.2	0.5	1.2	0.2094		10/5/2,4		0.26	
	MR 10, FFS	Air	34.0	153	88.5	88.5	88.5	100.0%	79.2	0.52	269.5	1.8	8400	0.2114	139.0	50 lbs/min		0.89	
	MR 2, IHE	Air	33.0	149	1996.8	3200.6	3200.6	116.3%	92.1	0.62	316.2	2.1	2.3	0.2163		10/5/2,4		1.04	Tensile Frame
	MR 3, EHE	3.5% NaCl @ -1.106V	33.0	149	62.4	46.8	37.3	42.4%	33.6	0.23	114.4	0.8	2.1	0.2134		10/5/2,4		0.38	
	MR 4, EHE	3.5% NaCl @ -1.106V	32.5	147	44.0	48.4	39.5	45.2%	35.8	0.24	122.2	0.8	1.6	0.2143		10/5/2,4		0.40	
	Center 2, FFS	Air	31.0	141	85.5	85.5	85.5	100.0%	77.1	0.55	262.7	1.9	8200	0.21267	138.8	50 lbs/min		0.87	
Threaded	Thd 5, FFS	Air	36.0	162	365.0	365.0	365.0	100.0%	99.4	0.61	243.4	1.5	2800	N/A		0.2 in/min	340.9	1.12	
	Thd 2, IHE	Air	35.0	157	256.0	362.6	354.1	96.4%	95.8	0.61	234.9	1.5	2	N/A		10/5/2,4	328.6	1.08	
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.5	159	285.8	329.1	241.3	66.7%	66.3	0.42	162.6	1.0	2.1	N/A		10/5/2,4	227.4	0.75	Did not crack in Holiday.
	Thd 4, EHE	3.5% NaCl @ -1.106V	35.5	159	248.0	310.1	258.8	72.1%	71.7	0.45	176.7	1.1	1.9	N/A		10/5/2,4	245.9	0.81	Did not crack in Holiday.
	Thd 6, EHE	3.5% NaCl @ -1.106V	36.0	162	210.0	294.0	250.4	70.4%	70.0	0.43	172.3	1.1	1.6	N/A		10/5/2,4	240.1	0.79	Did not crack in Holiday.

I.6 Fatigue Pre-cracked Specimen Test Results

I.6.1 OD 10, FFS:

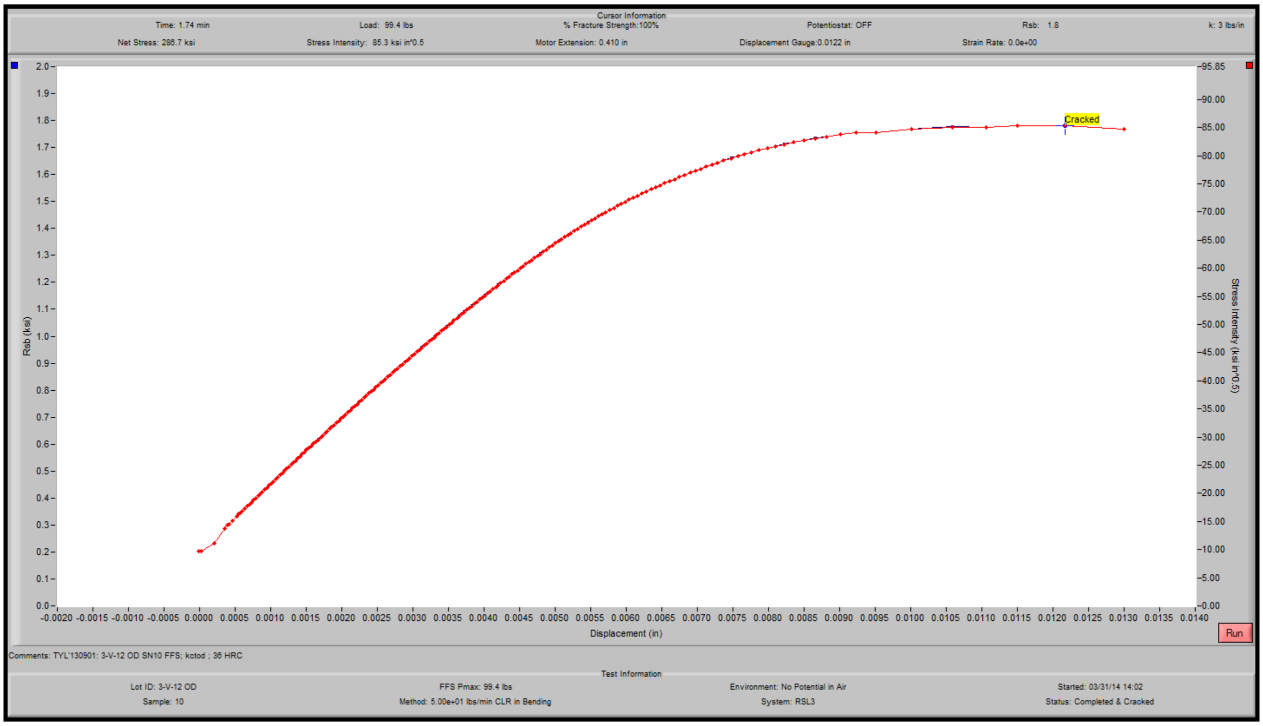


Figure I.6-1: Rod 3-V-12 OD 10, Graphical FFS Results

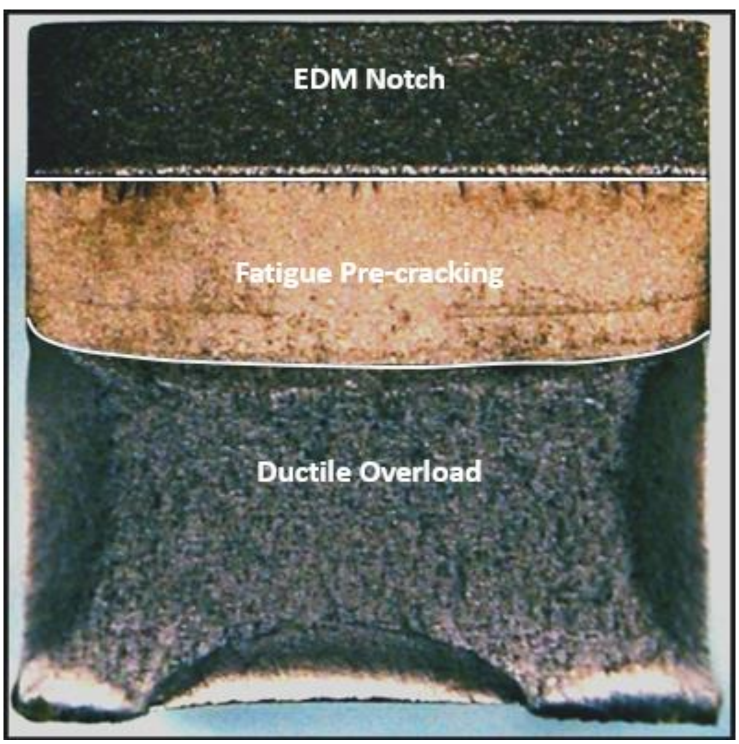


Figure I.6-2: Fracture Face of Rod 3-V-12 OD 10, FFS

I.6.2 OD 2, IHE:

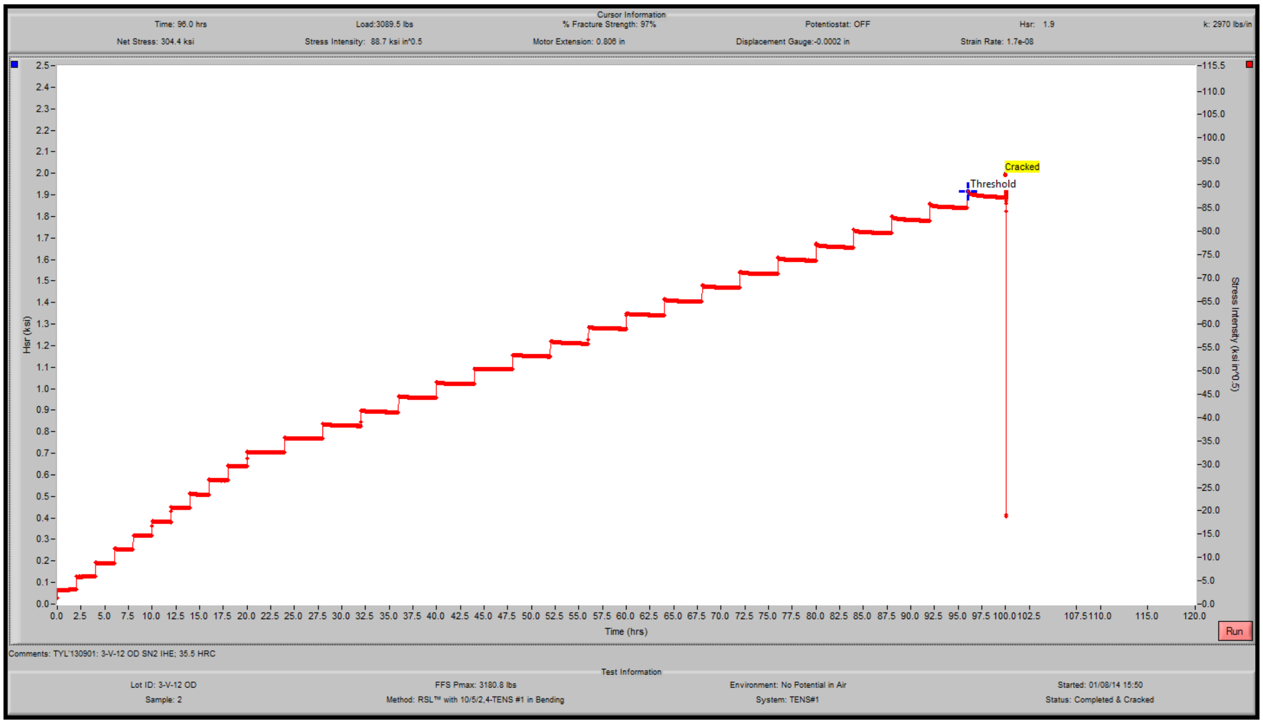


Figure I.6-3: Rod 3-V-12 OD 2, Graphical IHE Results

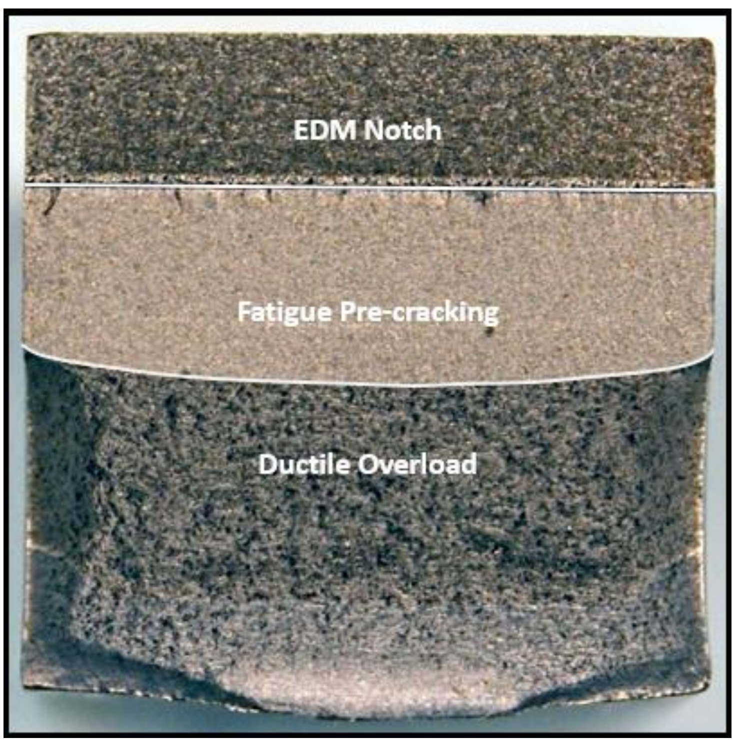


Figure I.6-4: Fracture Face of Rod 3-V-12 OD 2, IHE

I.6.3 OD 6, EHE:

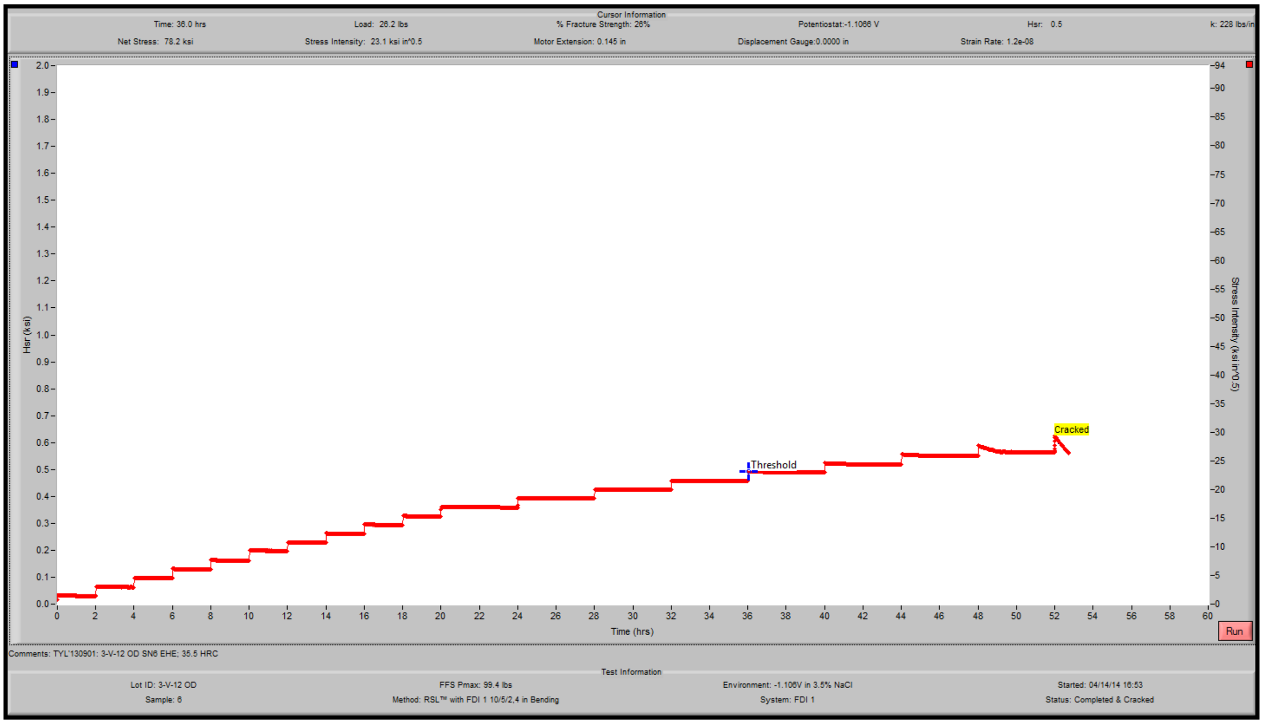


Figure I.6-5: Rod 3-V-12 OD 6, Graphical EHE Results

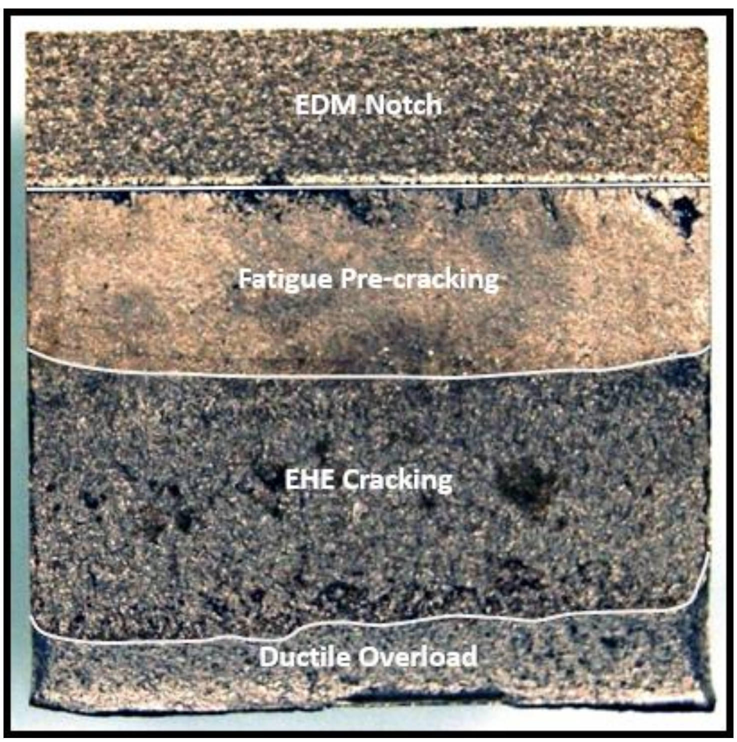


Figure I.6-6: Fracture Face of Rod 3-V-12 OD 6, EHE

I.6.4 MR 10, FFS:

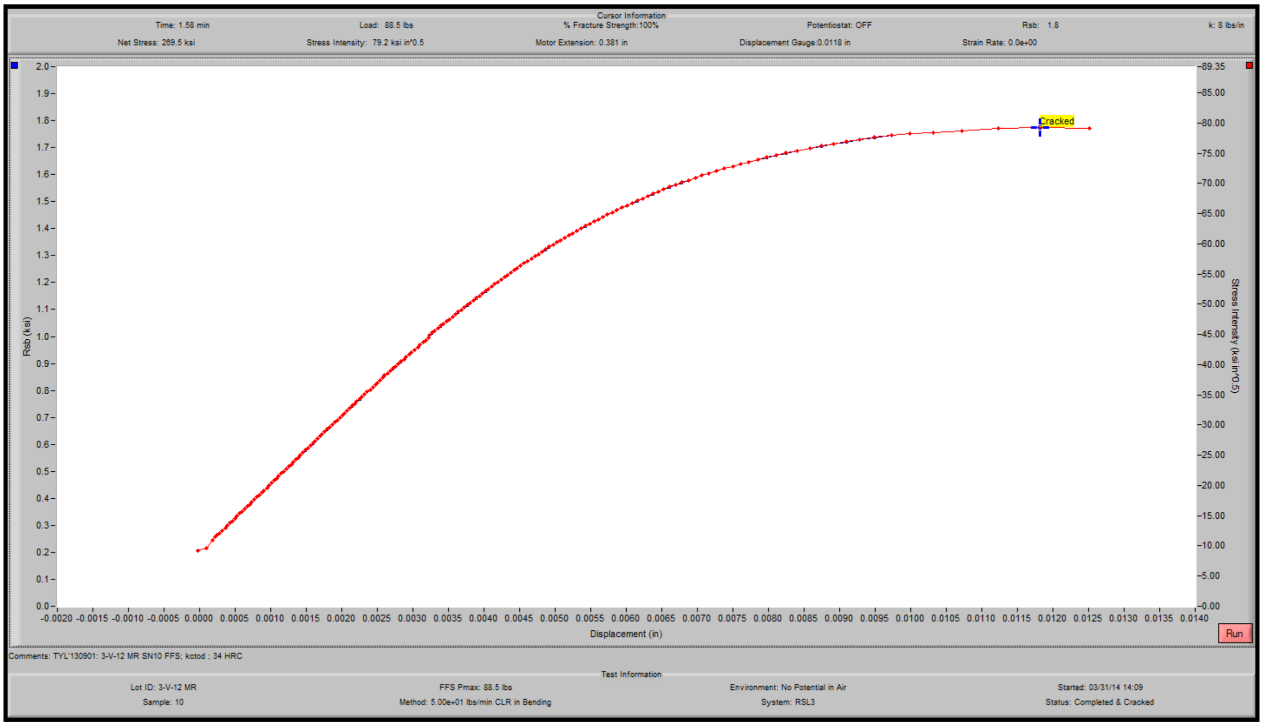


Figure I.6-7: Rod 3-V-12 MR 10, Graphical FFS Results

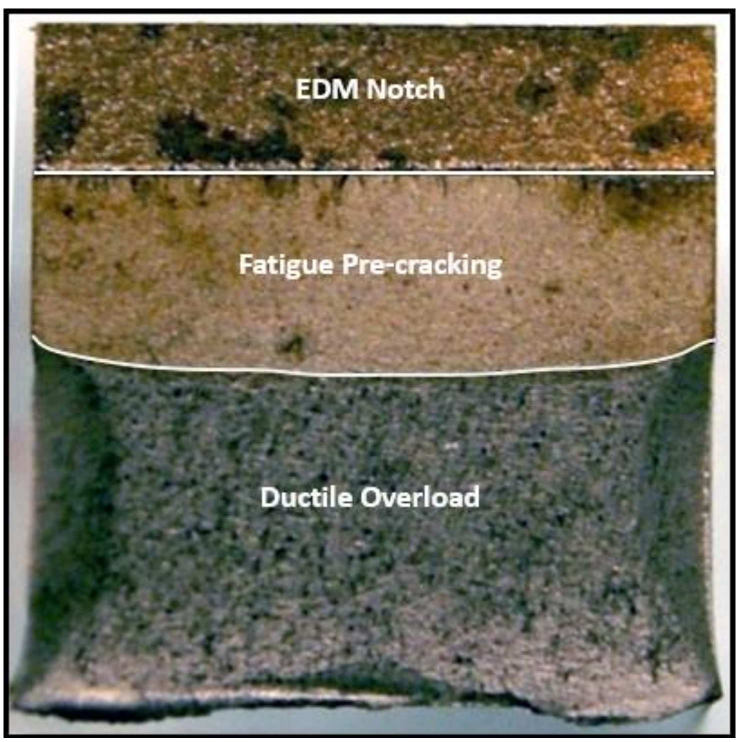


Figure I.6-8: Fracture Face of Rod 3-V-12 MR 10, FFS

I.6.5 MR 2, IHE:

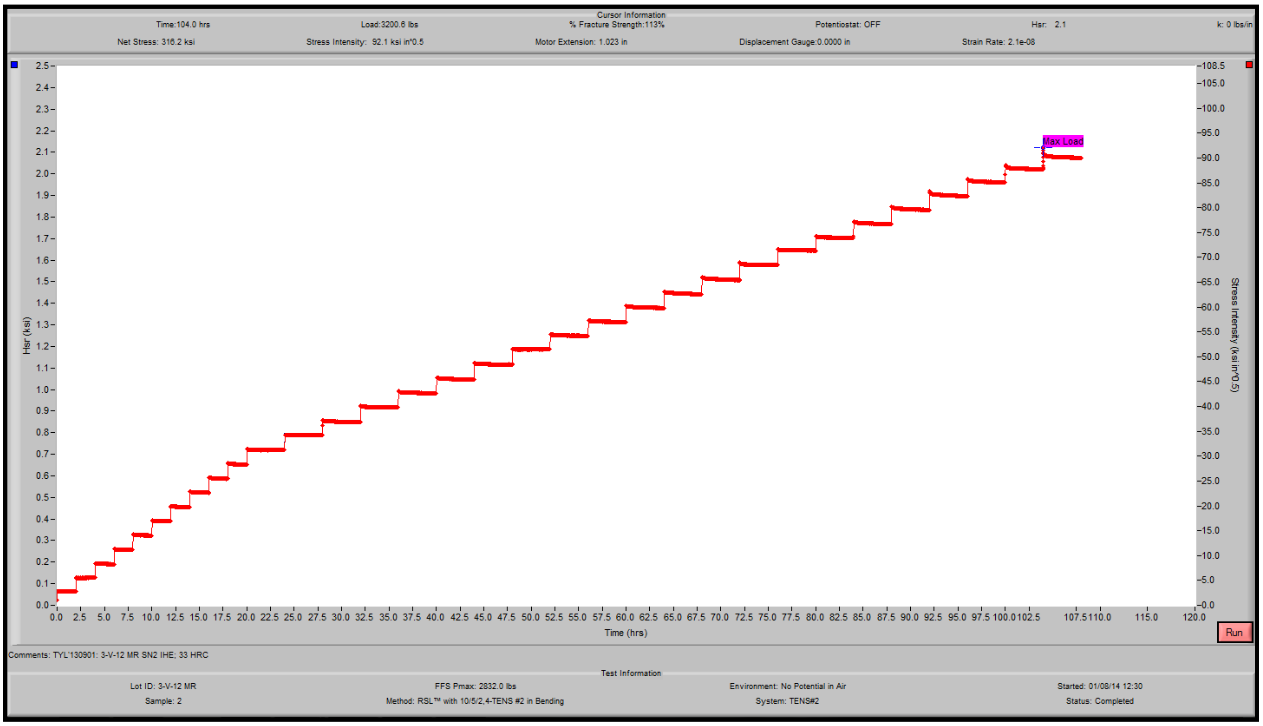


Figure I.6-9: Rod 3-V-12 MR 2, Graphical IHE Results

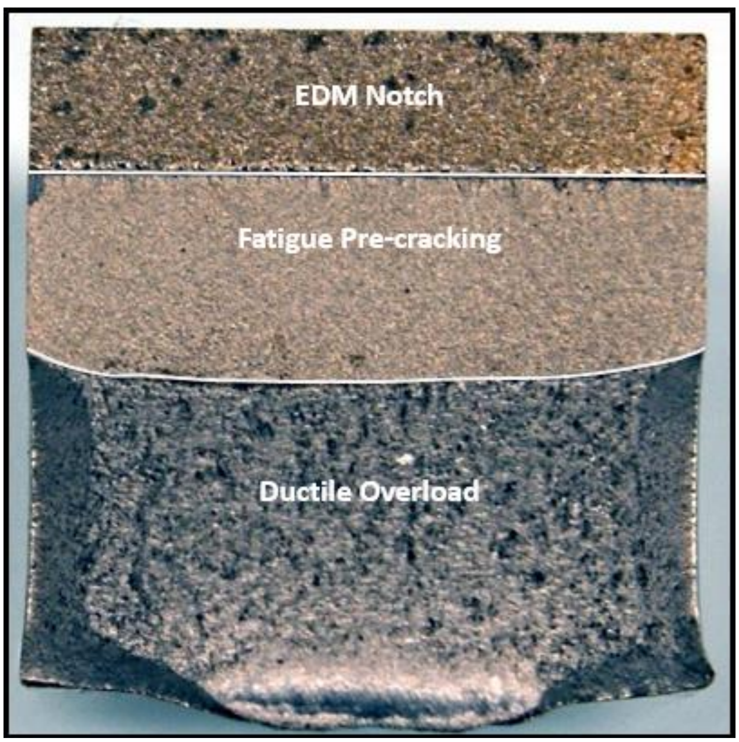


Figure I.6-10: Fracture Face of Rod 3-V-12 MR 2, IHE

I.6.6 MR 3, EHE:

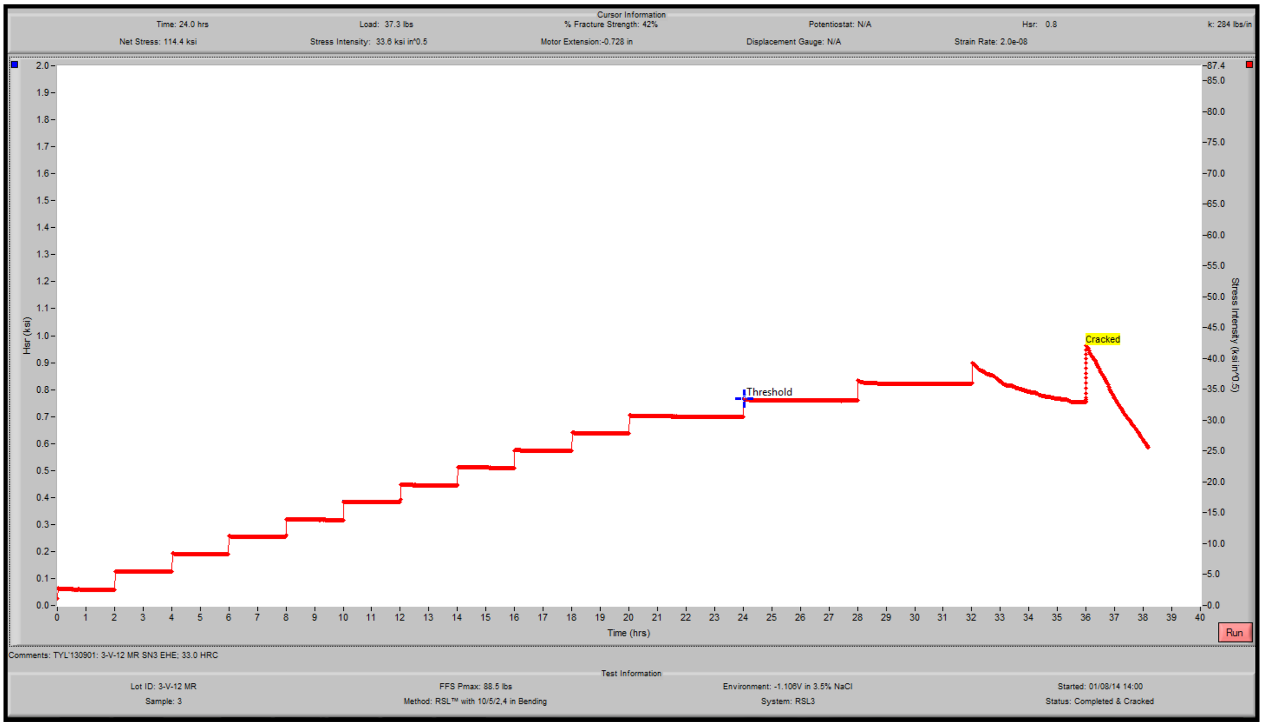


Figure I.6-11: Rod 3-V-12 MR 3, Graphical EHE Results

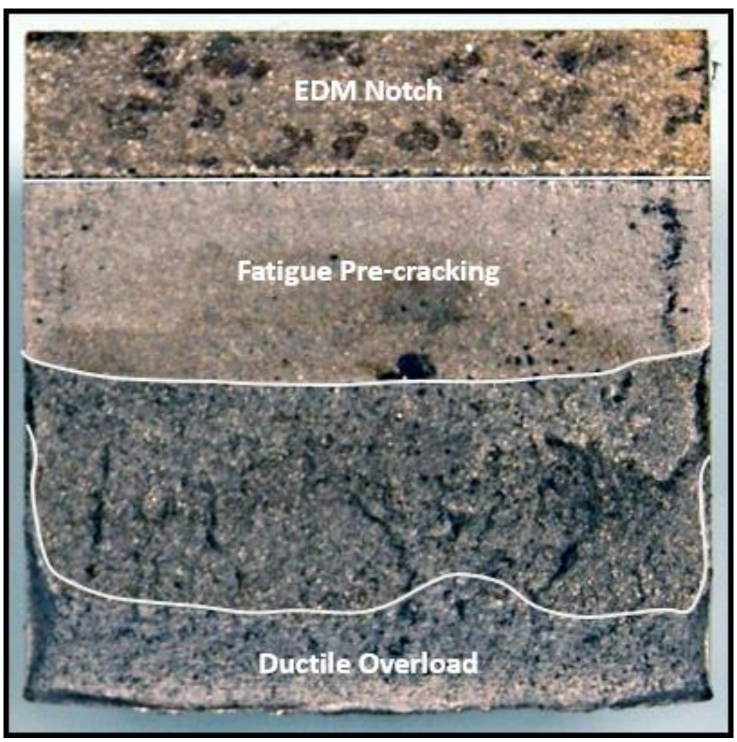


Figure I.6-12: Fracture Face of Rod 3-V-12 MR 3, EHE

I.6.7 MR 4, EHE:

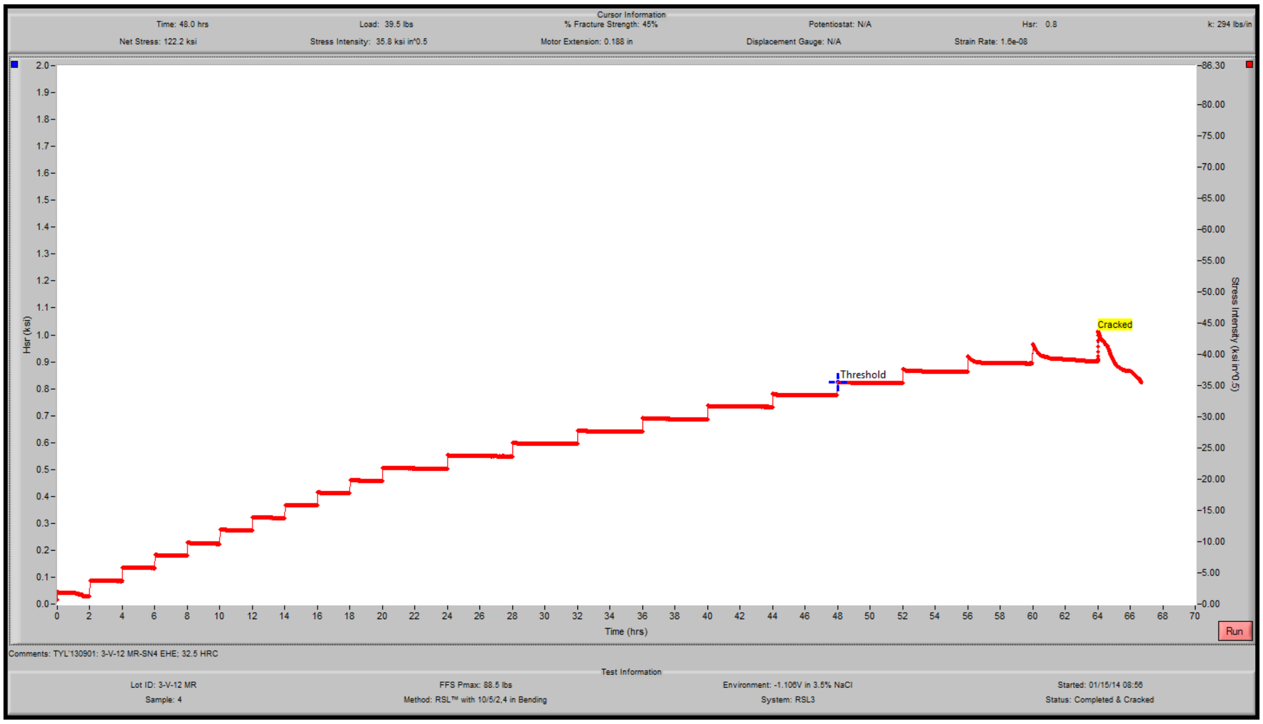


Figure I.6-13: Rod 3-V-12 MR 4, Graphical EHE Results

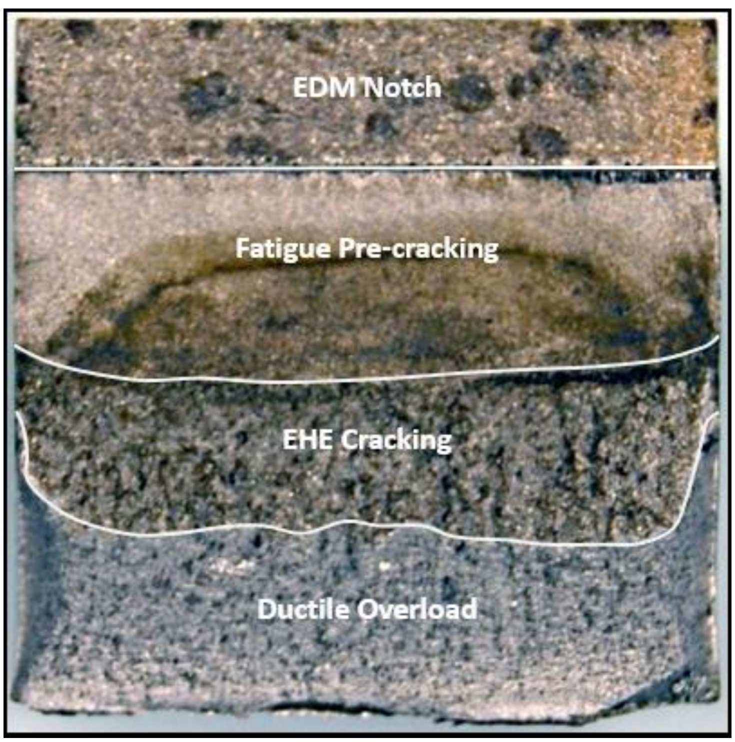


Figure I.6-14: Fracture Face of Rod 3-V-12 MR 4, EHE

I.6.8 Center 2, FFS:

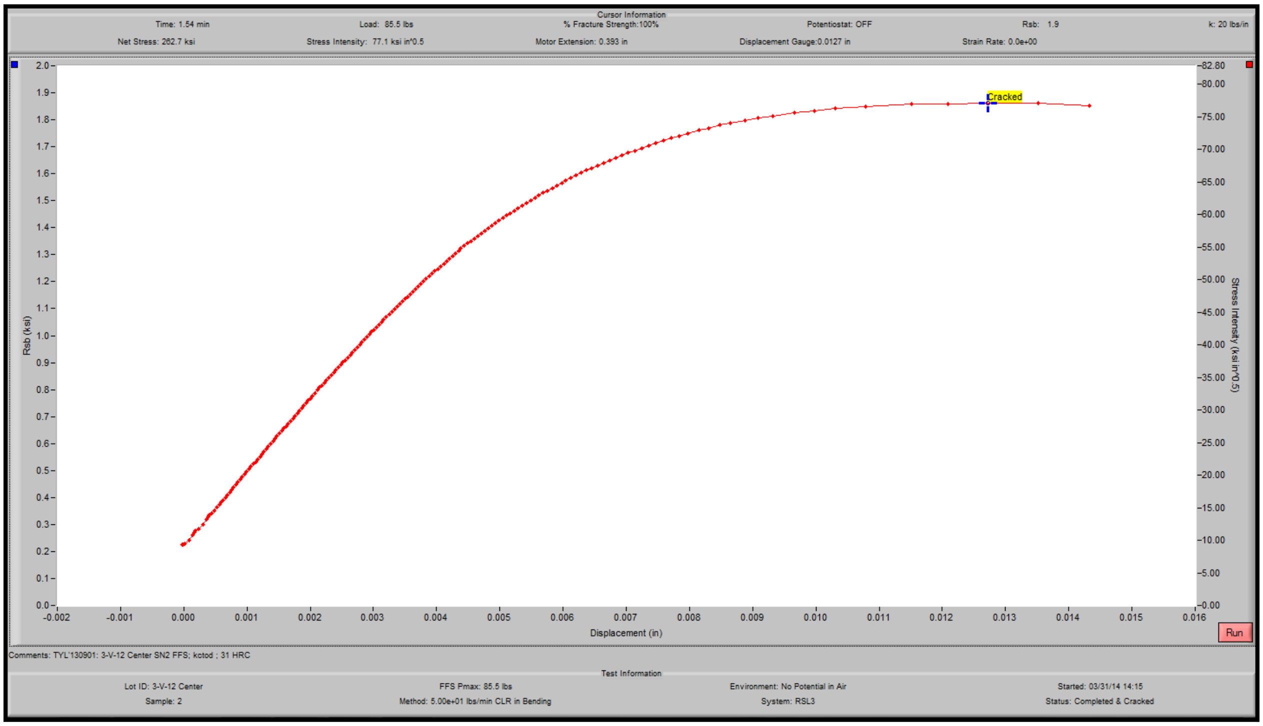


Figure I.6-15: Rod 3-V-12 Center 2, Graphical FFS Results

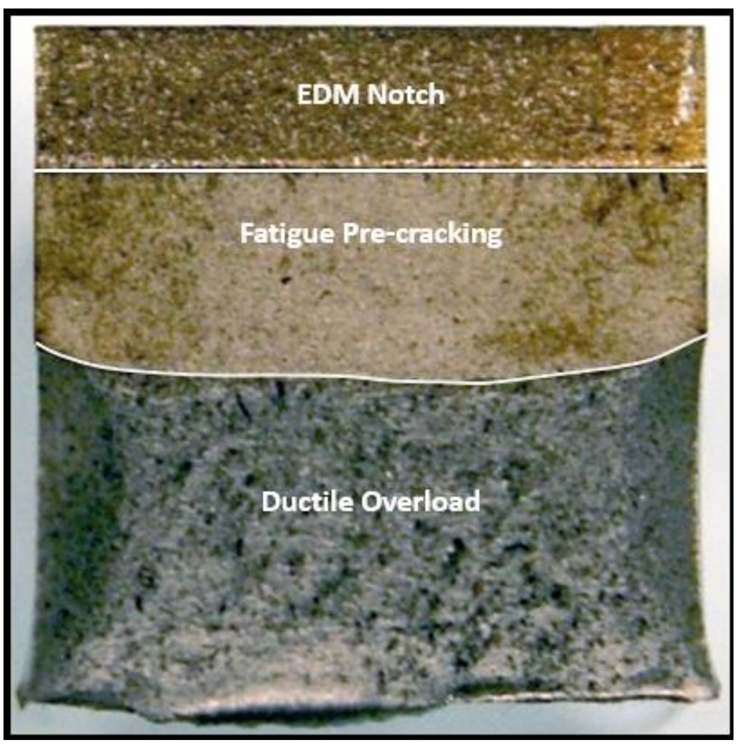
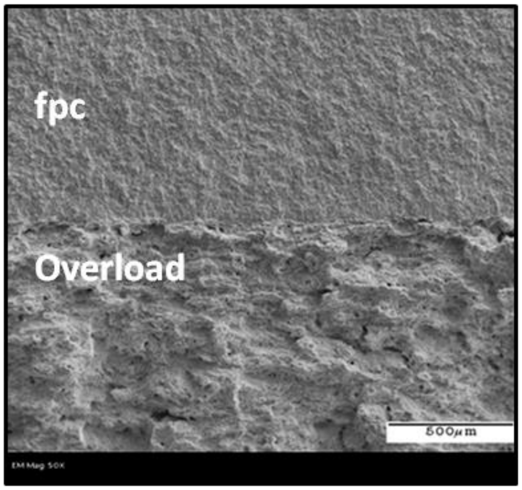
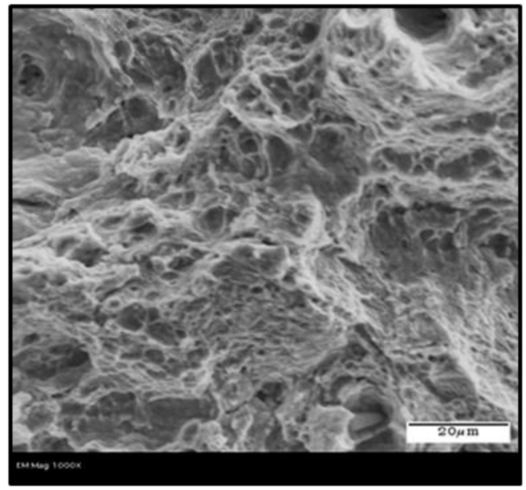


Figure I.6-16: Fracture Face of Rod 3-V-12 Center 2, FFS

Figure I.6-17: SEM of Rod 3-V-12 Center 2, FFS



fpc – OL transition 50X



Overload 1000X

I.7 Threaded Specimen Test Results

I.7.1 Thd 5, FFS:

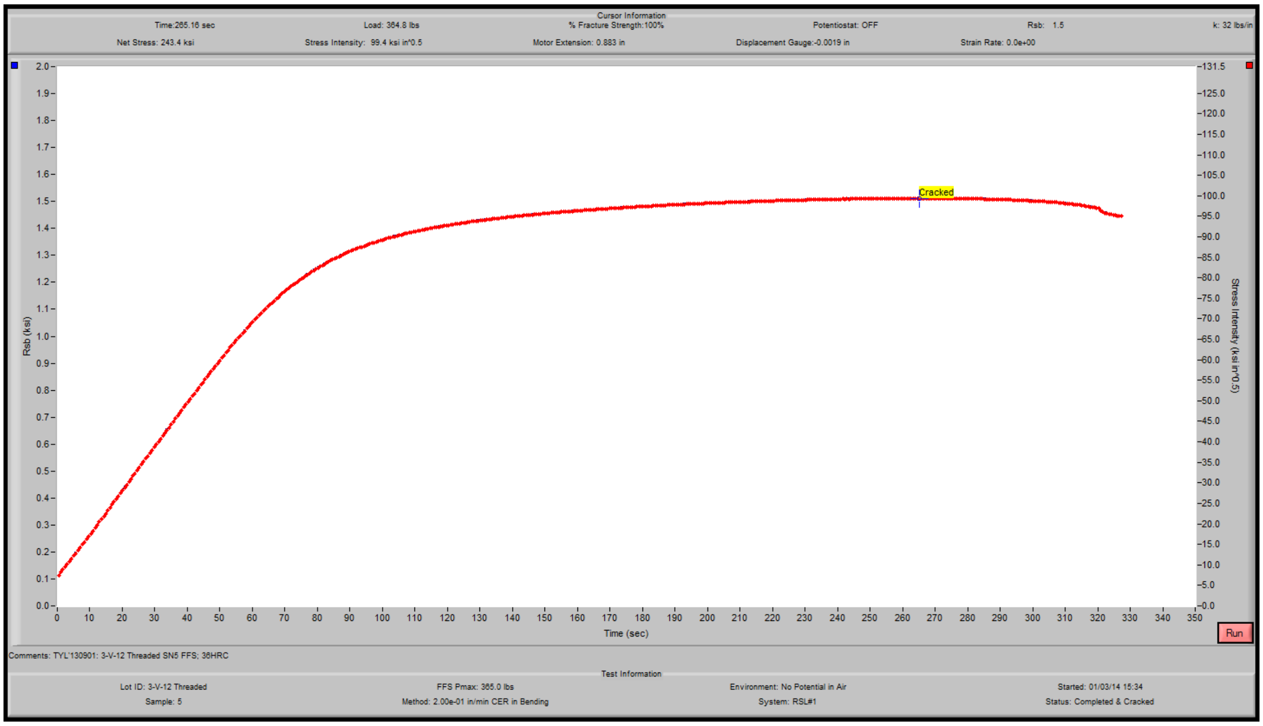


Figure I.7-1: Rod 3-V-12 Thd 5, Graphical FFS Results

Figure I.7-2: Rod 3-V-12 Thd 5 FFS Fracture Face

I.7.2 Thd 2, IHE:

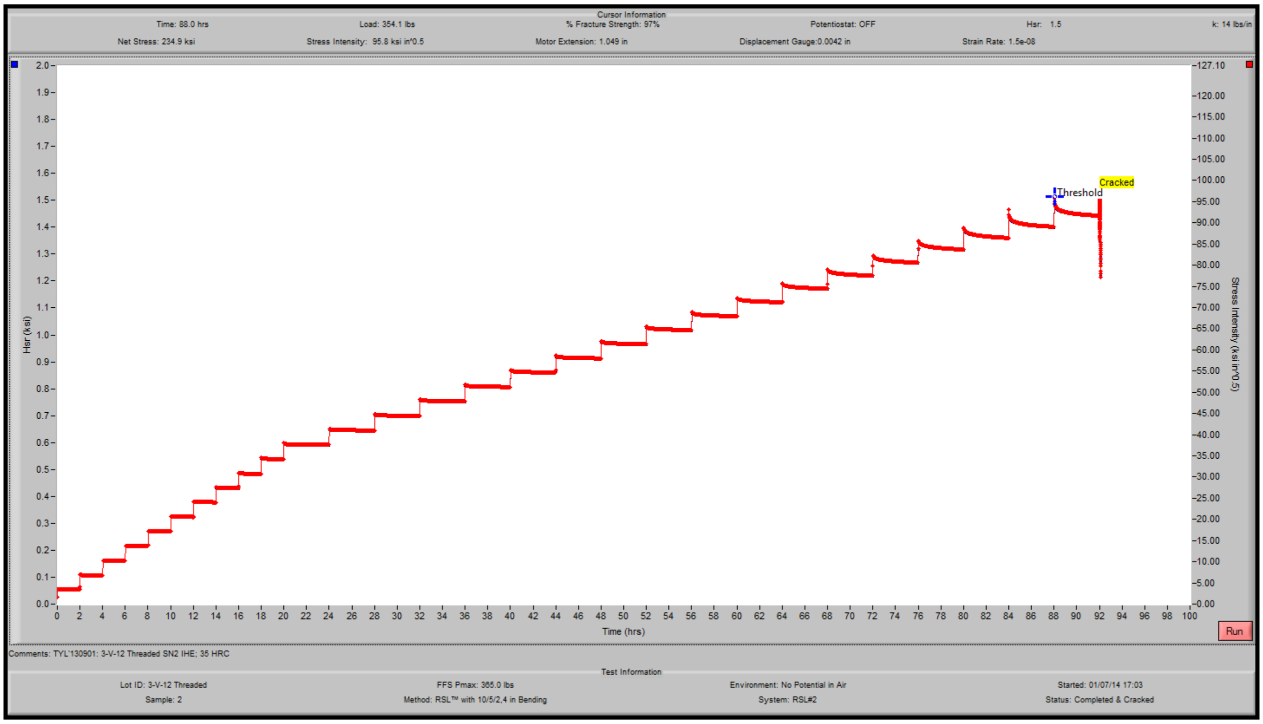


Figure I.7-3: Rod 3-V-12 Thd 2, Graphical IHE Results

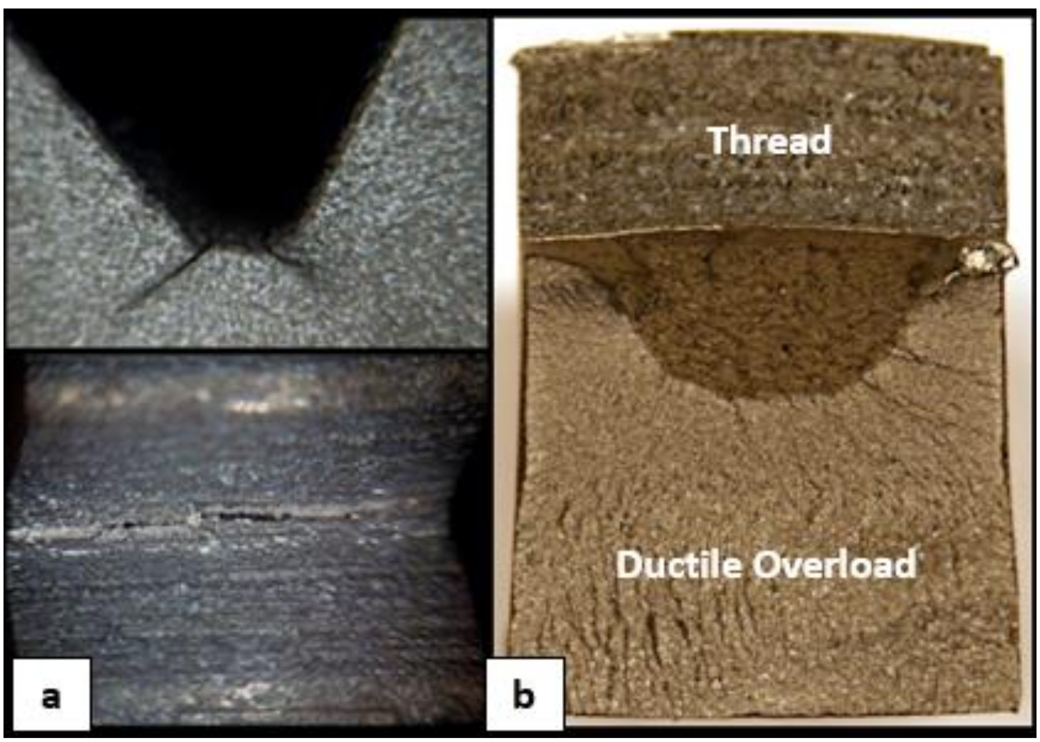


Figure I.7-4: Rod 3-V-12 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

I.7.3 Thd 3, EHE:

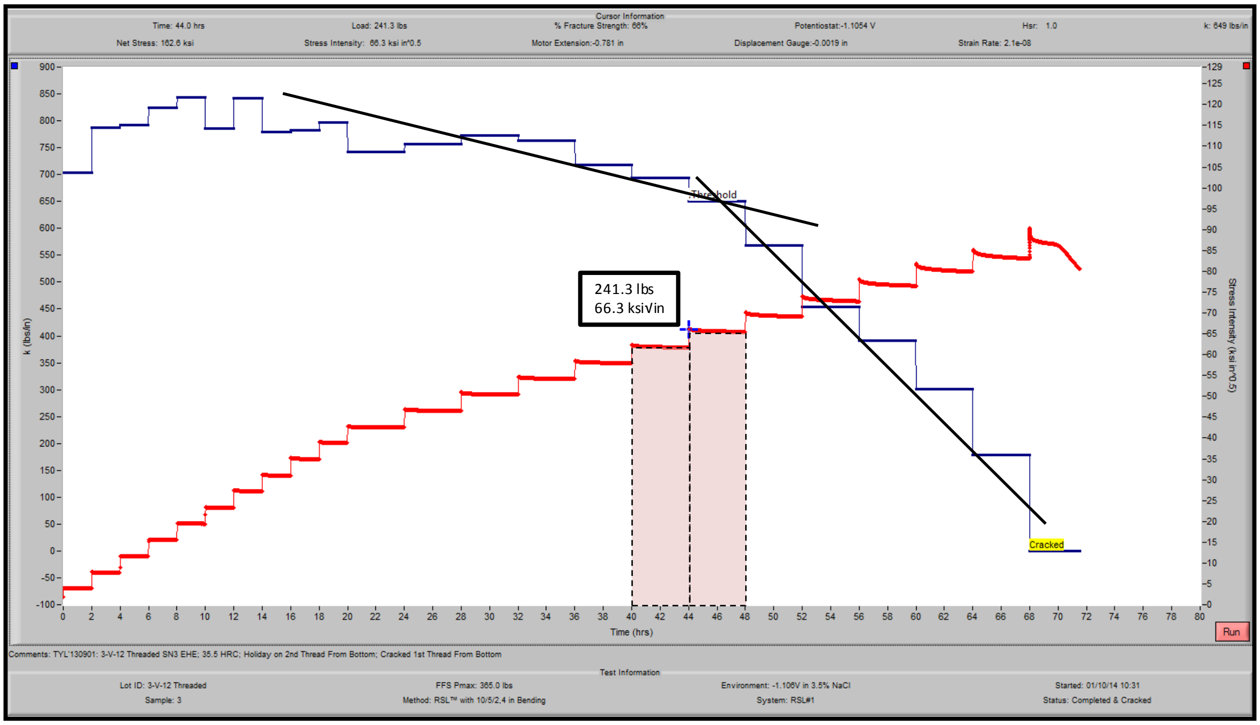
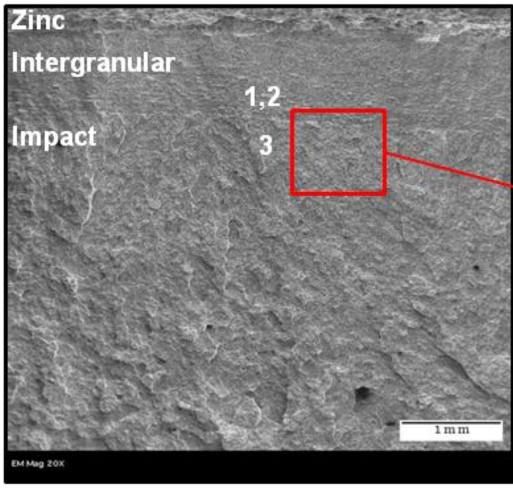


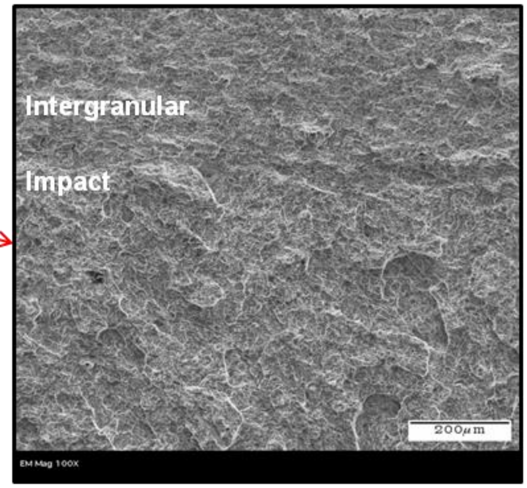
Figure I.7-5: Rod 3-V-12 Thd 3 Graphical EHE Results

Figure I.7-6: Rod 3-V-12 Thd 3 EHE Fracture Face

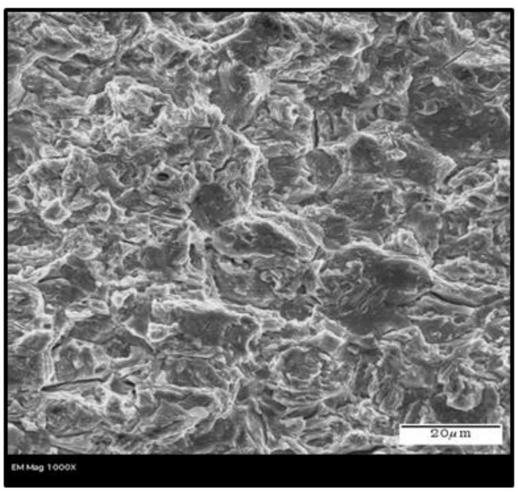
Figure I.7-7: SEM of Rod 3-V-12 Thd 3, EHE



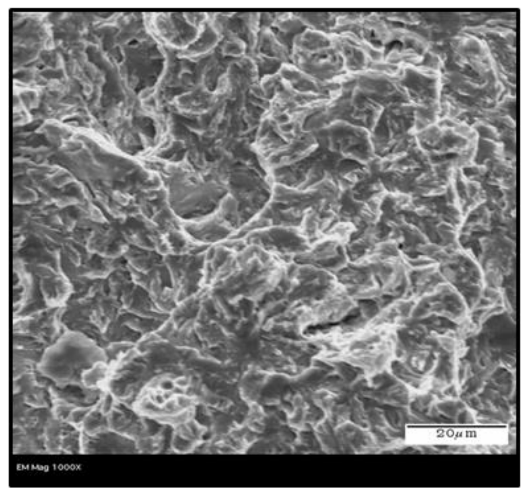
Thread Root 20X



1) Intergranular to Impact Transition 100X



2) Mixed: Cleavage, Intergranular 1000X



3) Impact, Cleavage 1000X

I.7.4 Thd 4, EHE:

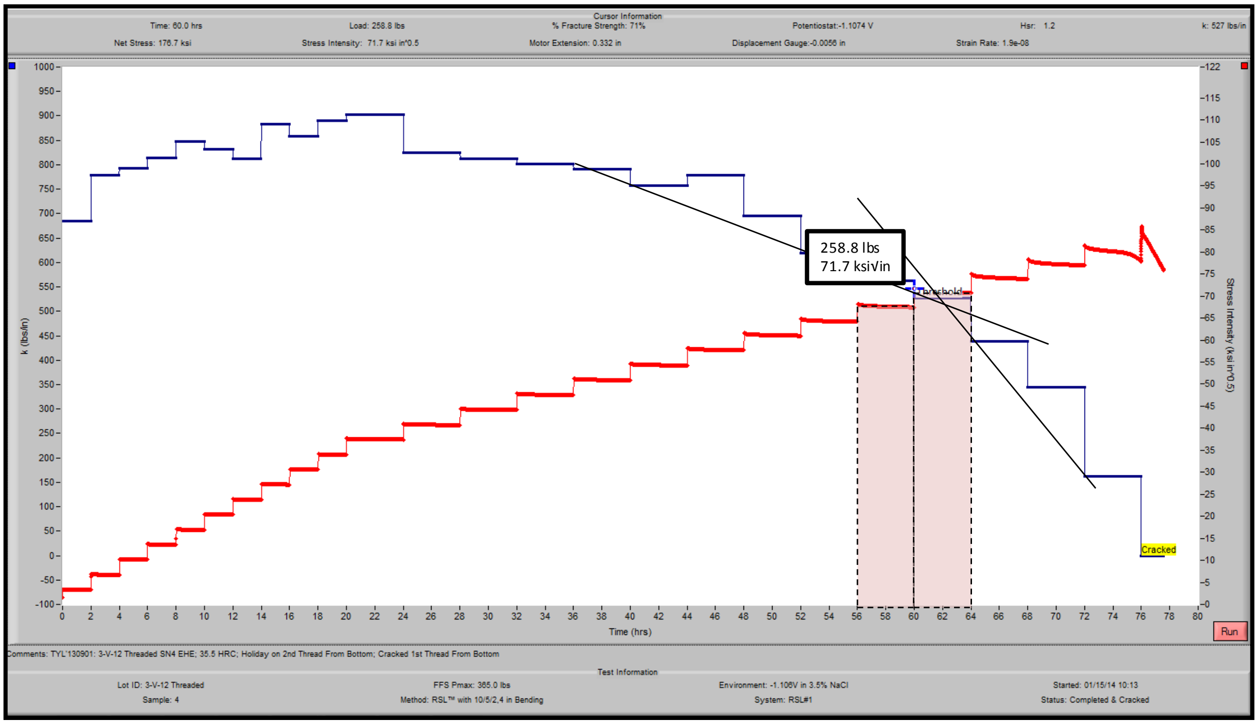
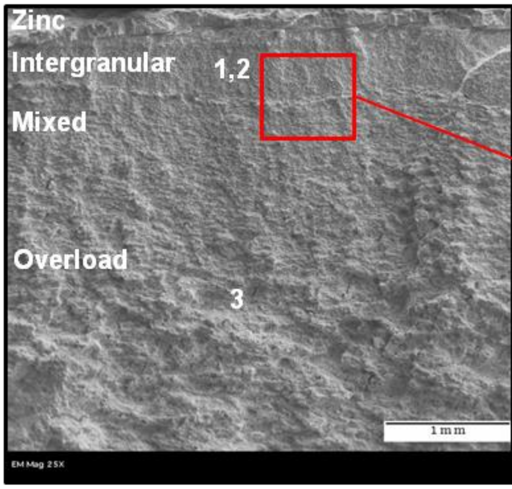


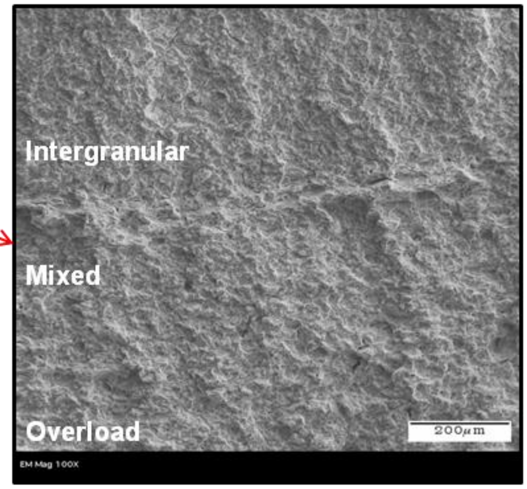
Figure I.7-8: Rod 3-V-12 Thd 4 Graphical EHE Results

Figure I.7-9: Rod 3-V-12 Thd 4, Thread Root from Side and Normal Views Post EHE Test

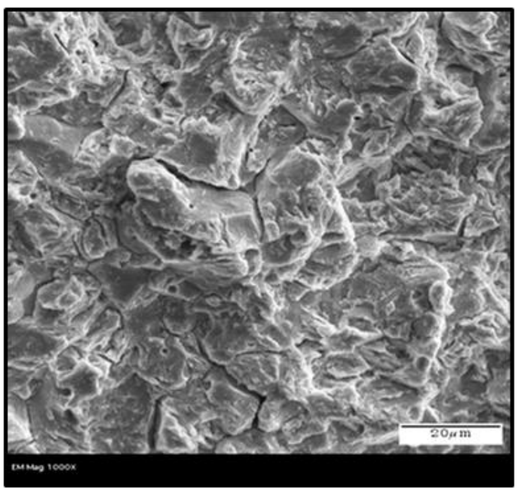
Figure I.7-10: SEM of Rod 3-V-12 Thd 4, EHE



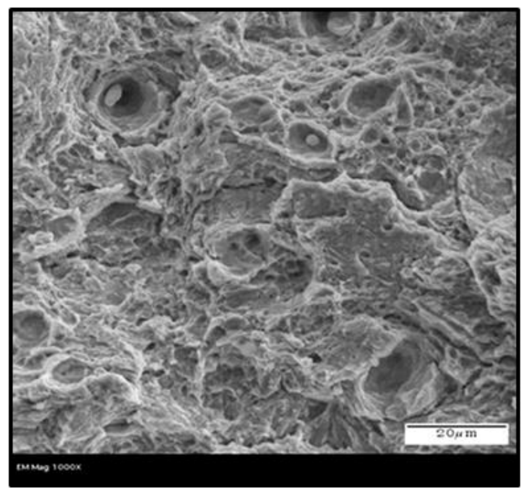
Thread Root 25X



1) Embrittlement, Mixed: Mode Transition 100X



2) Intergranular 1000X



3) Ductile Overload 1000X

I.7.5 Thd 6, EHE:

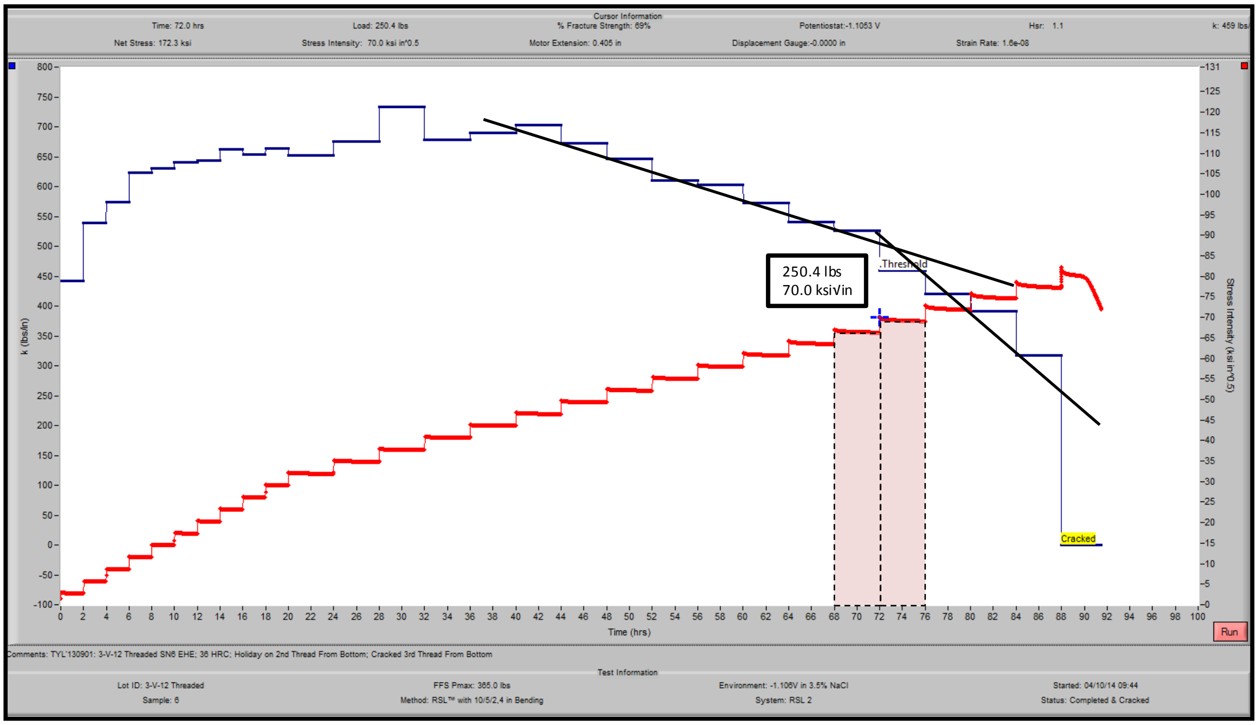


Figure I.7-11: Rod 3-V-12 Thd 6 Graphical EHE Results

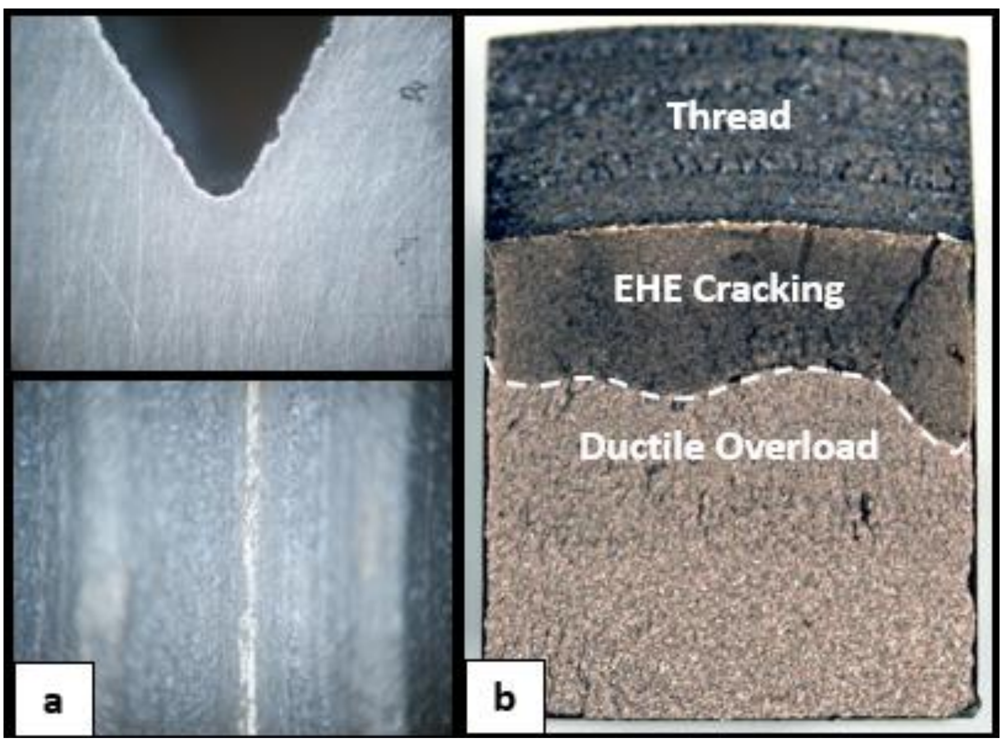


Figure I.7-12: Rod 3-V-12 Thd 6 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix J: Rod 12-V-B2E-4

J.1 Description of Sample

Rod 12-V-B2E-4 was a Tower Anchorage Anchor Bolt located at the bottom of the tower from the same group of material that was tested in Test Rig 6 in Test IV. It was AISI 4140 steel, ASTM A354 Grade BD threaded rod. These bolts are 3-inches in diameter with machined threads. The segment from this section of the rod provided to LRA is shown in **Figure J.1-1**.

Figure J.1-1: Tower Anchorage Anchor Bolt (Bottom), Rod 12-V-B2E-4

J.2 Thread Profile

The threads were compared using an optical comparator. A Shadowgraph of the threads from Rod 12-V-B2E-4 can be seen in **Figure J.2-1** where the black portion of the Shadowgraph represents the rod material. As can be seen from **Figure J.2-1,** these machined thread roots show non-uniformity and exhibit a sharp radius.

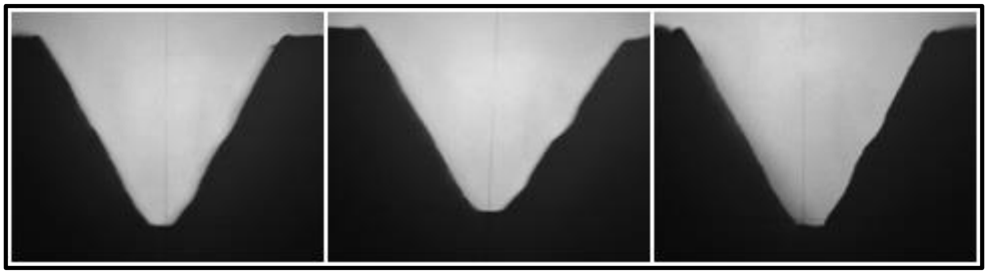


Figure J.2-1: Thread Comparison of Three Threads of Rod 12-V-B2E-4

J.3 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 12-V-B2E-4 and can be seen versus time in **Figure J**.3-1. The final OCP recorded for Rod 12-V-B2E-4 was Vsce=-0.830 V.

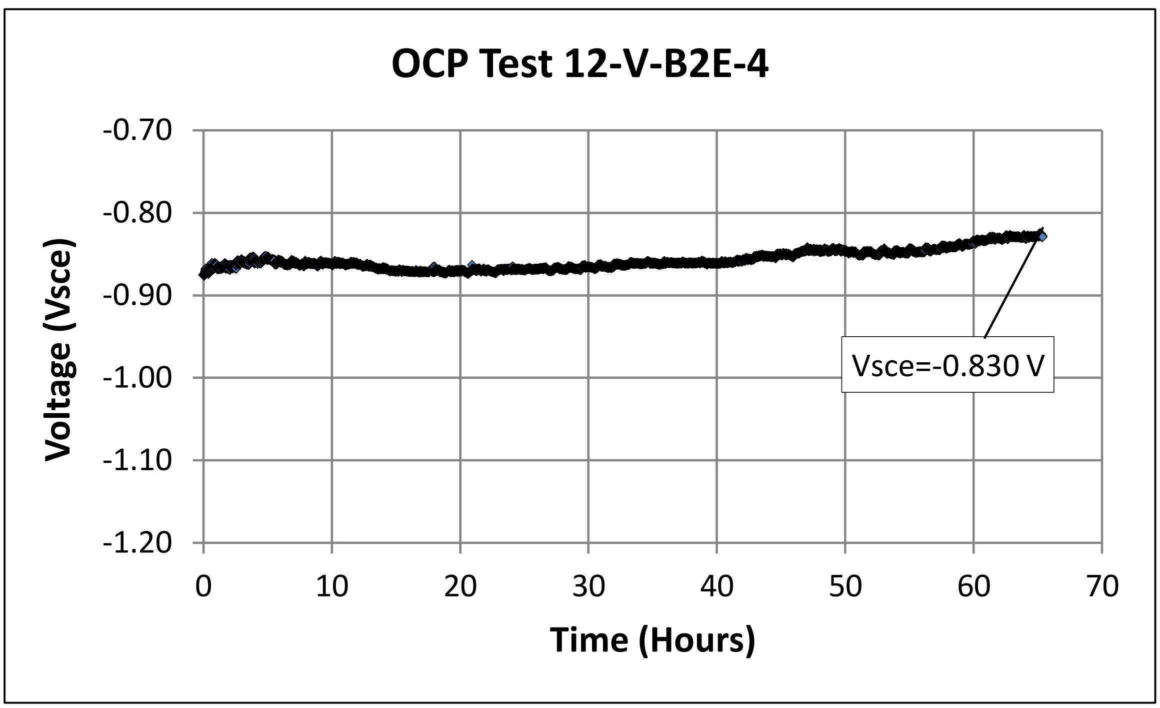


Figure J.3-1: Open Circuit Potential for Rod 12-V-B2E-4

J.4 Hardness

The hardness data and profile for sample 12-V-B2E-4 are shown in **Table J.4-1** and **Figure J.4-1**.

Table J.4-1: Hardness Data of Rod 12-V-B2E-4 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	30.0	30.0
MR 1, FFS	37.0	35.0
MR 2, IHE	35.5	
MR 3, EHE	33.5	
MR 4, EHE	34.0	
OD 1, FFS	37.5	37.0
OD 2, IHE	37.0	
OD 5, EHE	37.0	
OD 6, EHE	36.5	
Thd 1, FFS	36.5	
Thd 2, IHE	37.0	
Thd 3, EHE	37.5	
Thd 4, EHE	37.0	

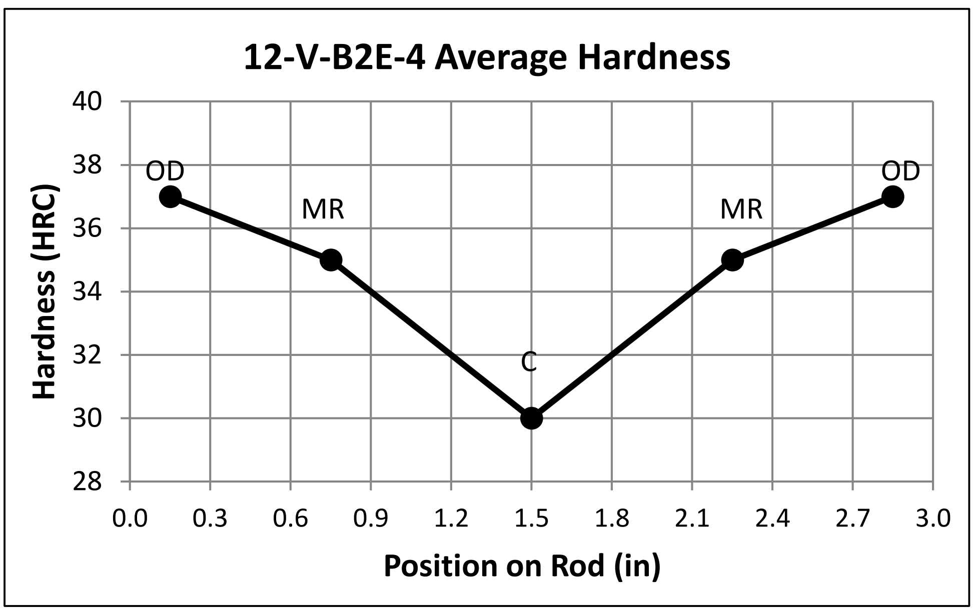


Figure J.4-1: Hardness Profile of Rod 12-V-B2E-4

J.5 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

J.5.1 Fatigue Pre-cracked Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 12-V-b2E-4						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts) **Comments**: Machined Threads; Same Group as Test Rig #6 in Test IV				
Rod#:	**12-V-b2E-4**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**37.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	90.7 0.54 1.02 8500		
	OD 2, IHE	**37.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		86.8 0.52 0.98 2.1	
	OD 5, EHE	**37.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			22.6 0.14 0.26 1.0
	OD 6, EHE	**36.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			24.3 0.15 0.27 1.0
	MR 1, FFS	**37.0**	K_{max} Fu Rsb-Max Strain Rate ($x10^{-8}$ in/in/sec)	86.2 0.52 0.97 8150		

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 12-V-b2E-4						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts)				
Rod#:	**12-V-b2E-4**					
Product Form:	**1e**	**Comments**: Machined Threads; Same Group as Test Rig #6 in Test IV				
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 2, IHE**	**35.5**	$K_{threshold}$		89.9	
			DTI_{th}		0.56	
			Fu		1.02	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.5	
	MR 3, EHE	**33.5**	$K_{threshold}$			42.7
			DTI_{th}			0.28
			Fu			0.48
			Strain Rate ($x10^{-8}$ in/in/sec)			2.4
	MR 4, EHE	**34.0**	$K_{threshold}$			39.8
			DTI_{th}			0.26
			Fu			0.45
			Strain Rate ($x10^{-8}$ in/in/sec)			2.0
	Center 1, FFS	**30.0**	K_{max}	79.5		
			DTI_{th}	0.58		
			Fu	0.90		
			Strain Rate ($x10^{-8}$ in/in/sec)	8600		

J.5.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 12-V-b2E-4						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts) **Comments**: Machined Threads; Same Group as Test Rig #6 in Test IV				
Rod#:	**12-V-b2E-4**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**36.5**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	334.4 1.10 1.5 2900		
	Thd 2, IHE	**37.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		331.0 1.09 1.4 2.2	
	Thd 3, EHE	**37.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			218.1 0.72 0.9 2.4
	Thd 4, EHE	**37.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			222.9 0.73 0.9 1.6

J.5.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 12-V-b2E-4
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**12-V-b2E-4**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, $KIp_{\text{-EHE}}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	$\delta\varepsilon/\delta t$ ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	37.5	169	97.5	97.5	97.5	100.0%	90.7	0.54	311.8	1.8	8500	0.2163	152.3	50 lbs/min		1.02	
	OD 2, IHE	Air	37.0	167	2016.0	3125.9	3125.9	95.7%	86.8	0.52	294.3	1.8	2.1	0.2099		10/5/2,4		0.98	Tensile Frame
	OD 5, EHE	3.5% NaCl @ -1.106V	37.0	167	30.0	30.0	25.4	24.9%	22.6	0.14	76.7	0.5	1.0	0.2075		10/5/2,4		0.26	
	OD 6, EHE	3.5% NaCl @ -1.106V	36.5	164	28.0	29.4	26.5	26.8%	24.3	0.15	83.0	0.5	1.0	0.2115		10/5/2,4		0.27	
	MR 1, FFS	Air	37.0	167	97.3	97.3	97.3	100.0%	86.2	0.52	292.2	1.8	8150	0.2092	143.4	50 lbs/min		0.97	
	MR 2, IHE	Air	35.5	159	2144.0	3108.8	3108.8	104.3%	89.9	0.56	308.3	1.9	2.5	0.2143		10/5/2,4		1.02	Tensile Frame
	MR 3, EHE	3.5% NaCl @ -1.106V	33.5	151	66.6	56.6	46.6	49.5%	42.7	0.28	146.0	1.0	2.4	0.213		10/5/2,4		0.48	
	MR 4, EHE	3.5% NaCl @ -1.106V	34.0	153	58.0	55.2	43.4	46.2%	39.8	0.26	136.3	0.9	2.0	0.2137		10/5/2,4		0.45	
	Center 1, FFS	Air	30.0	138	85.8	85.8	85.8	100.0%	79.5	0.58	272.9	2.0	8600	0.2144	141.6	50 lbs/min		0.90	
Threaded	Thd 1, FFS	Air	36.5	164	294.4	294.4	294.4	100.0%	97.5	0.59	249.9	1.5	2900	N/A		0.2 in/min	334.4	1.10	
	Thd 2, IHE	Air	37.0	167	294.0	356.0	351.5	99.0%	96.5	0.58	237.2	1.4	2.2	N/A		10/5/2,4	331.0	1.09	
	Thd 3, EHE	3.5% NaCl @ -1.106V	37.5	169	294.4	294.7	219.8	65.2%	63.6	0.38	158.1	0.9	2.4	N/A		10/5/2,4	218.1	0.72	Did Not Crack in Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	37.0	167	235.0	352.8	256.9	66.7%	65.0	0.39	156.3	0.9	1.6	N/A		10/5/2,4	222.9	0.73	Did Not Crack in Holiday

J.6 Fatigue Pre-cracked Specimen Test Results

J.6.1 OD 1, FFS:

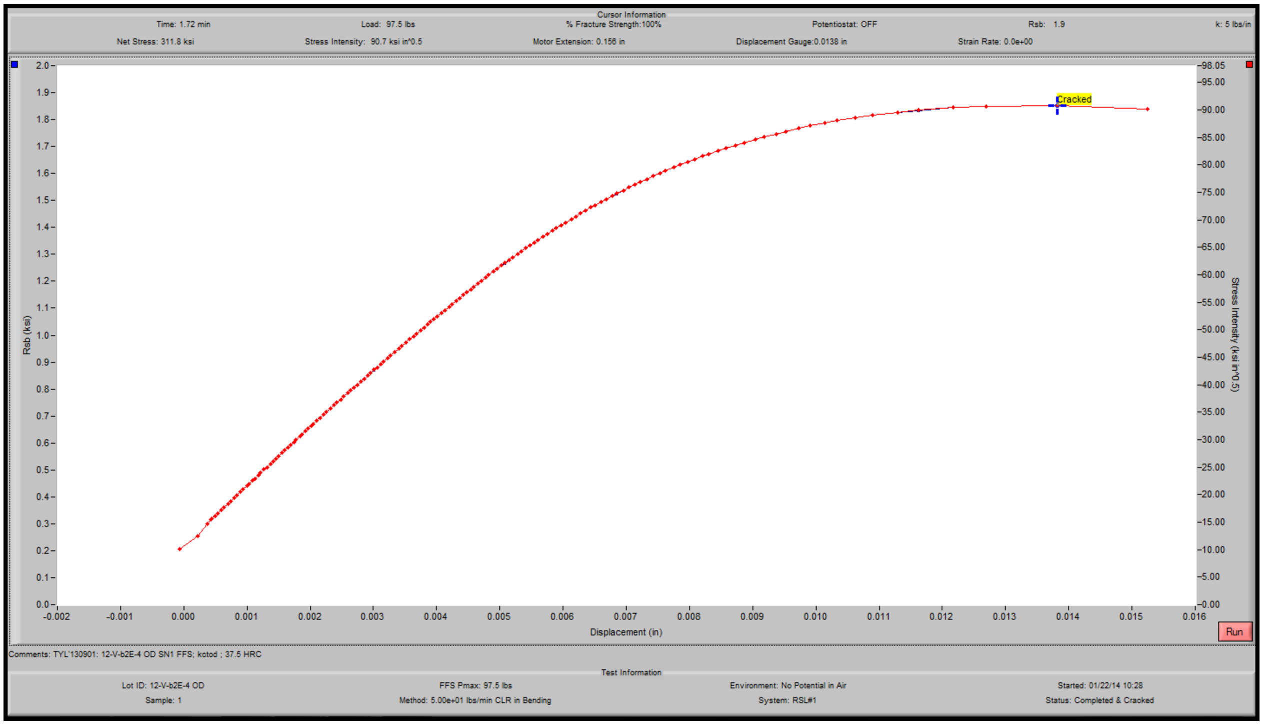


Figure J.6-1: Rod 12-V-B2E-4 OD 1, Graphical FFS Results

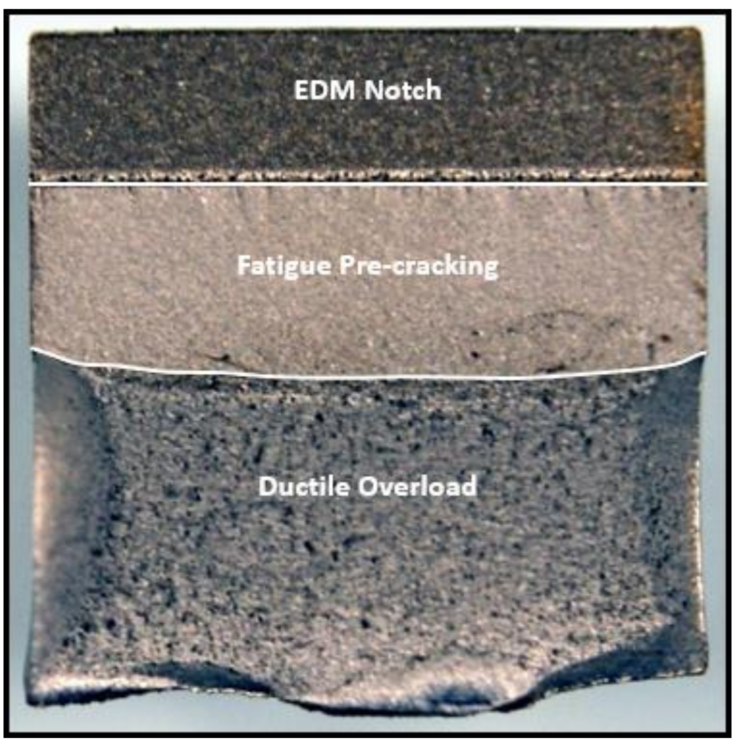


Figure J.6-2: Fracture Face of Rod 12-V-B2E-4 OD 1, FFS

J.6.2 OD 2, IHE:

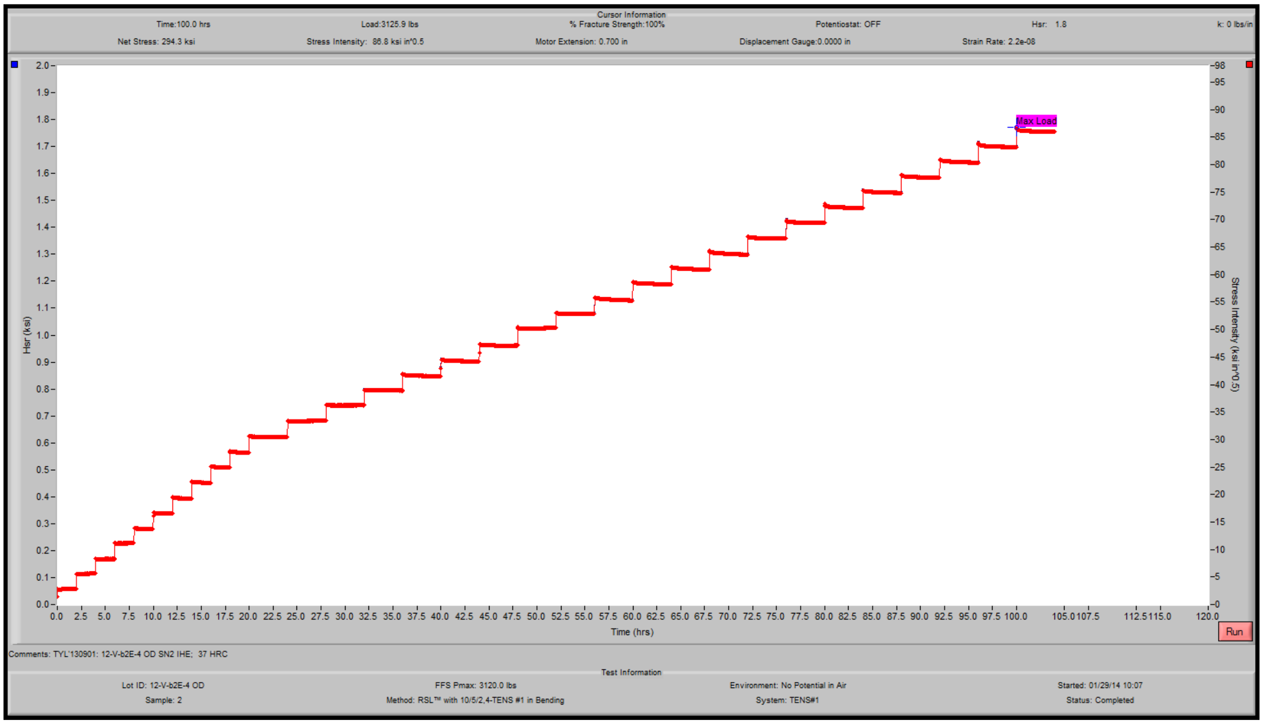


Figure J.6-3: Rod 12-V-B2E-4 OD 2, Graphical IHE Results

Figure J.6-4: Fracture Face of Rod 12-V-B2E-4 OD 2, IHE

J.6.3 OD 5, EHE:

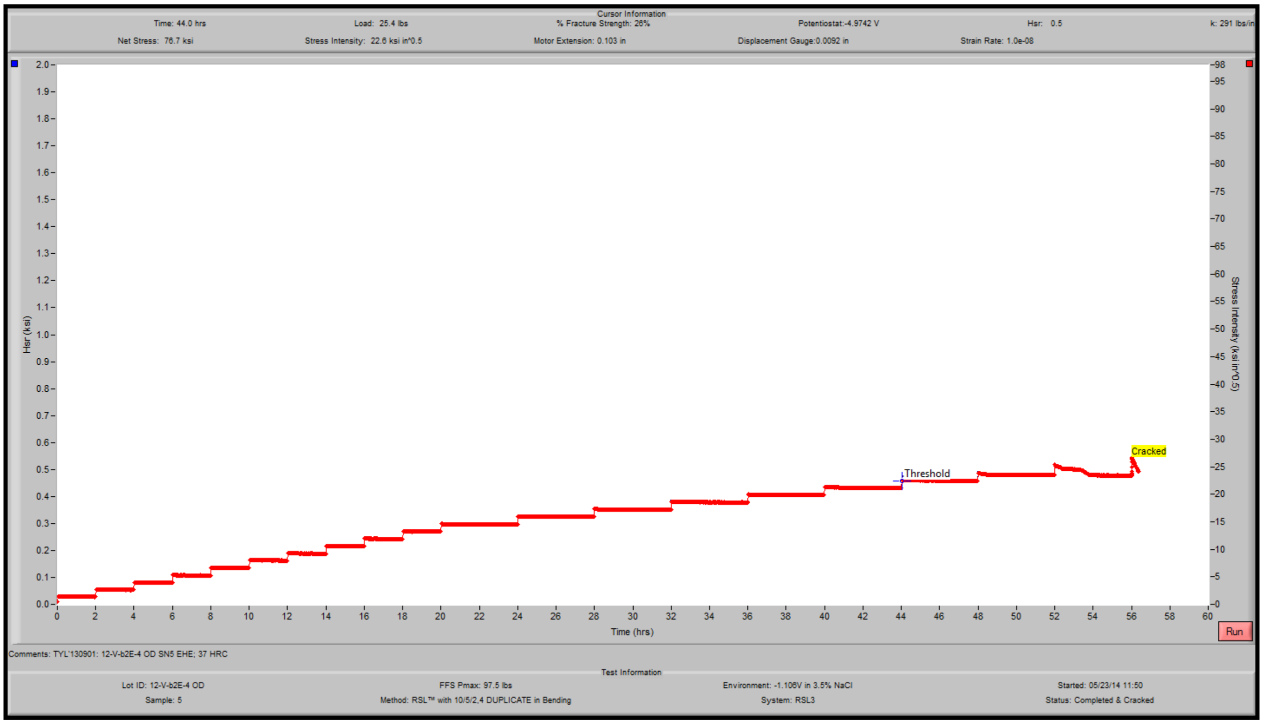


Figure J.6-5: Rod 12-V-B2E-4 OD 5, Graphical EHE Results

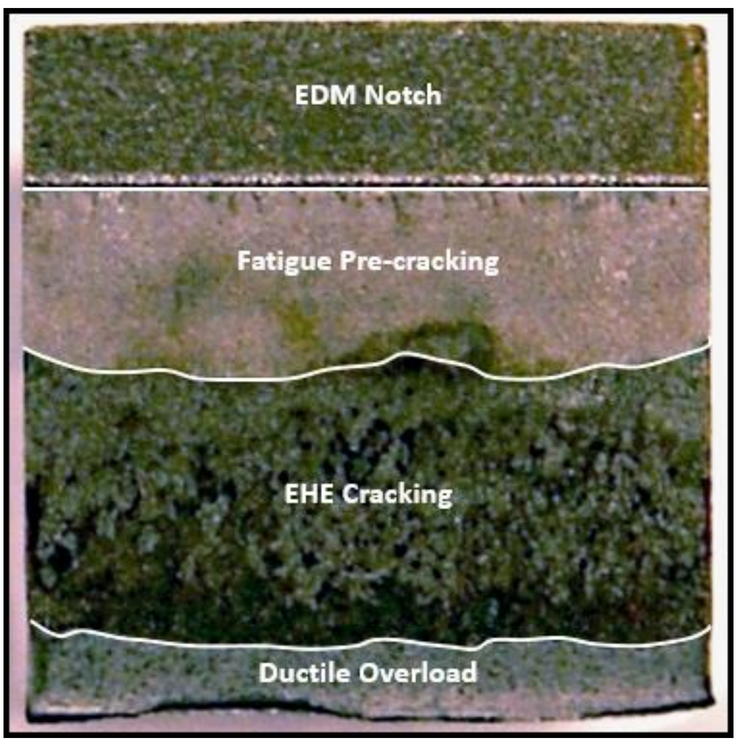


Figure J.6-6: Fracture Face of Rod 12-V-B2E-4 OD 5, EHE

J.6.4 OD 6, EHE:

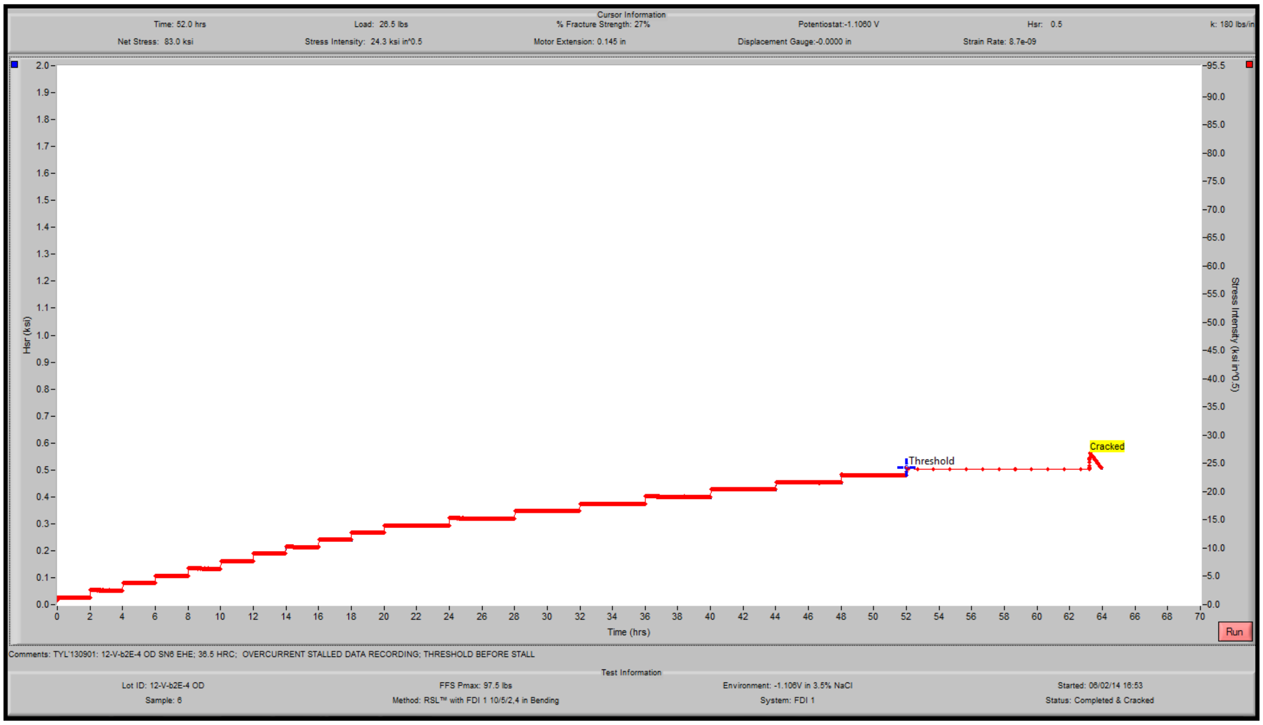


Figure J.6-7: Rod 12-V-B2E-4 OD 6, Graphical EHE Results

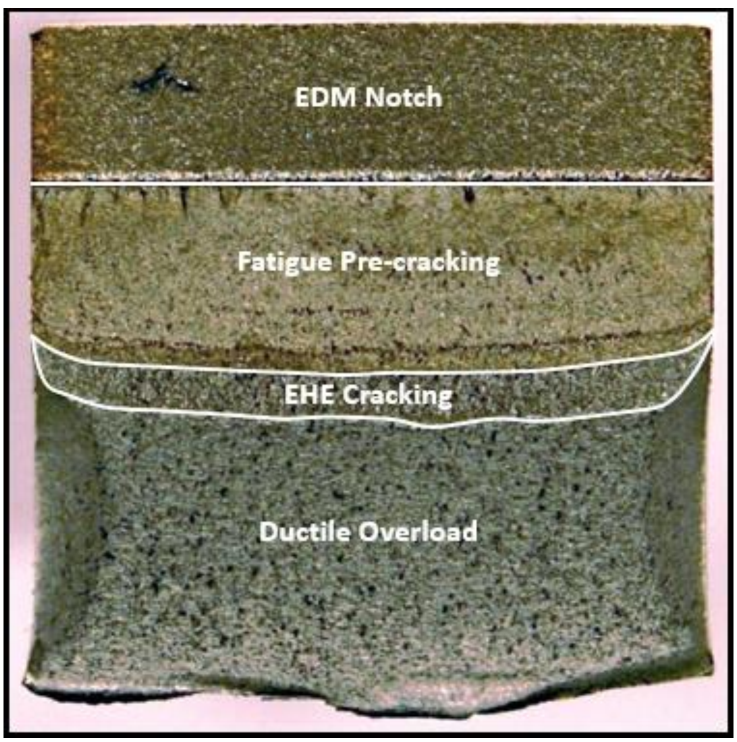


Figure J.6-8: Fracture Face of Rod 12-V-B2E-4 OD 6, EHE

J.6.5 MR 1, FFS:

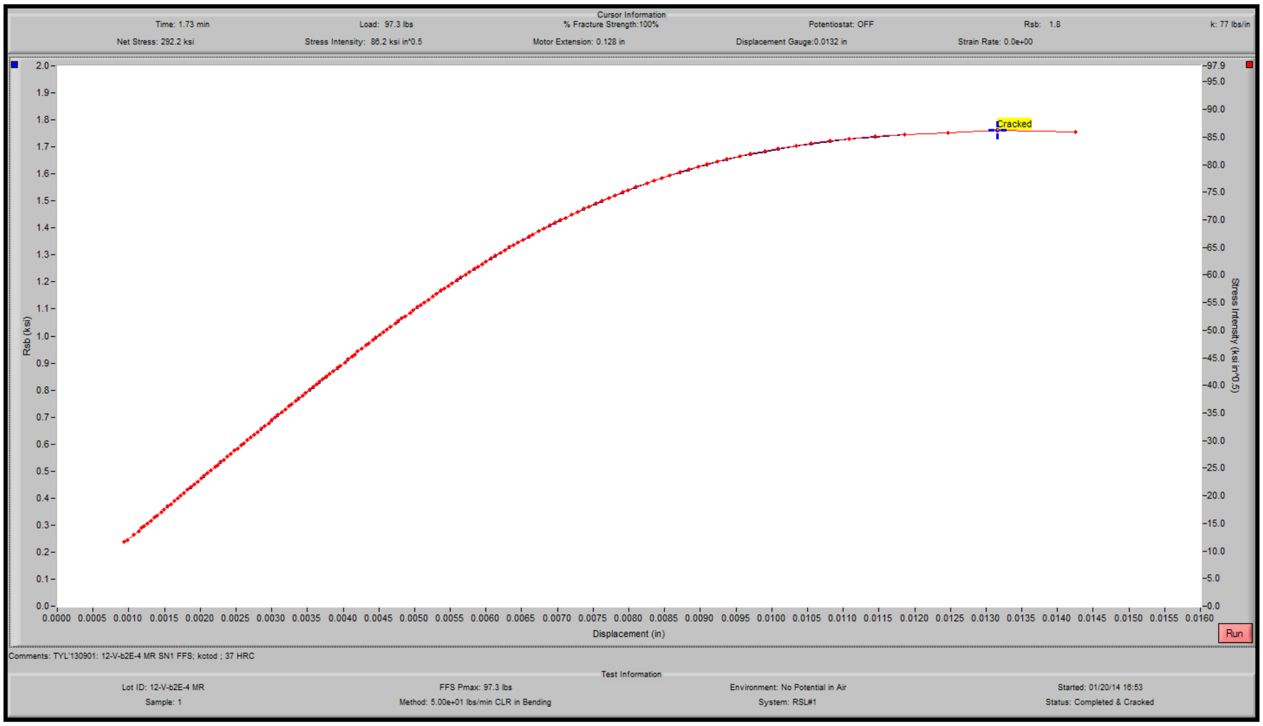


Figure J.6-9: Rod 12-V-B2E-4 MR 1, Graphical FFS Results

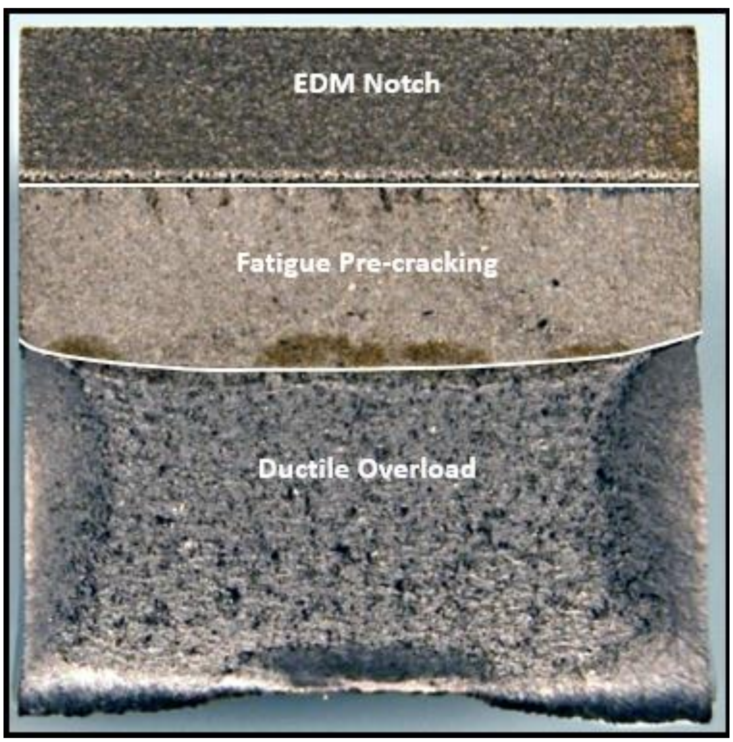


Figure J.6-10: Fracture Face of Rod 12-V-B2E-4 MR 1, FFS

J.6.6 MR 2, IHE:

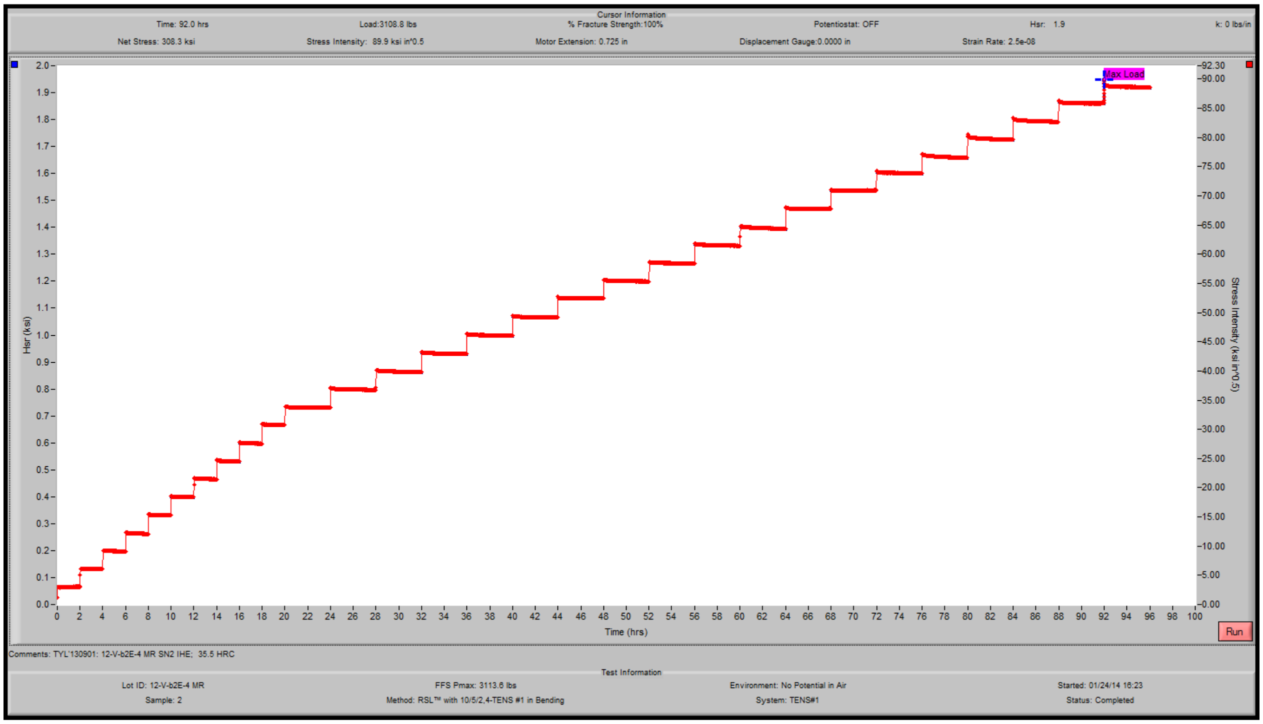


Figure J.6-11: Rod 12-V-B2E-4 MR 2, Graphical IHE Results

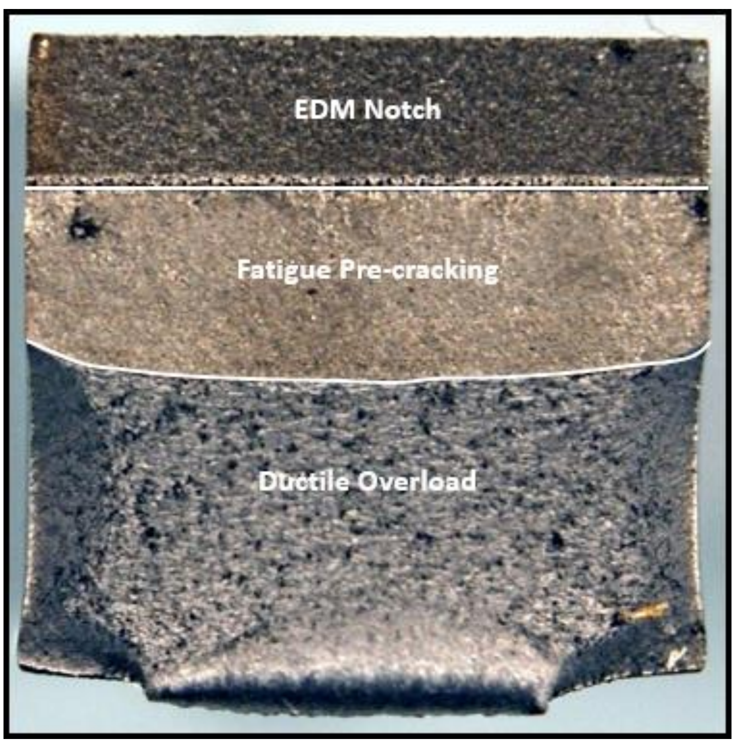


Figure J.6-12: Fracture Face of Rod 12-V-B2E-4 MR 2, IHE

J.6.7 MR 3, EHE:

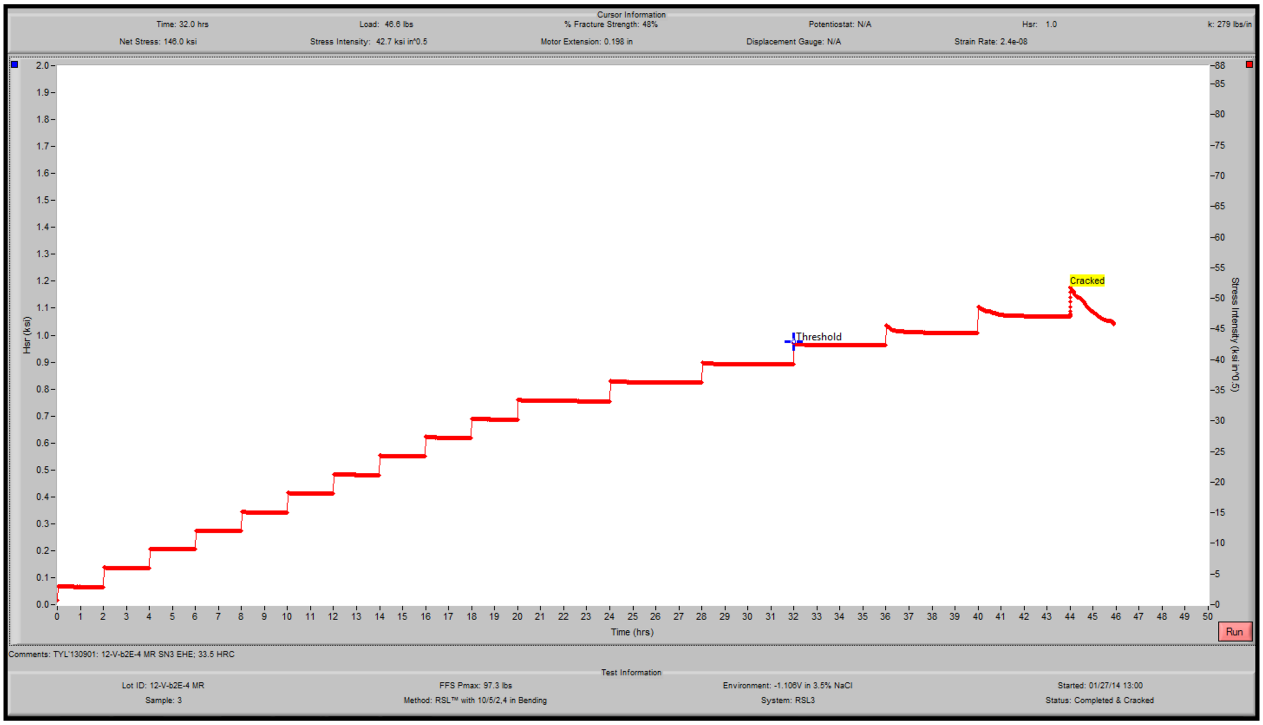


Figure J.6-13: Rod 12-V-B2E-4 MR 3, Graphical EHE Results

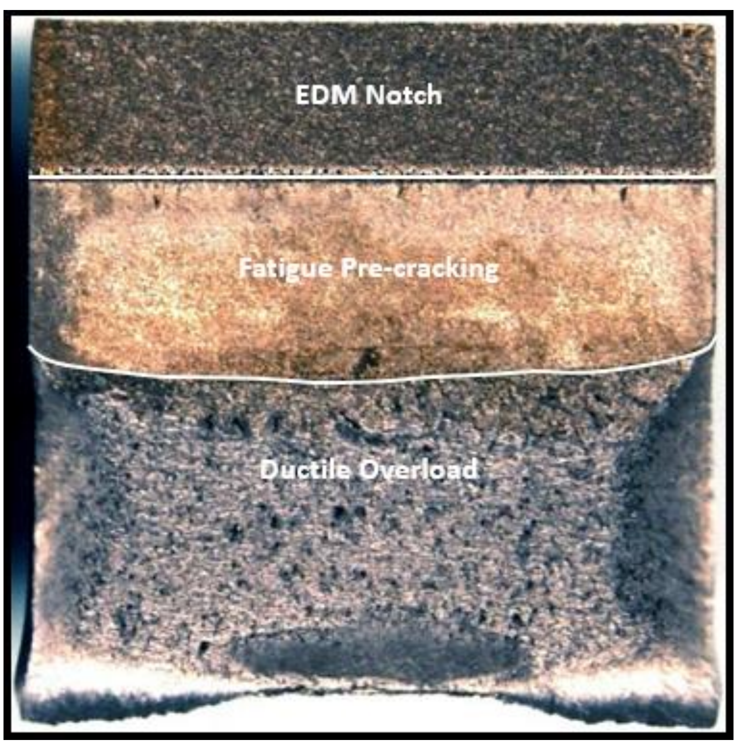


Figure J.6-14: Fracture Face of Rod 12-V-B2E-4 MR 3, EHE

J.6.8 MR 4, EHE:

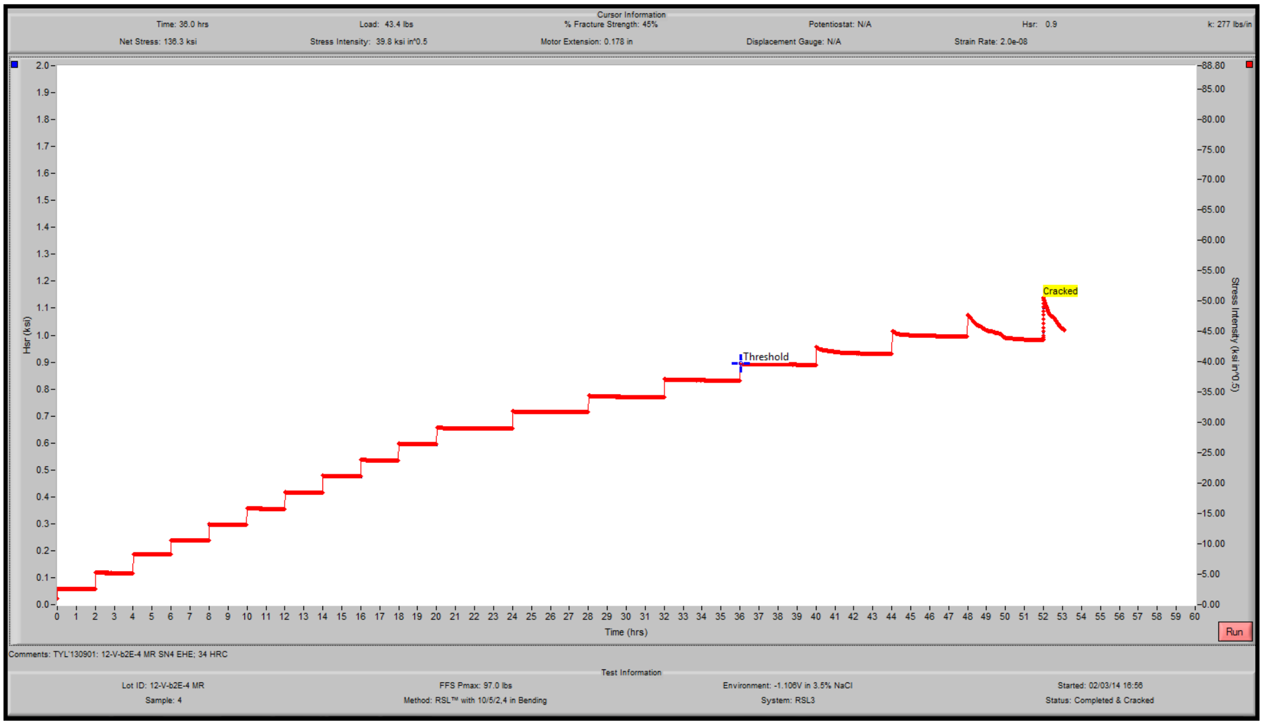


Figure J.6-15: Rod 12-V-B2E-4 MR 4, Graphical EHE Results

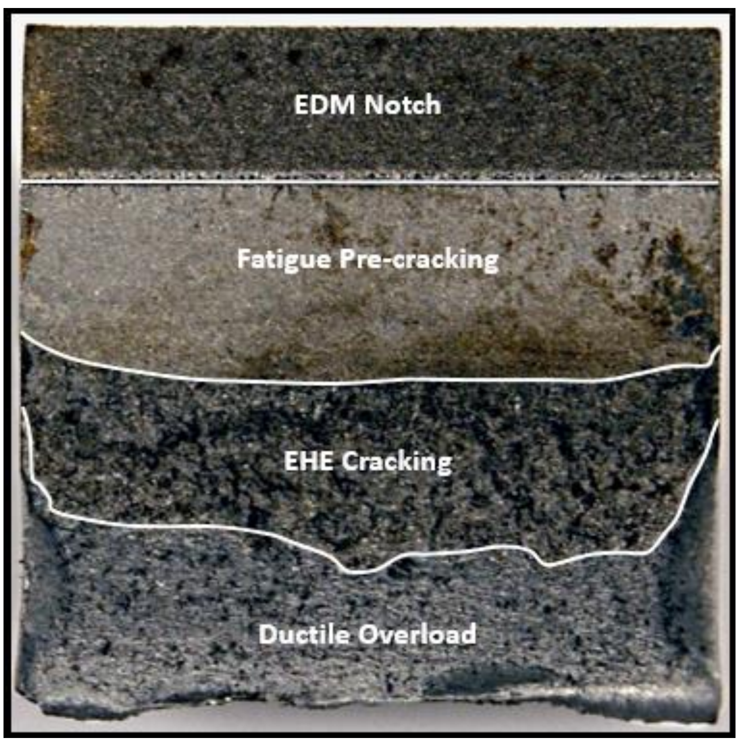


Figure J.6-16: Fracture Face of Rod 12-V-B2E-4 MR 4, EHE

J.6.9 Center 1, FFS:

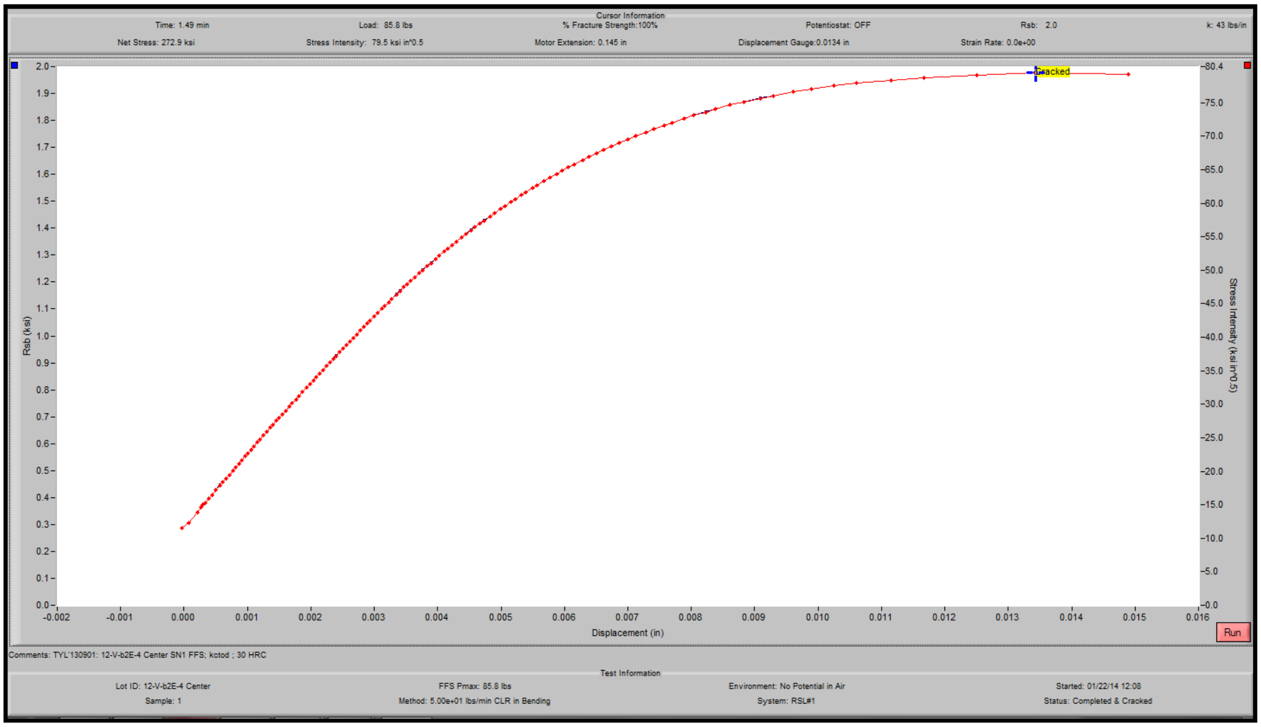


Figure J.6-17: Rod 12-V-B2E-4 Center 1, Graphical FFS Results

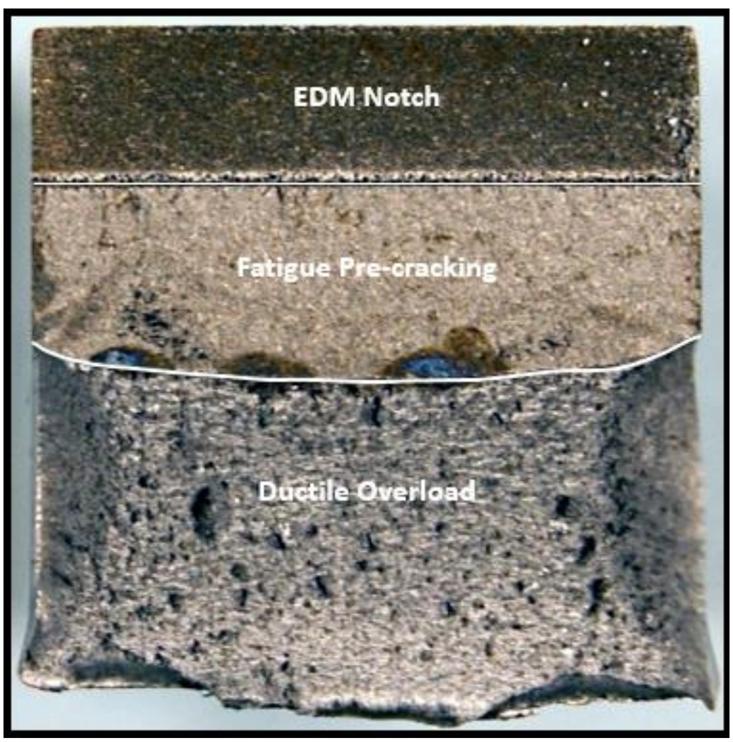


Figure J.6-18: Fracture Face of Rod 12-V-B2E-4 Center 1, FFS

J.7 Threaded Specimen Test Results

J.7.1 Thd 1, FFS:

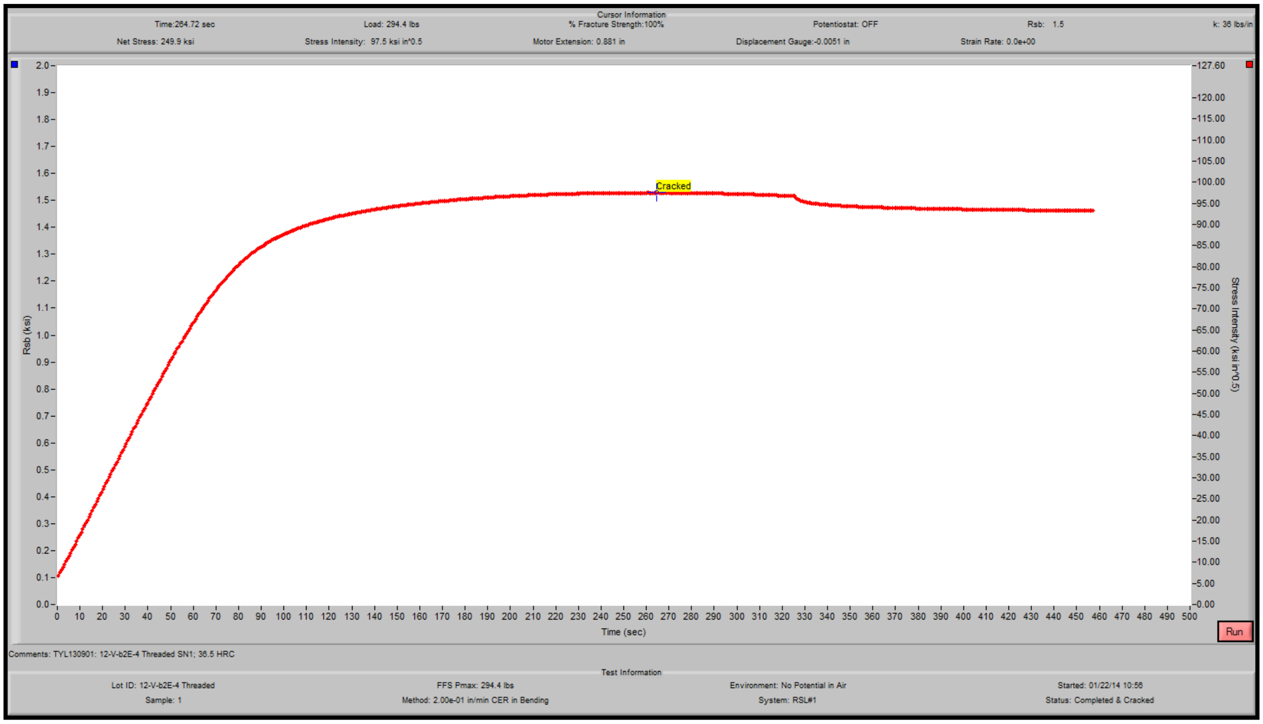


Figure J.7-1: Rod 12-V-B2E-4 Thd 1, Graphical FFS Results

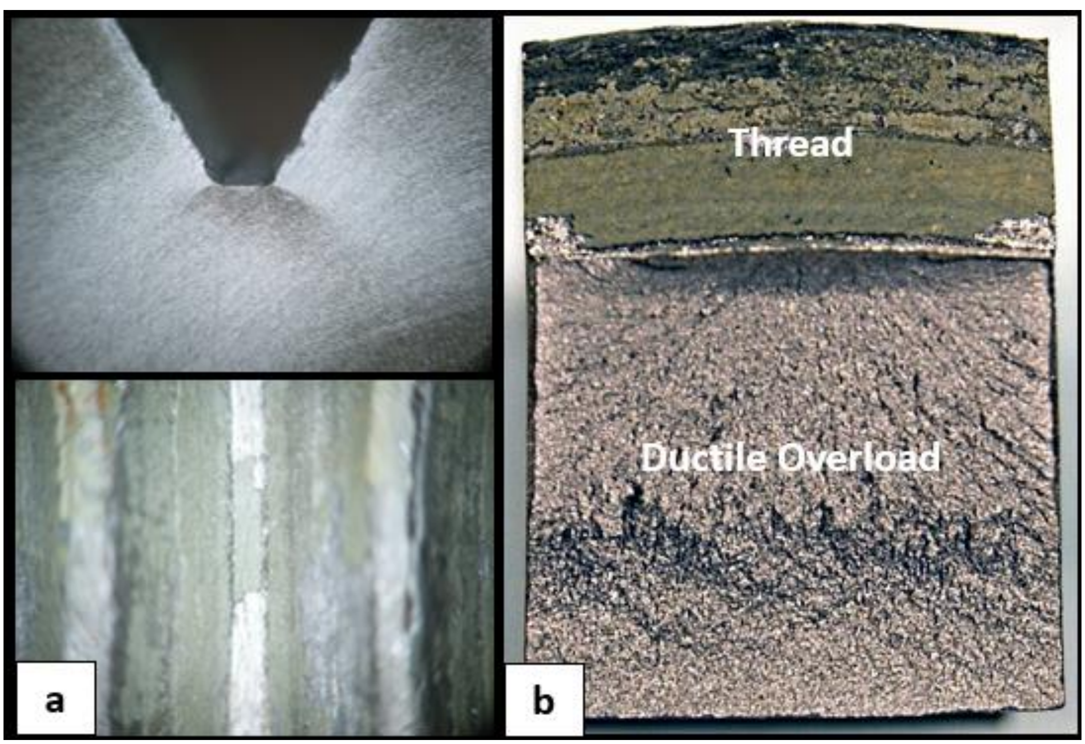


Figure J.7-2: Rod 12-V-B2E-4 Thd 1 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

J.7.2 Thd 2, IHE:

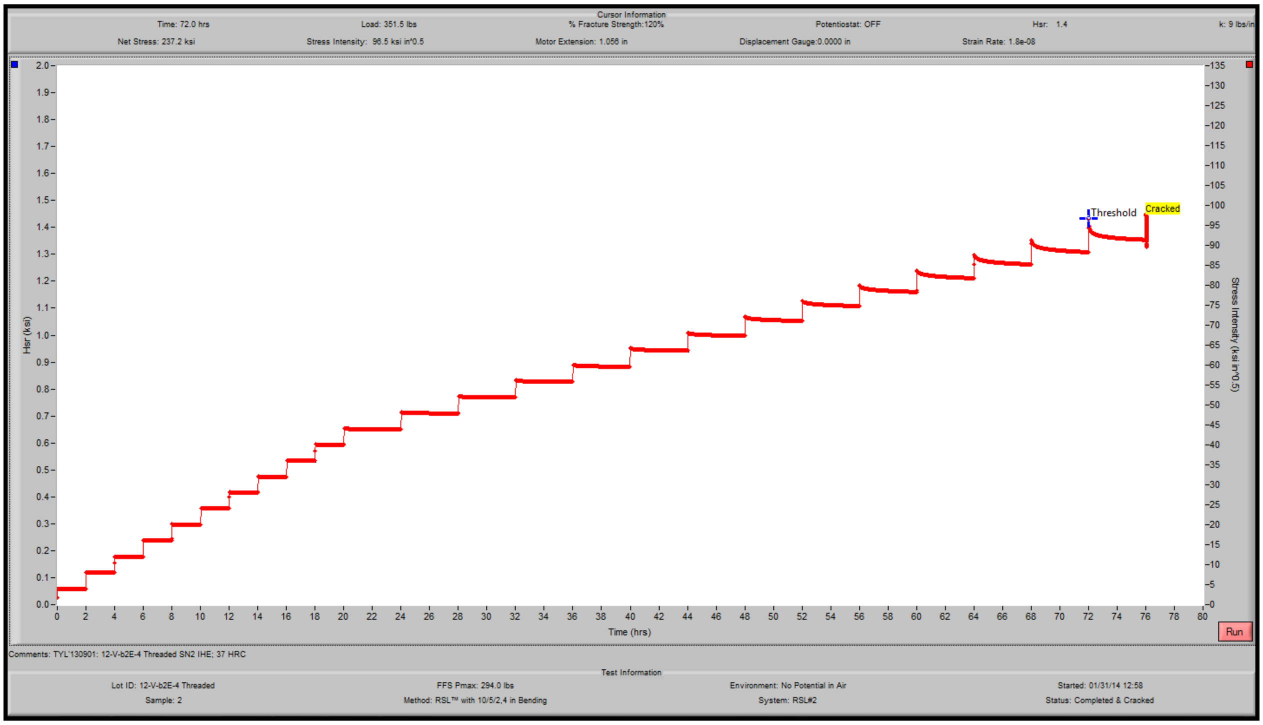


Figure J.7-3: Rod 12-V-B2E-4 Thd 2, Graphical IHE Results

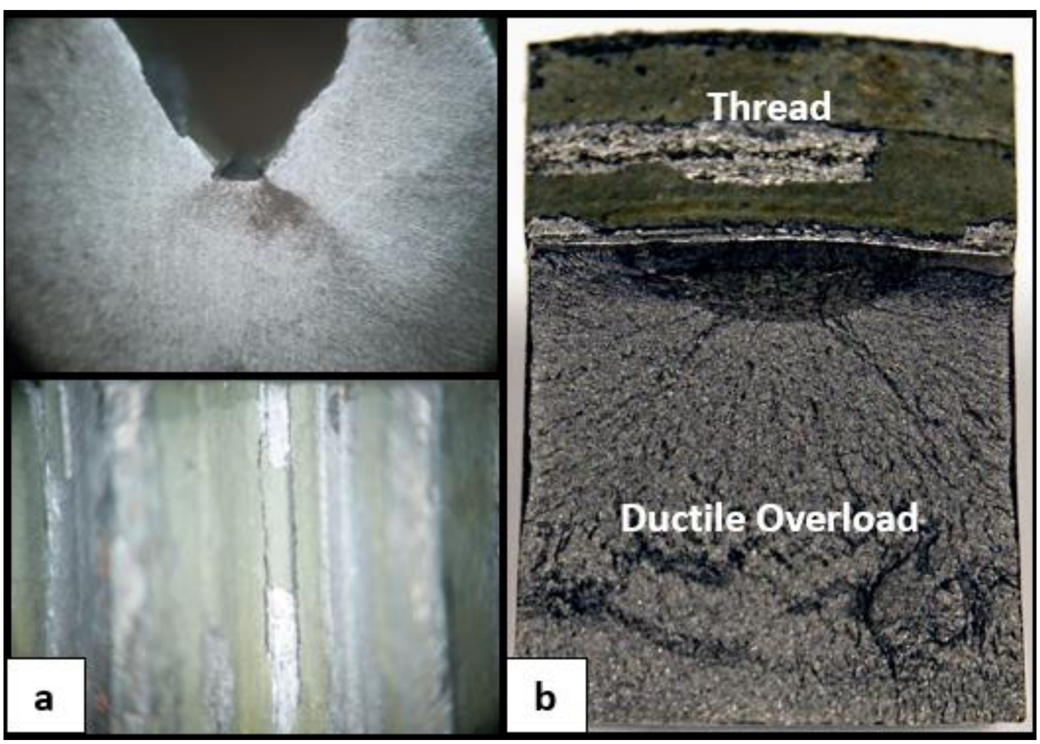


Figure J.7-4: Rod 12-V-B2E-4 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

J.7.3 Thd 3, EHE:

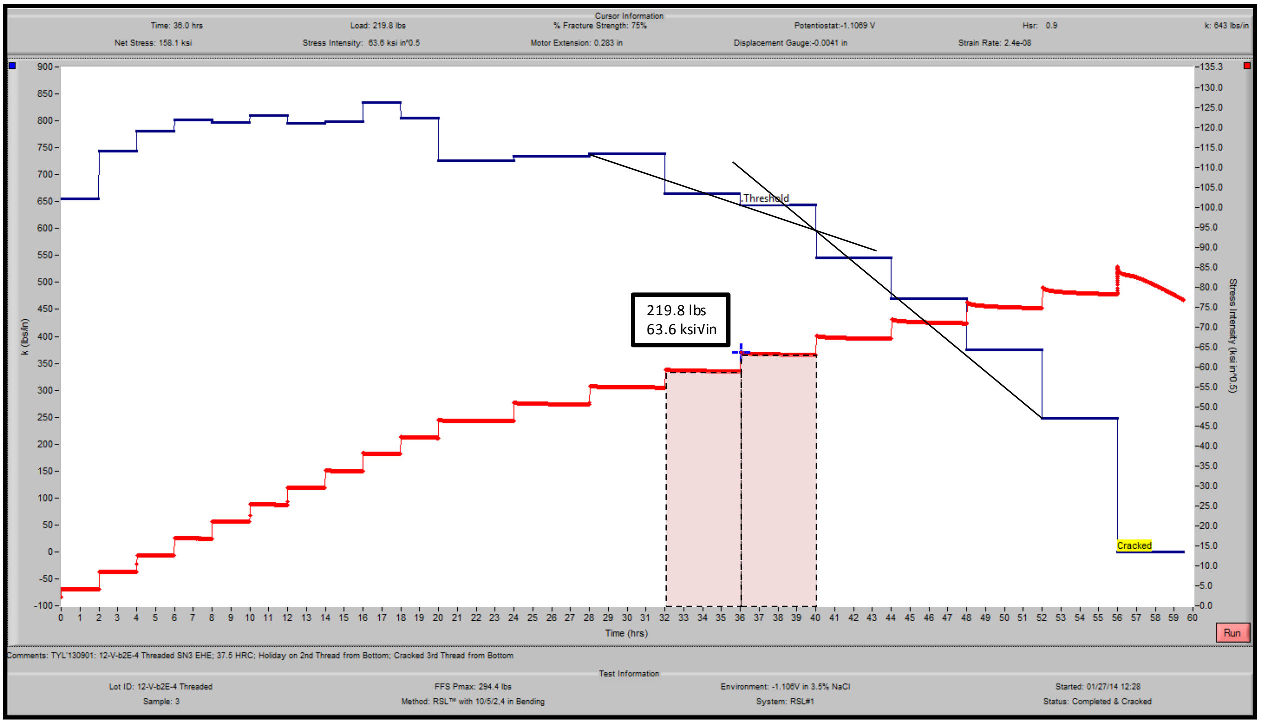


Figure J.7-5: Rod 12-V-B2E-4 Thd 3 Graphical EHE Results

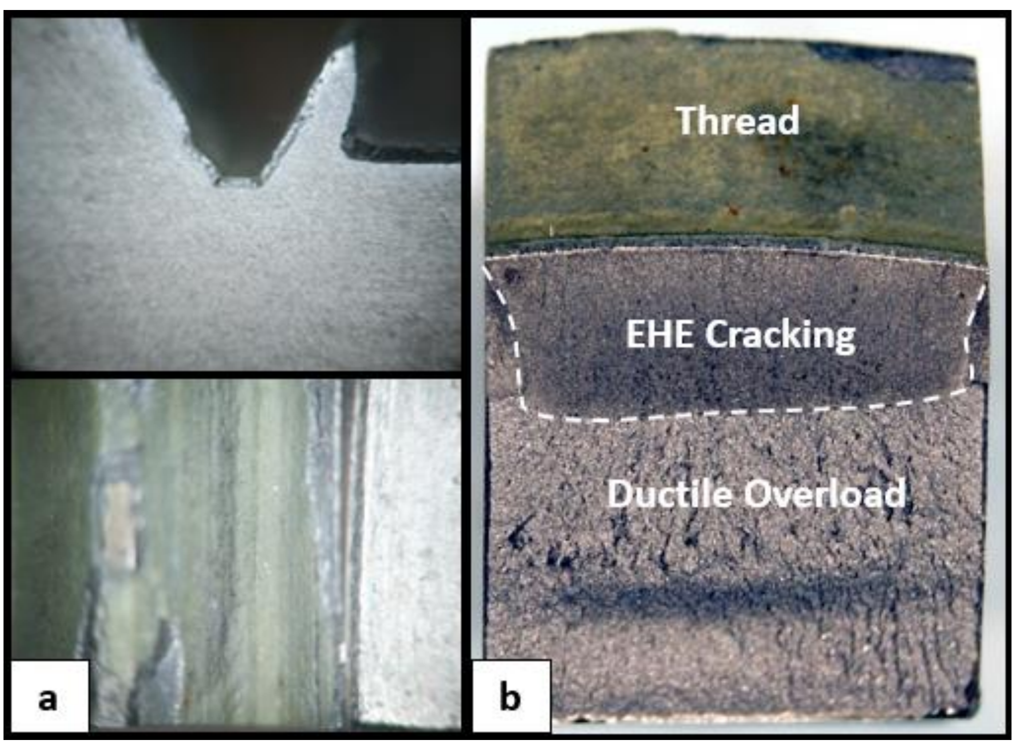
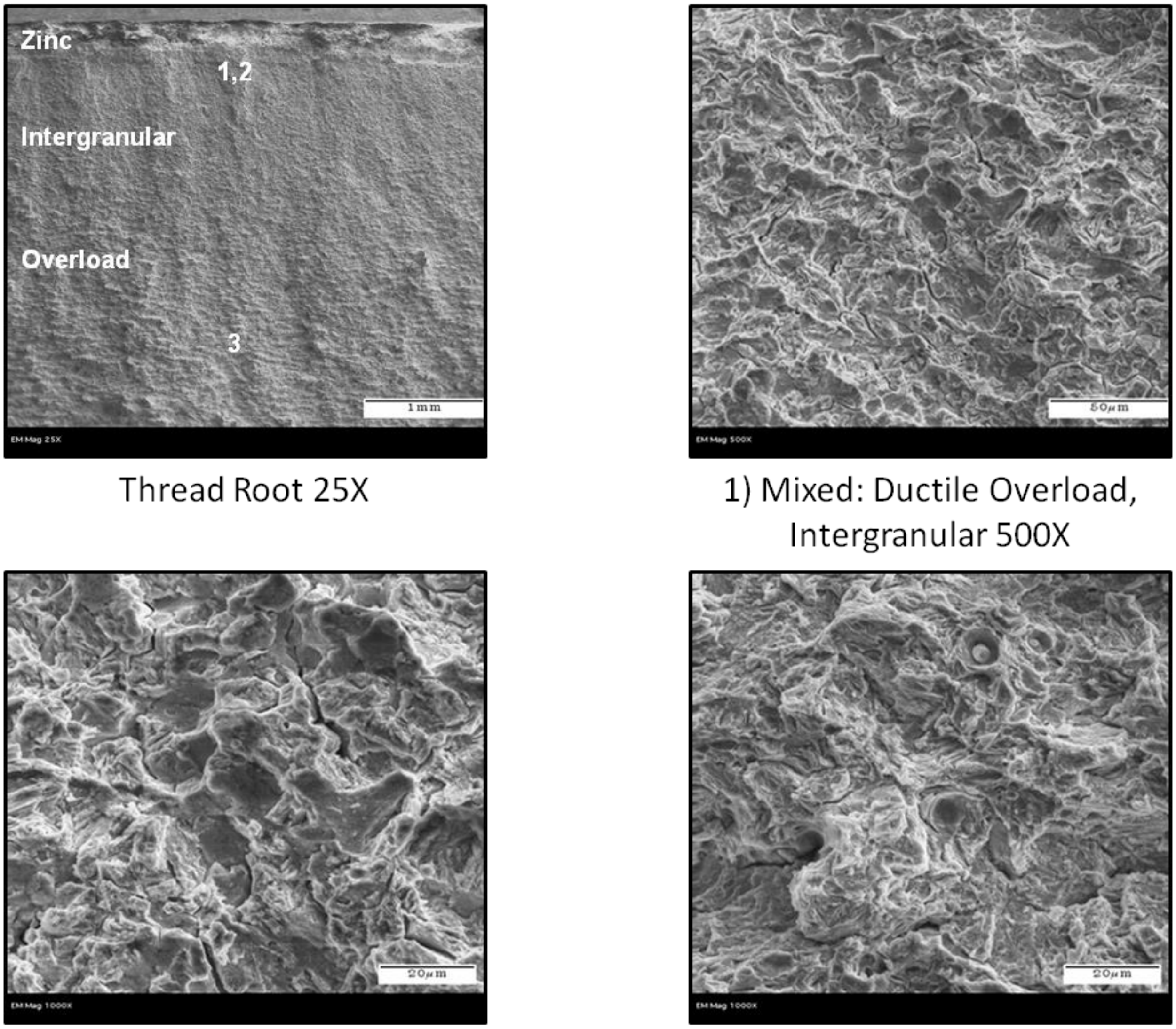


Figure J.7-6: Rod 12-V-B2E-4 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure J.7-7: SEM of Rod 12-V-B2E-4 Thd 3, EHE



Thread Root 25X

1) Mixed: Ductile Overload, Intergranular 500X

2) Mixed: Ductile Overload, Intergranular 1000X

3) Ductile Overload 1000X

J.7.4 Thd 4, EHE:

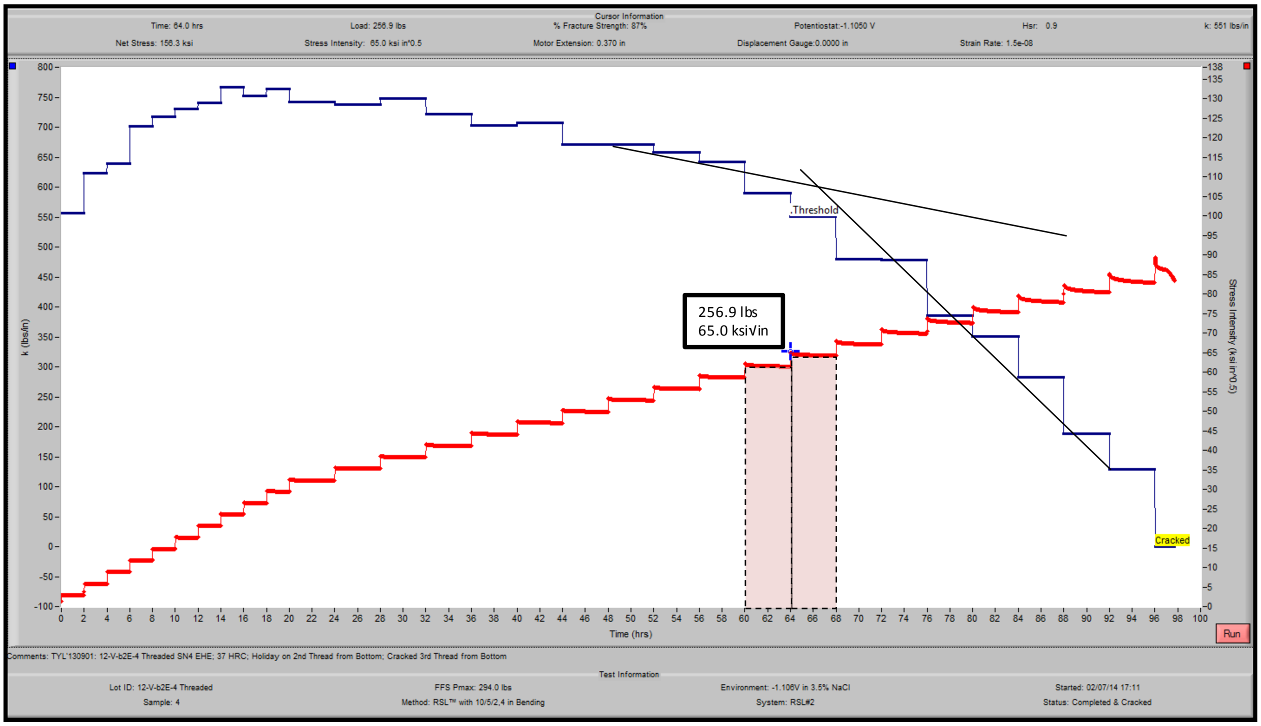


Figure J.7-8: Rod 12-V-B2E-4 Thd 4 Graphical EHE Results

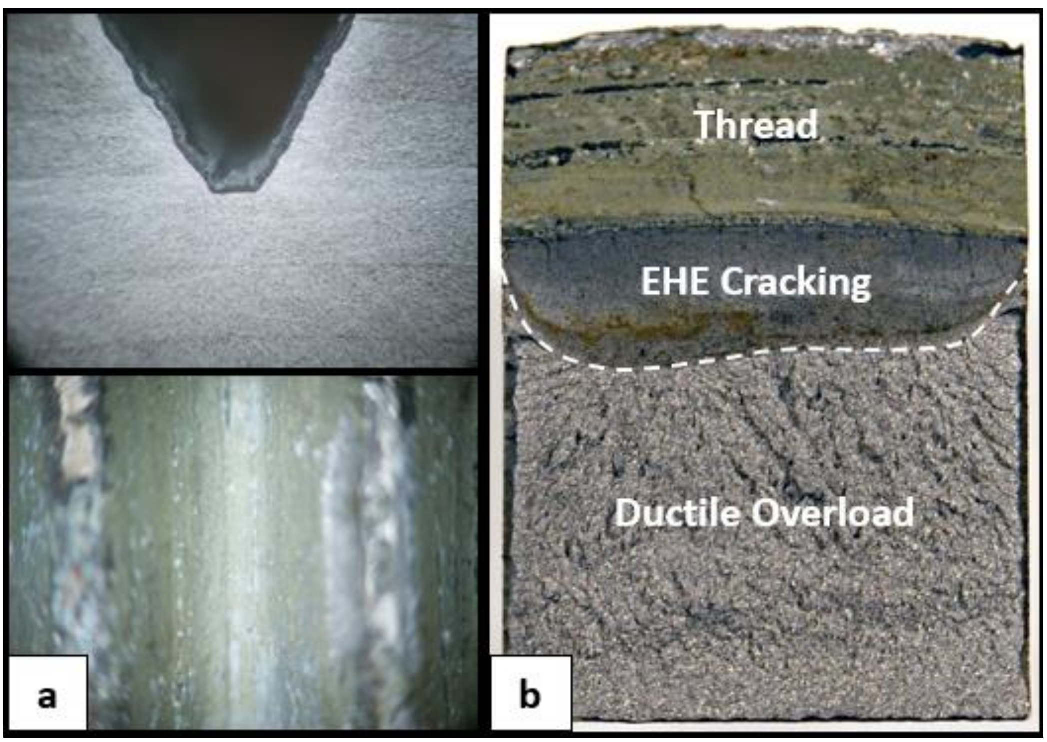
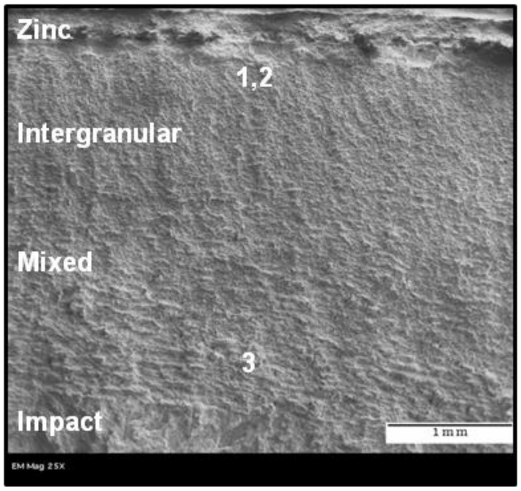
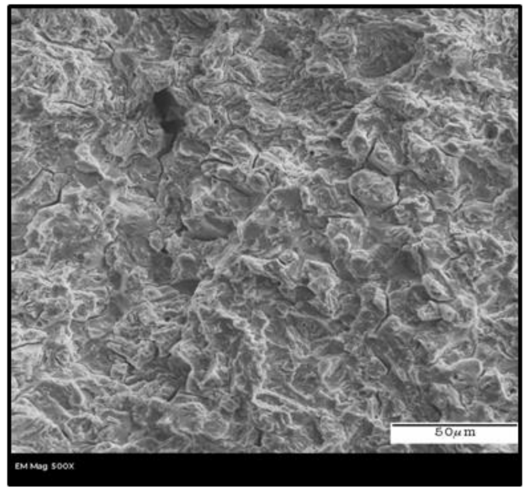


Figure J.7-9: Rod 12-V-B2E-4 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

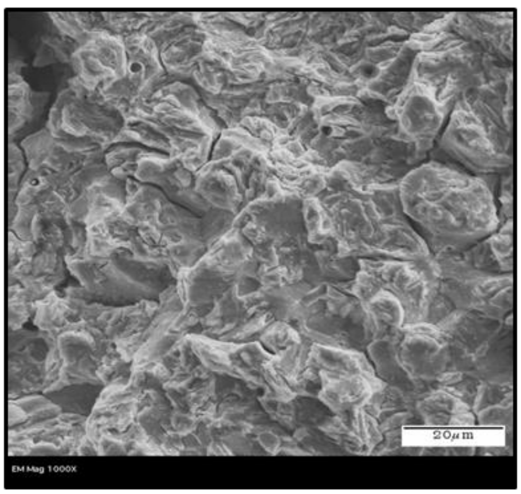
Figure J.7-10: SEM of Rod 12-V-B2E-4 Thd 4, EHE



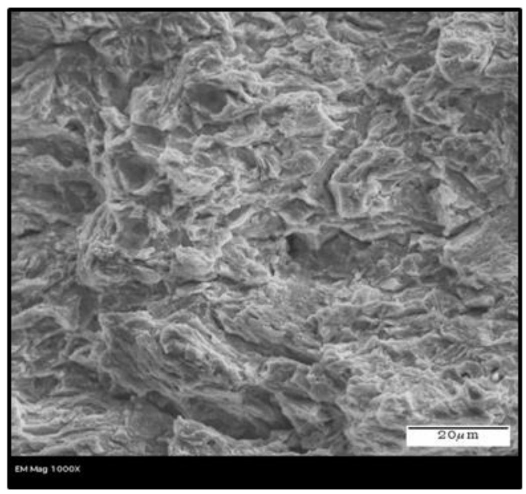
Thread Root 25X



1) Mixed: Ductile Overload, Intergranular 500X



2) Mixed: Ductile Overload, Intergranular 1000X



3) Mixed: Ductile Overload, Intergranular 1000X

Appendix K: Rod 12-V-E109

K.1 Description of Sample

Rod 12-V-E109 was a Tower Anchorage Anchor Bolt located at the bottom of the tower from the same group of material that was tested in Test Rig 6 in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. The bolts are 3 inches in diameter with machined threads. The segment from this section of the rod provided to LRA is shown in **Figure K.1-1**.

Figure K.1-1: Tower Anchorage Anchor Bolt (Bottom), Rod 12-V-E109

K.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 12-V-E109 and can be seen versus time in **Figure K**.2-1. The final OCP recorded for Rod 12-V-E109 was Vsce=-0.887 V.

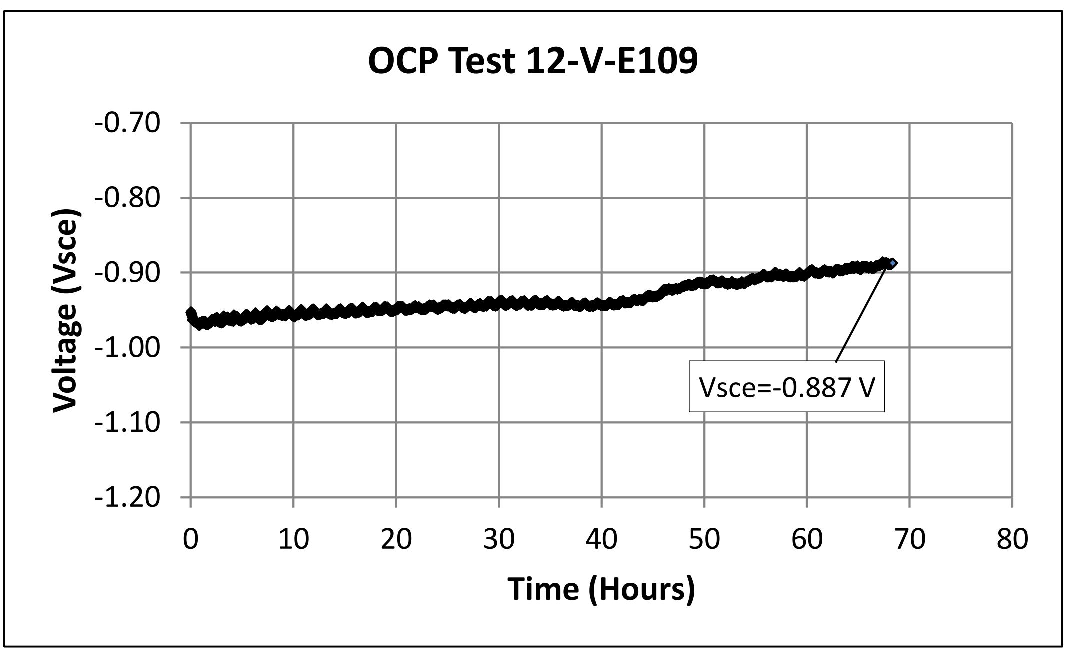


Figure K.2-1: Open Circuit Potential for Rod 12-V-E109

K.3 Hardness

The hardness data and profile for sample 12-V-E109 are shown in **Table K.3-1** and **Figure K.3-1**.

Table K.3-1: Hardness Data of Rod 12-V-E109 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	31.5	31.5
MR 1, FFS	37.0	36.5
MR 2, IHE	35.5	
MR 3, EHE	37.5	
MR 5, EHE	36.0	
OD 1, FFS	38.0	37.9
OD 2, IHE	38.0	
OD 3, EHE	38.5	
OD 5, EHE	38.0	
Thd 1, FFS	38.0	
Thd 3, EHE	37.5	
Thd 5, EHE	37.5	

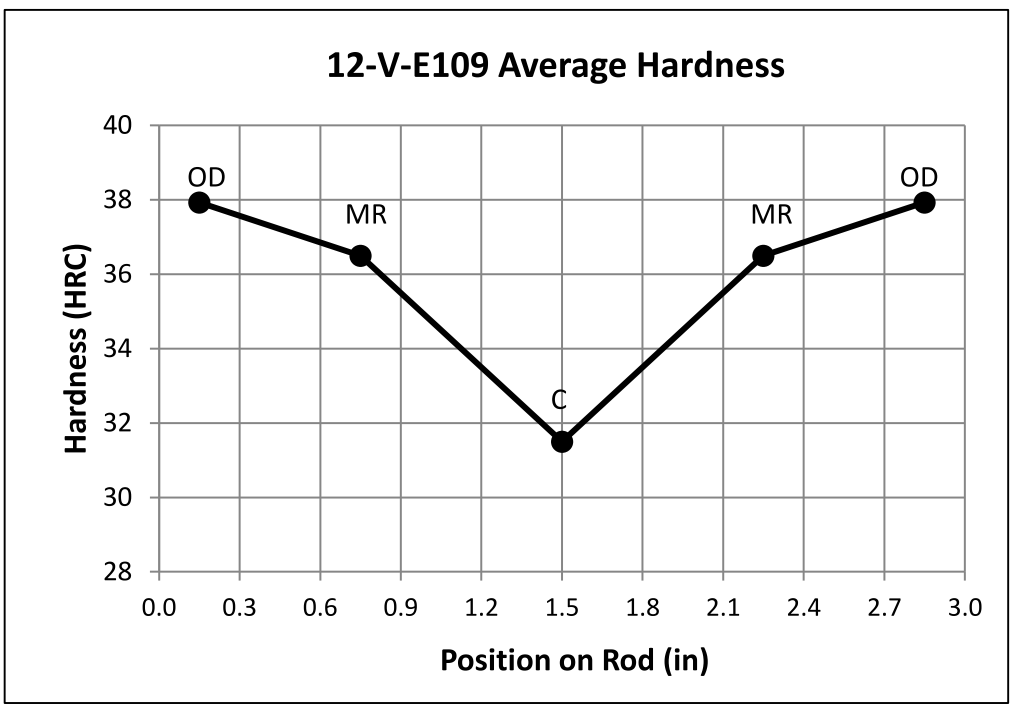


Figure K.3-1: Hardness Profile of Rod 12-V-E109

K.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following “checker board” tables.

K.4.1 Fatigue Pre-crack Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 12-V-E109						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts) **Comments**: Machined Threads; Same Group as Test Rig #6 in Test IV				
Rod#:	**12-V-E109**					
Product Form:	**1e**					
Rod OD:	**3"**					
Fatigue Pre-cracked	**Sample #/ID**	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
	OD 1, FFS	**38.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	92.1 0.54 1.04 7900		
	OD 2, IHE	**38.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		89.8 0.52 1.01 2.5	
	OD 3, EHE	**38.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			21.5 0.12 0.24 4.8
	OD 5, EHE	**38.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			19.2 0.11 0.22 1.0
	MR 1, FFS	**37.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	86.2 0.52 0.97 7500		

Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 12-V-E109

LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts)
Rod#:	**12-V-E109**	
Product Form:	**1e**	**Comments**: Machined Threads; Same Group as Test Rig #6 in Test IV
Rod OD:	**3"**	

Fatigue Pre-cracked	**MR 2, IHE**	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)		86.6 0.54 0.98 2.5	
	MR 3, EHE	**37.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			24.3 0.14 0.27 4.1
	MR 5, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			27.6 0.17 0.31 1.3
	Center 1, FFS	**31.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	82.1 0.57 0.93 8200		

K.4.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 12-V-E109						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts)				
Rod#:	**12-V-E109**					
Product Form:	**1e**	**Comments**: Machined Threads; Same Group as Test Rig #6 in Test IV				
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**38.0**	Pmax* (lbs)	307.6		
			Fu	1.01		
			Rsb	1.4		
			Strain Rate ($x10^{-8}$ in/in/sec)	1600		
	Thd 3, EHE	**37.5**	$P_{threshold}$* (lbs)			209.2
			Fu			0.69
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			2.3
	Thd 5, EHE	**37.5**	$P_{threshold}$* (lbs)			218.5
			Fu			0.72
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			1.1

K.4.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 12-V-E109
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**12-V-E109**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{SCC}, $KI_{P\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	38.0	172	105.3	105.3	105.3	100.0%	92.1	0.54	311.5	1.8	7900	0.2097	157.5	50 lbs/min		1.04	
	OD 2, IHE	Air	38.0	172	2240.0	3137.9	3137.9	97.5%	89.8	0.52	307.7	1.8	2.5	0.2144		10/5/2,4		1.01	
	OD 3, EHE	3.5% NaCl @ -1.106V	38.5	174	70.0	31.5	24.5	23.3%	21.5	0.12	72.7	0.4	4.8	0.2093		10/5/2,4		0.24	
	OD 5, EHE	3.5% NaCl @ -1.106V	38.0	172	31.0	26.4	21.6	20.8%	19.2	0.11	65.2	0.4	1	0.2108		10/5/2,4		0.22	
	MR 1, FFS	Air	37.0	167	99.5	99.5	99.5	100.0%	86.2	0.52	290.4	1.7	7500	0.2075	152.9	50 lbs/min		0.97	
	MR 2, IHE	Air	35.5	159	2208.0	3092.9	3092.9	100.5%	86.6	0.54	294.6	1.8	2.5	0.2119		10/5/2,4		0.98	
	MR 3, EHE	3.5% NaCl @ -1.106V	37.5	169	69.0	38.0	27.6	28.2%	24.3	0.14	82.4	0.5	4.1	0.2100		10/5/2,4		0.27	
	MR 5, EHE	3.5% NaCl @ -1.106V	36.0	162	34.0	34.0	28.8	32.0%	27.6	0.17	95.8	0.6	1.3	0.2207				0.31	
	Center 1, FFS	Air	31.5	143	91.2	91.2	91.2	100.0%	82.1	0.57	280.0	2.0	8200	0.2126	147.4	50 lbs/min		0.93	
Threaded	Thd 1, FFS	Air	38.0	172	320.3	320.3	320.3	100.0%	89.7	0.52	242.2	1.4	1600	N/A		0.2 in/min	307.6	1.01	
	Thd 3, EHE	3.5% NaCl @ -1.106V	37.5	169	272.0	299.3	215.7	68.0%	61.0	0.36	165.1	1.0	2.3	N/A		10/5/2,4	209.2	0.69	Did Crack In Holiday
	Thd 5, EHE	3.5% NaCl @ -1.106V	37.5	169	120.0	270.3	209.4	71.0%	63.7	0.38	171.8	1.0	1.1	N/A		10/5/2,4	218.5	0.72	Did Not Crack In Holiday

K.5 Fatigue Pre-cracked Specimen Test Results

K.5.1 OD 1, FFS:

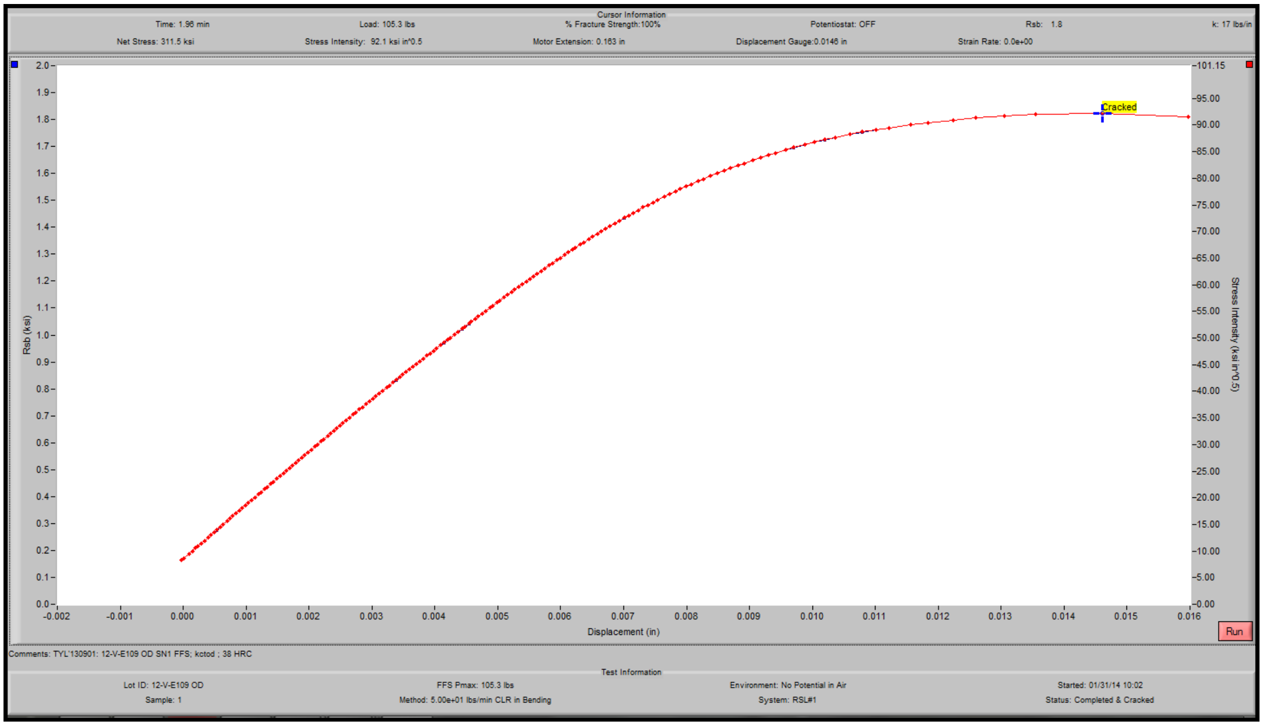


Figure K.5-1: Rod 12-V-E109 OD 1, Graphical FFS Results

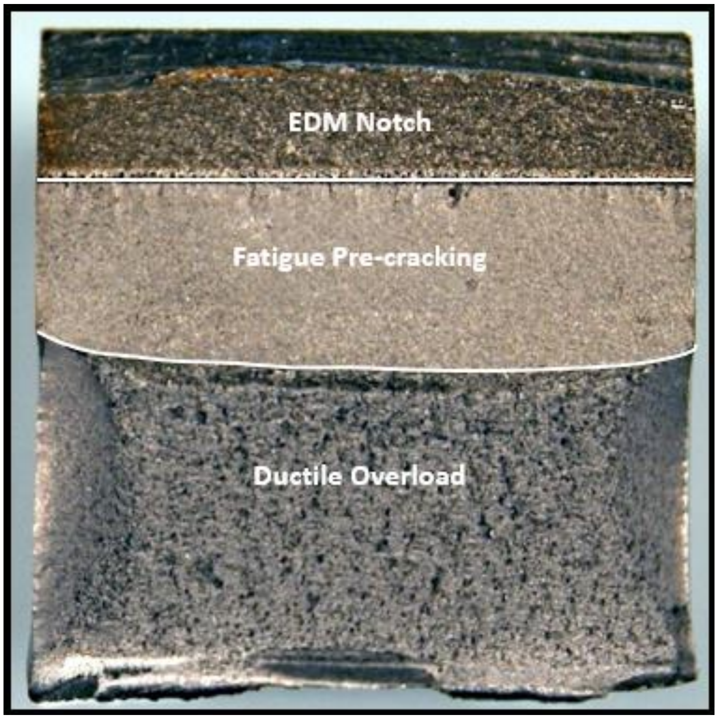


Figure K.5-2: Fracture Face of Rod 12-V-E109 OD 1, FFS

K.5.2 OD 2, IHE:

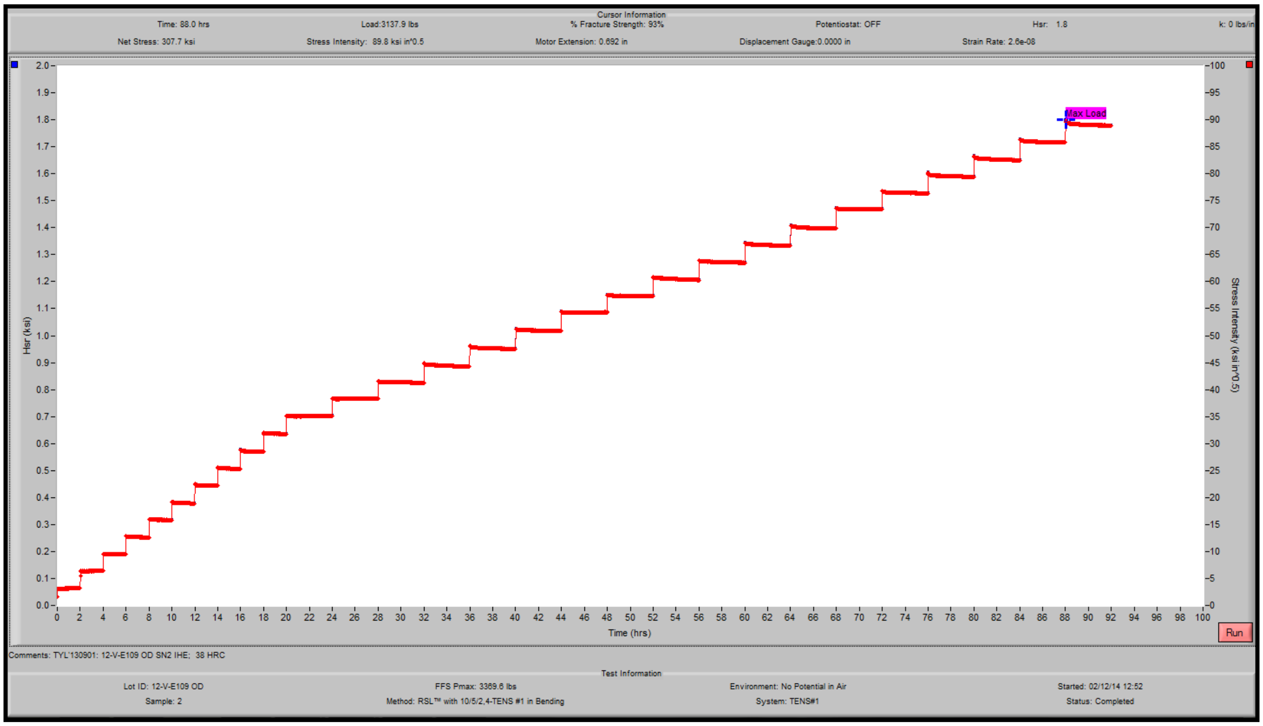


Figure K.5-3: Rod 12-V-E109 OD 2, Graphical IHE Results

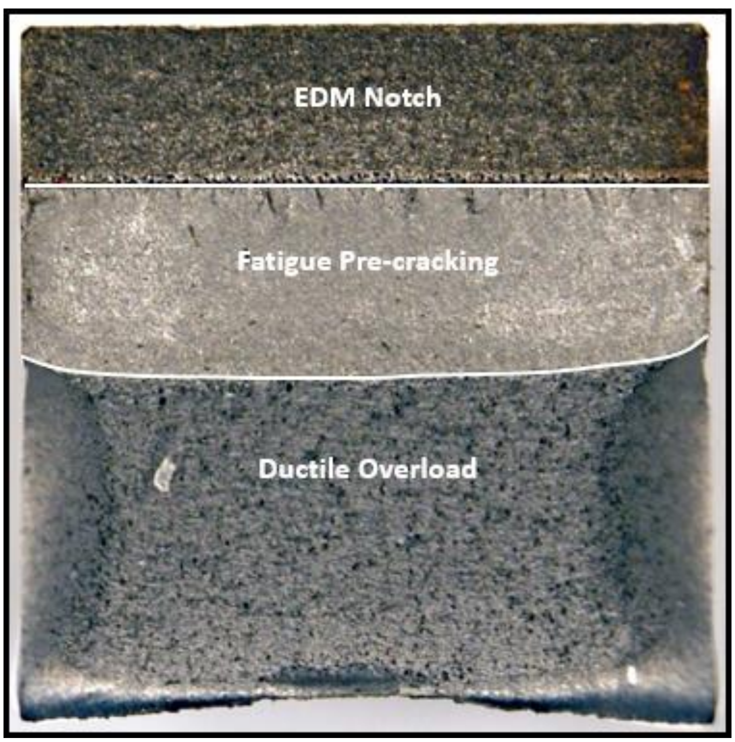


Figure K.5-4: Fracture Face of Rod 12-V-E109 OD 2, IHE

K.5.3 OD 3, EHE:

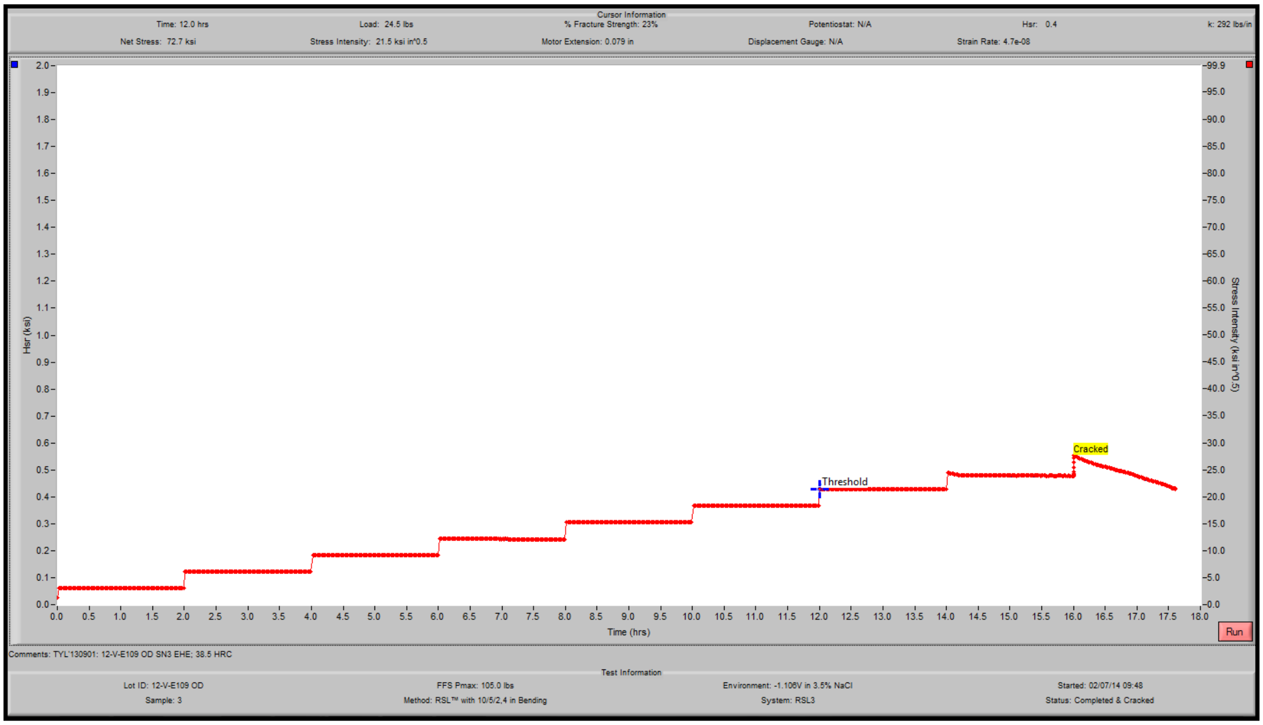


Figure K.5-5: Rod 12-V-E109 OD 3, Graphical EHE Results

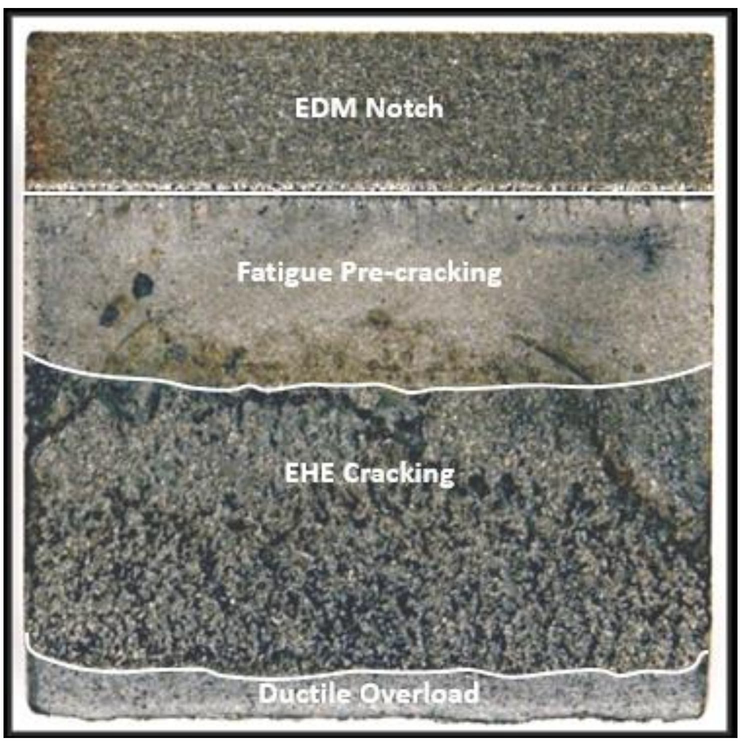


Figure K.5-6: Fracture Face of Rod 12-V-E109 OD 3, EHE

K.5.4 OD 5, EHE:

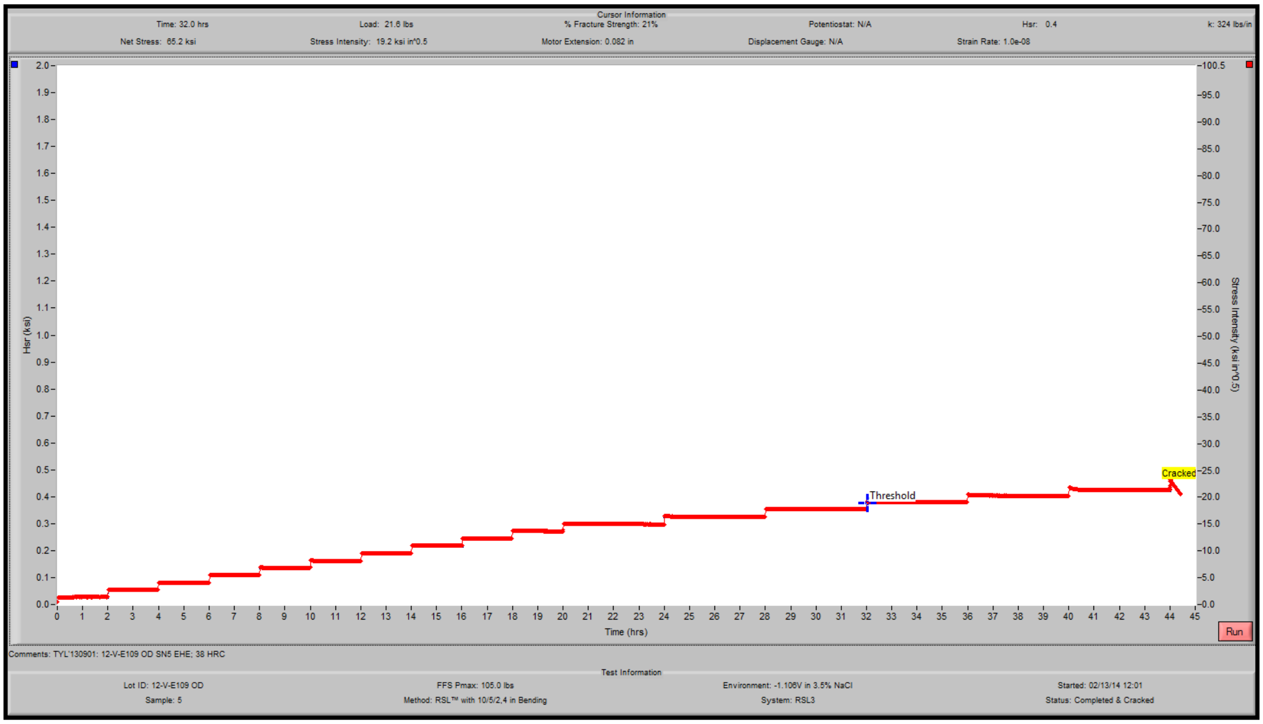


Figure K.5-7: Rod 12-V-E109 OD 5, Graphical EHE Results

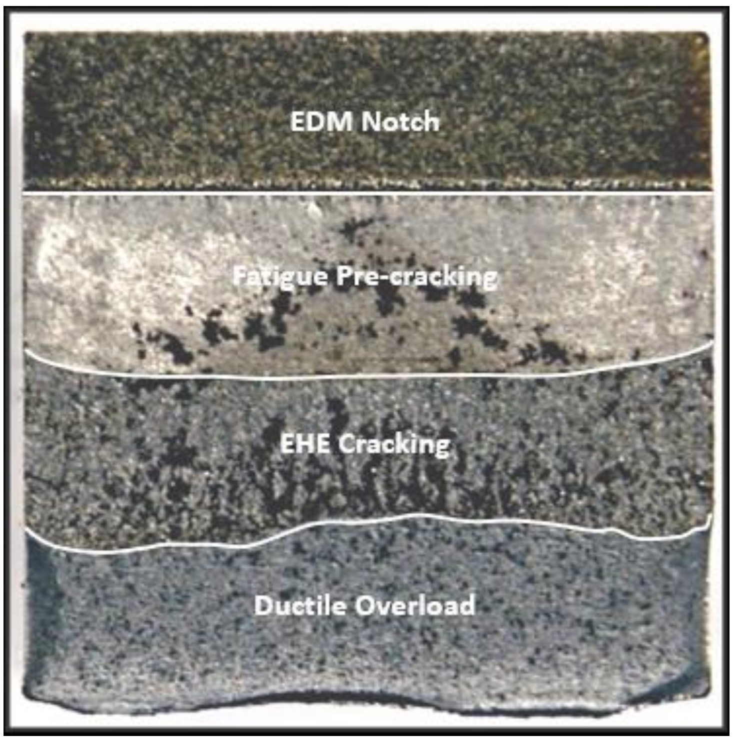


Figure K.5-8: Fracture Face of Rod 12-V-E109 OD 5, EHE

K.5.5 MR 1, FFS:

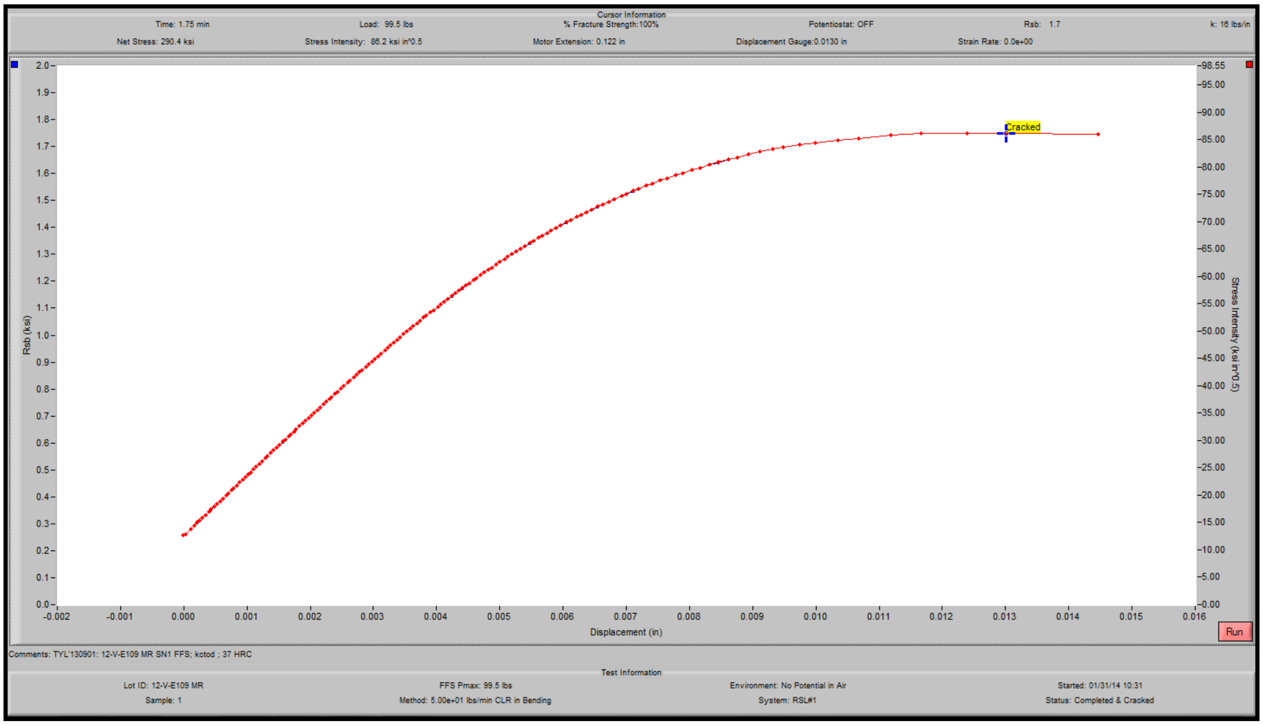


Figure K.5-9: Rod 12-V-E109 MR 1, Graphical FFS Results

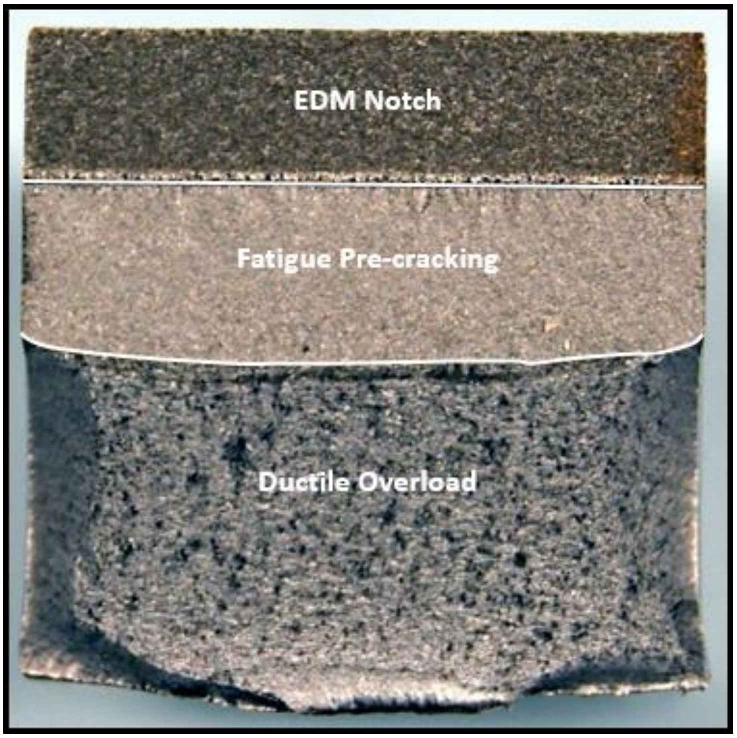


Figure K.5-10: Fracture Face of Rod 12-V-E109 MR 1, FFS

K.5.6 MR 2, IHE:

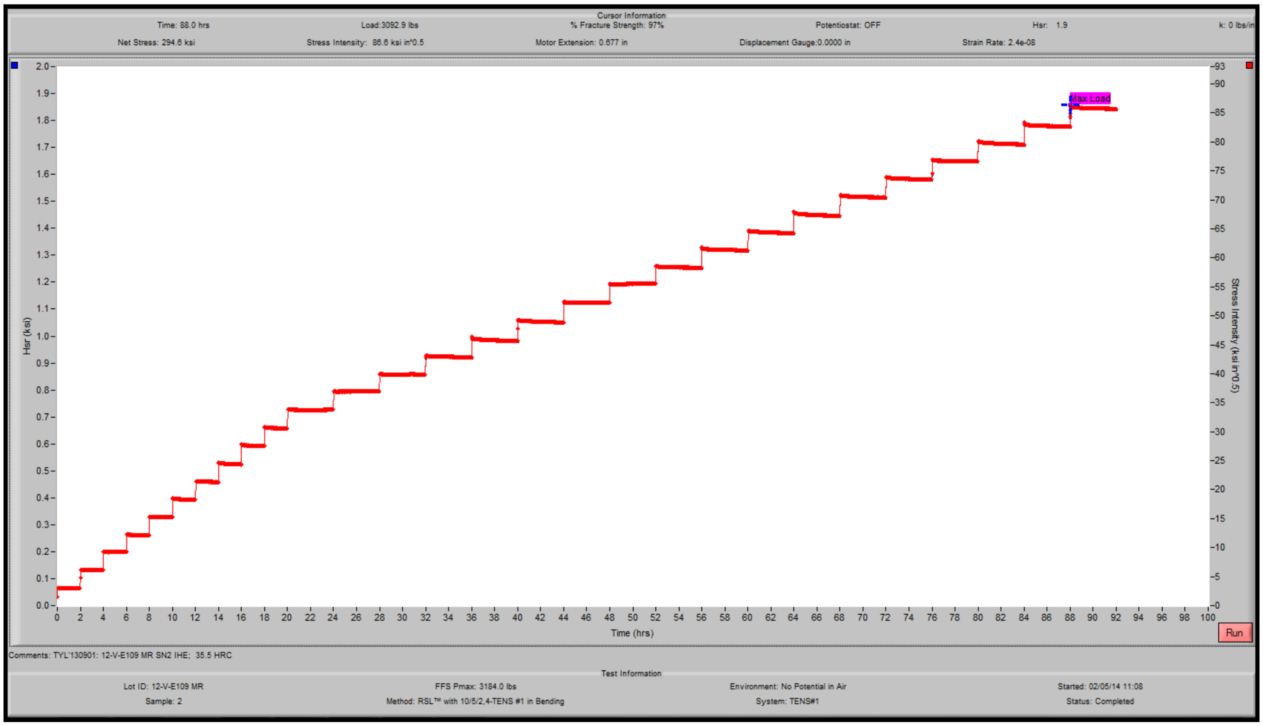


Figure K.5-11: Rod 12-V-E109 MR 2, Graphical IHE Results

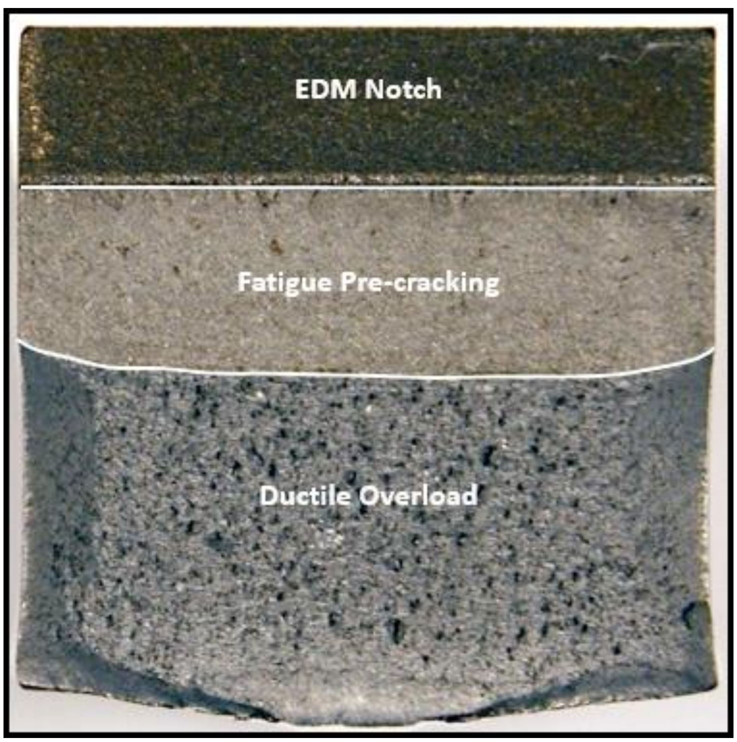


Figure K.5-12: Fracture Face of Rod 12-V-E109 MR 2, IHE

K.5.7 MR 3, EHE:

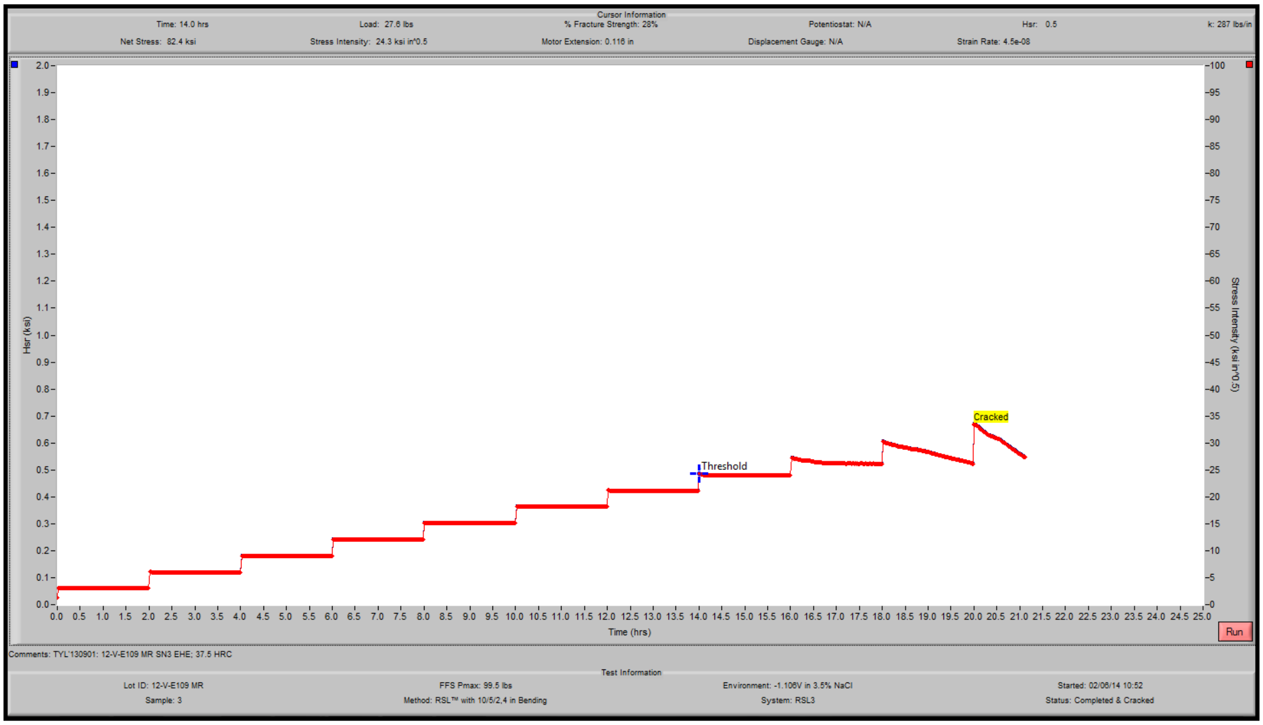


Figure K.5-13: Rod 12-V-E109 MR 3, Graphical EHE Results

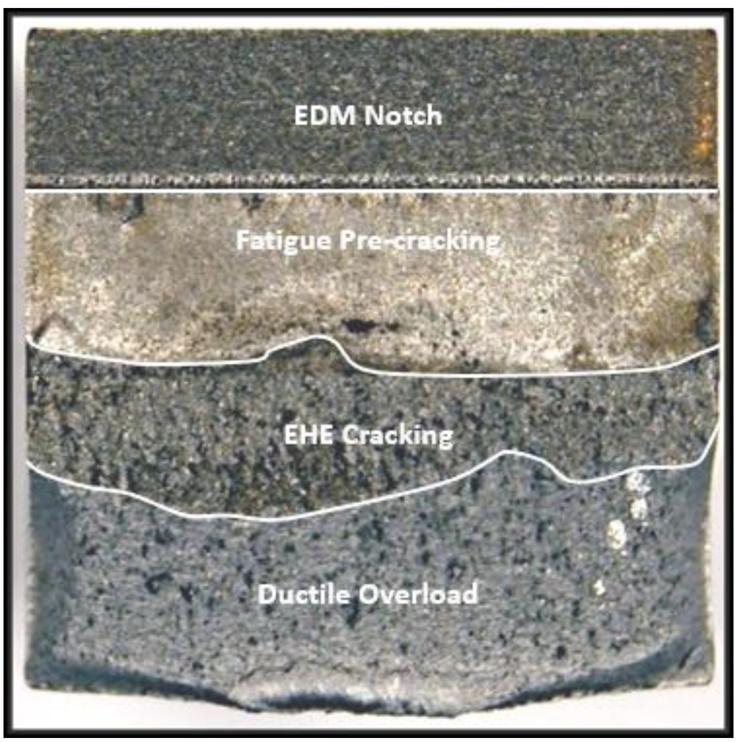


Figure K.5-14: Fracture Face of Rod 12-V-E109 MR 3, EHE

K.5.8 MR 5, EHE:

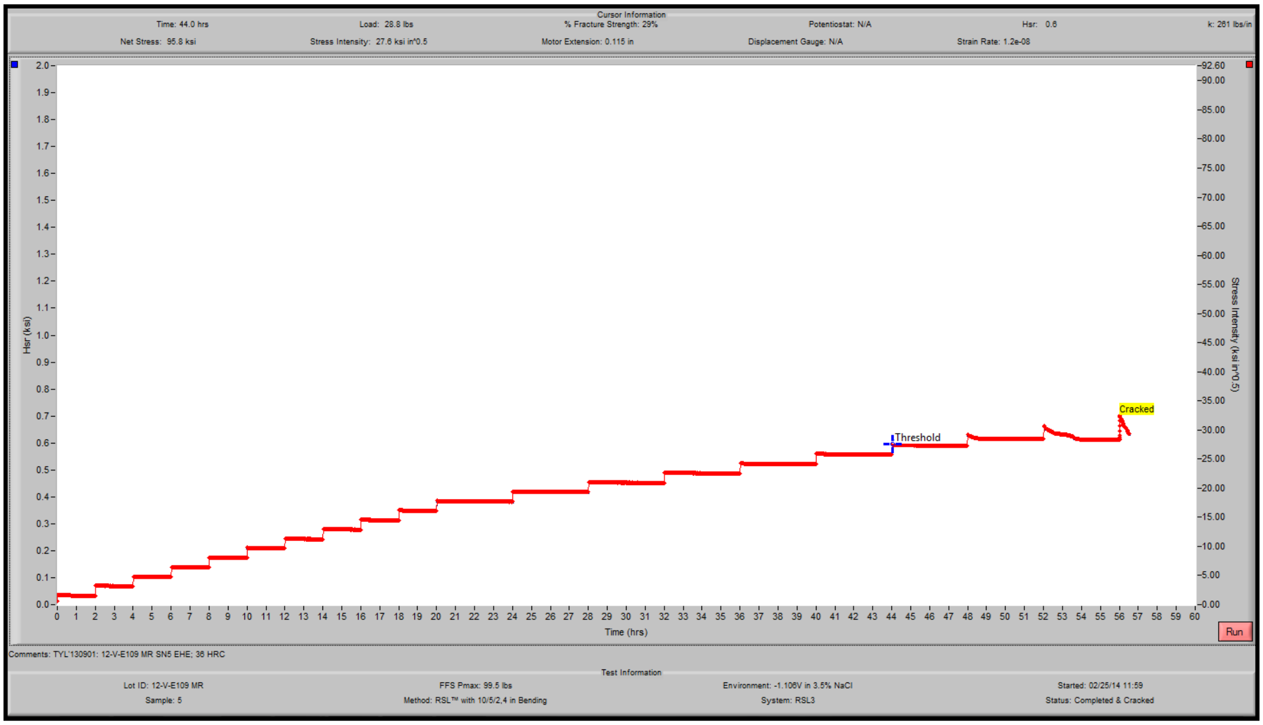


Figure K.5-15: Rod 12-V-E109 MR 5, Graphical EHE Results

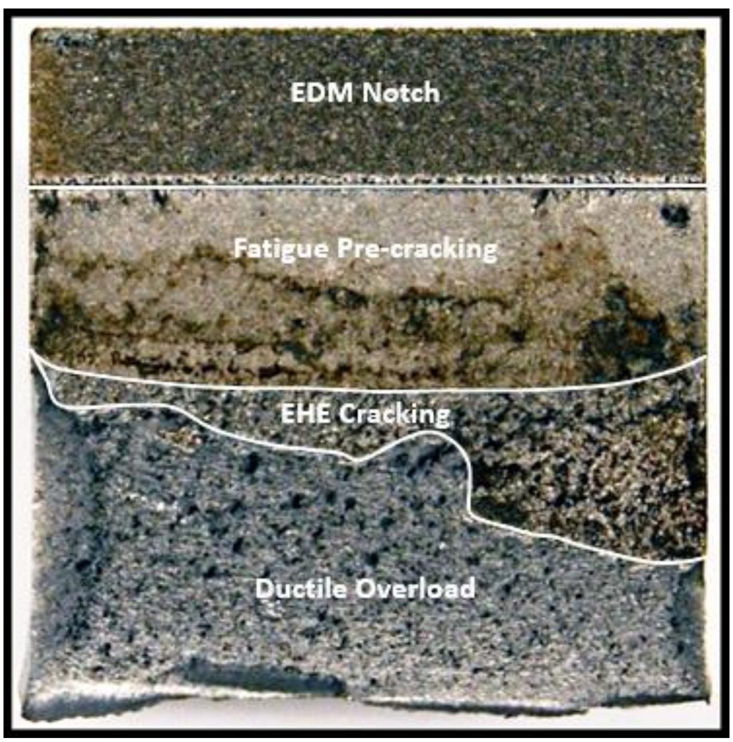


Figure K.5-16: Fracture Face of Rod 12-V-E109 MR 5, EHE

K.5.9 Center 1, FFS:

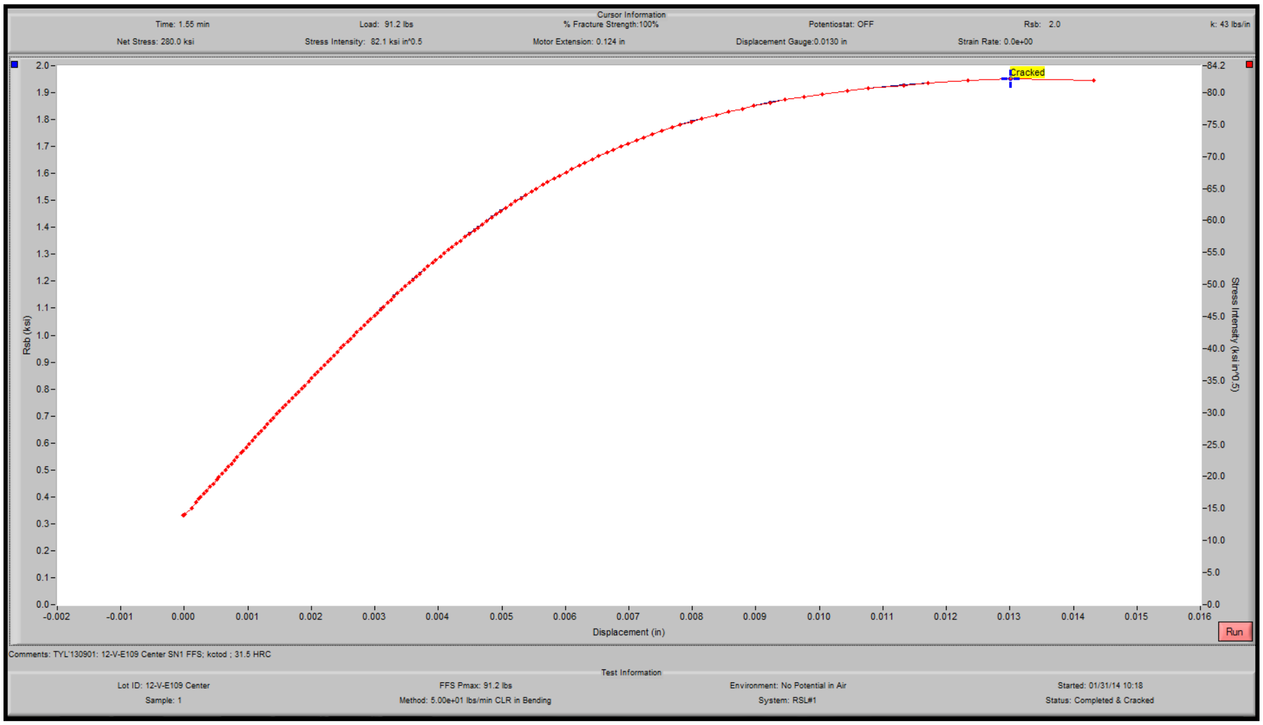


Figure K.5-17: Rod 12-V-E109 Center 1, Graphical FFS Results

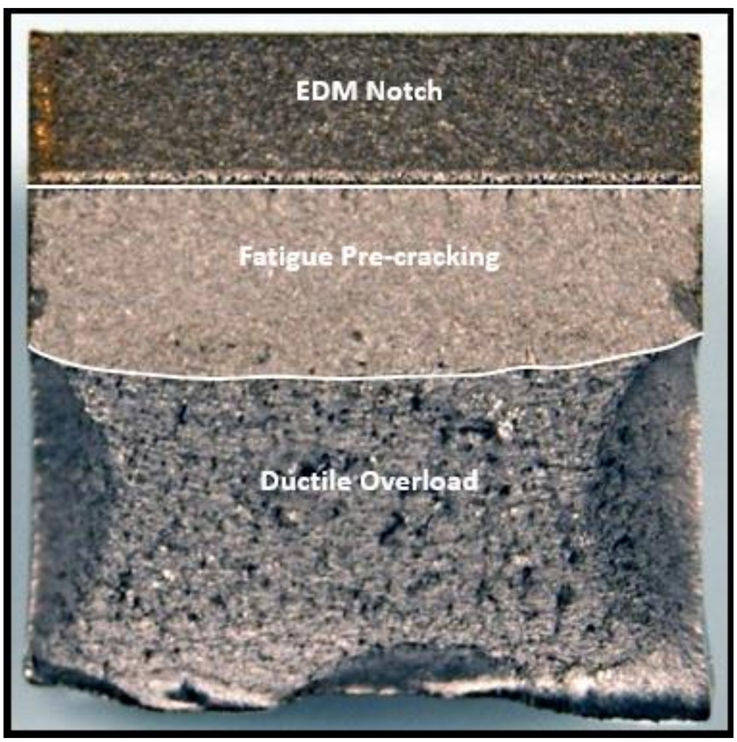


Figure K.5-18: Fracture Face of Rod 12-V-E109 Center 1, FFS

K.6 Threaded Specimen Test Results

K.6.1 Thd 1, FFS:

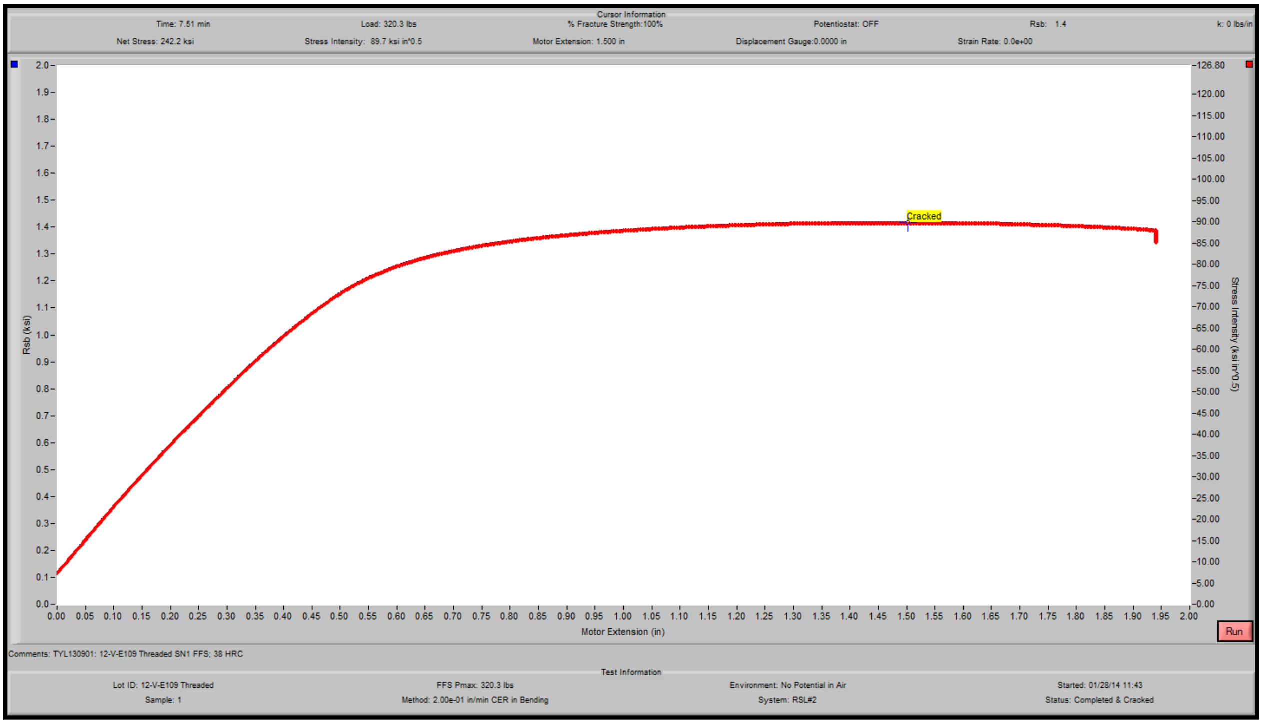


Figure K.6-1: Rod 12-V-E109 Thd 1, Graphical FFS Results

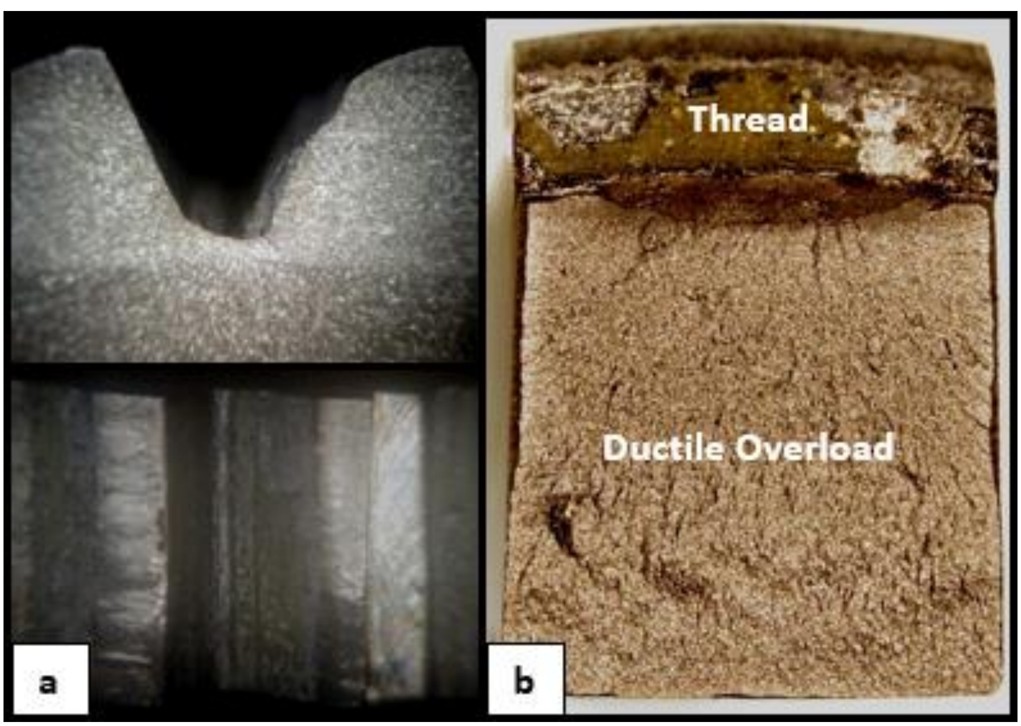


Figure K.6-2: Rod 12-V-E109 Thd 1 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

K.6.2 Thd 3, EHE:

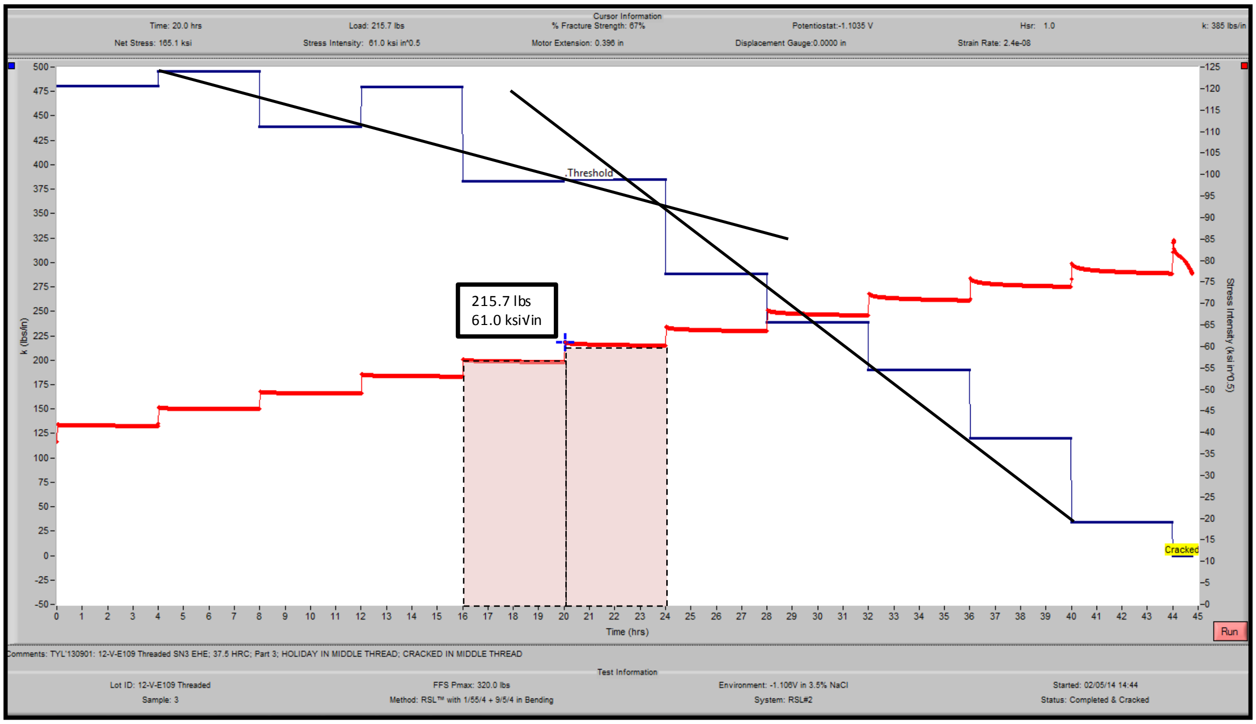


Figure K.6-3: Rod 12-V-E109 Thd 3, Graphical EHE Results

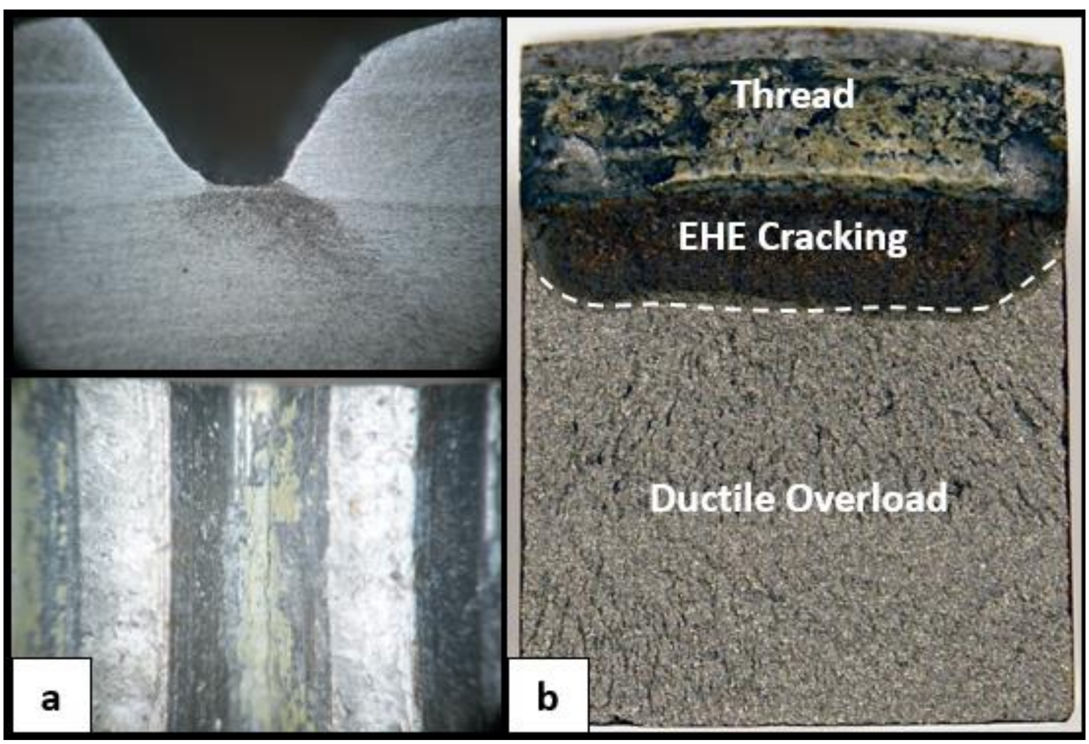
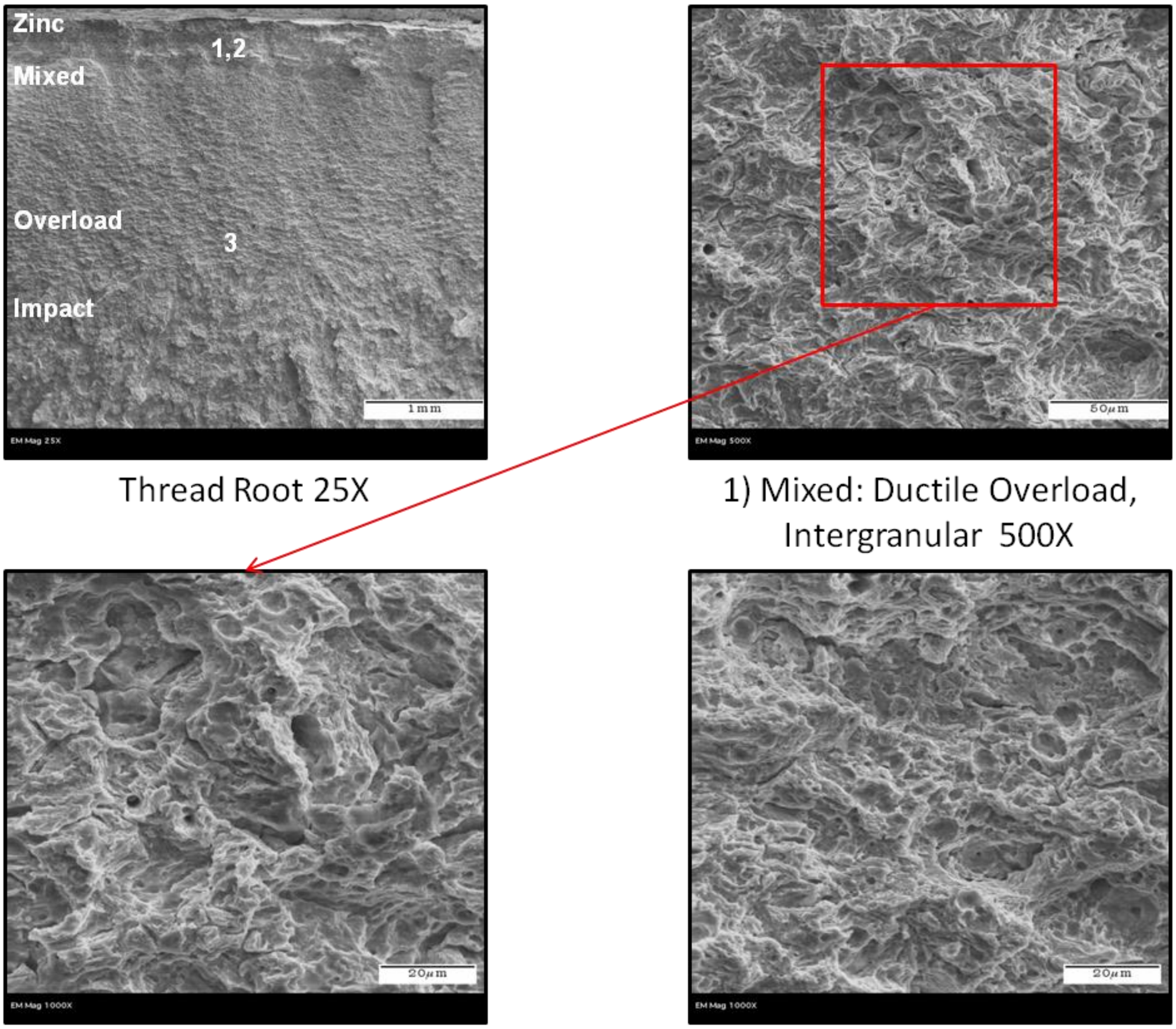


Figure K.6-4: Rod 12-V-E109 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure K.6-5: SEM of Rod 12-V-E109 Thd 3, EHE



Thread Root 25X

1) Mixed: Ductile Overload, Intergranular 500X

2) Mixed: Ductile Overload, Intergranular 1000X

3) Ductile Overload 1000X

K.6.3 Thd 5, EHE:

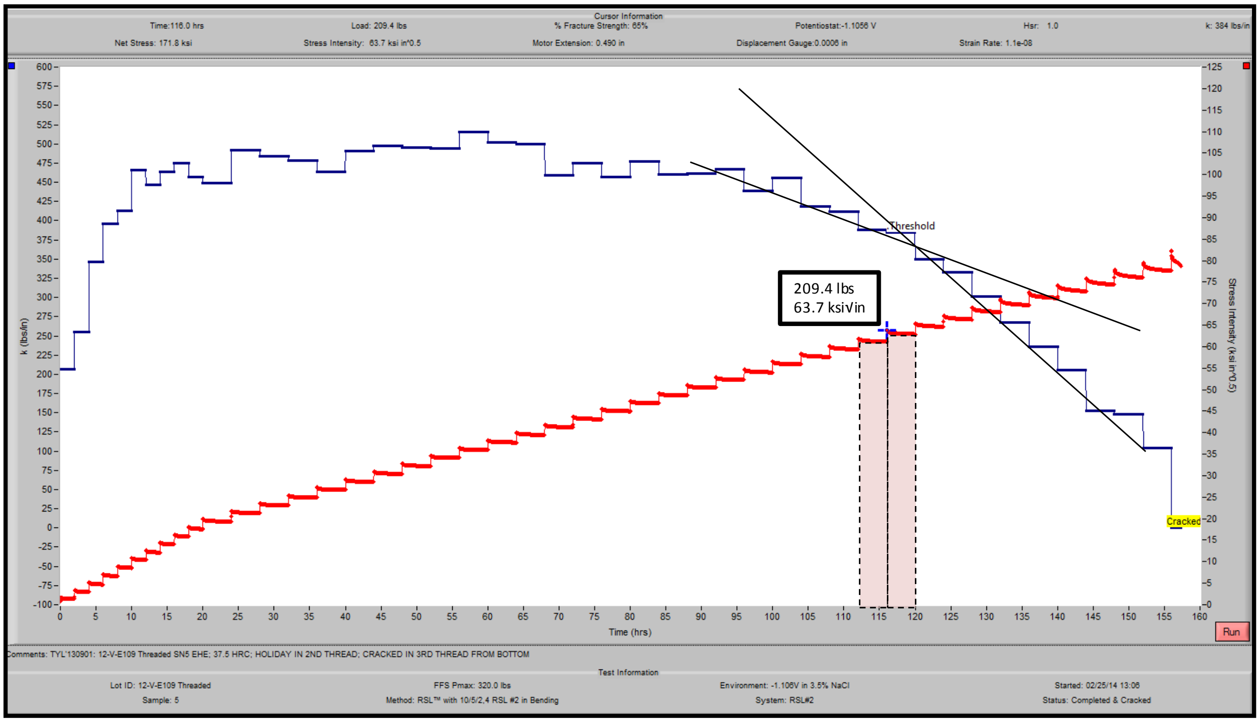


Figure K.6-6: Rod 12-V-E109 Thd 5 Graphical EHE Results

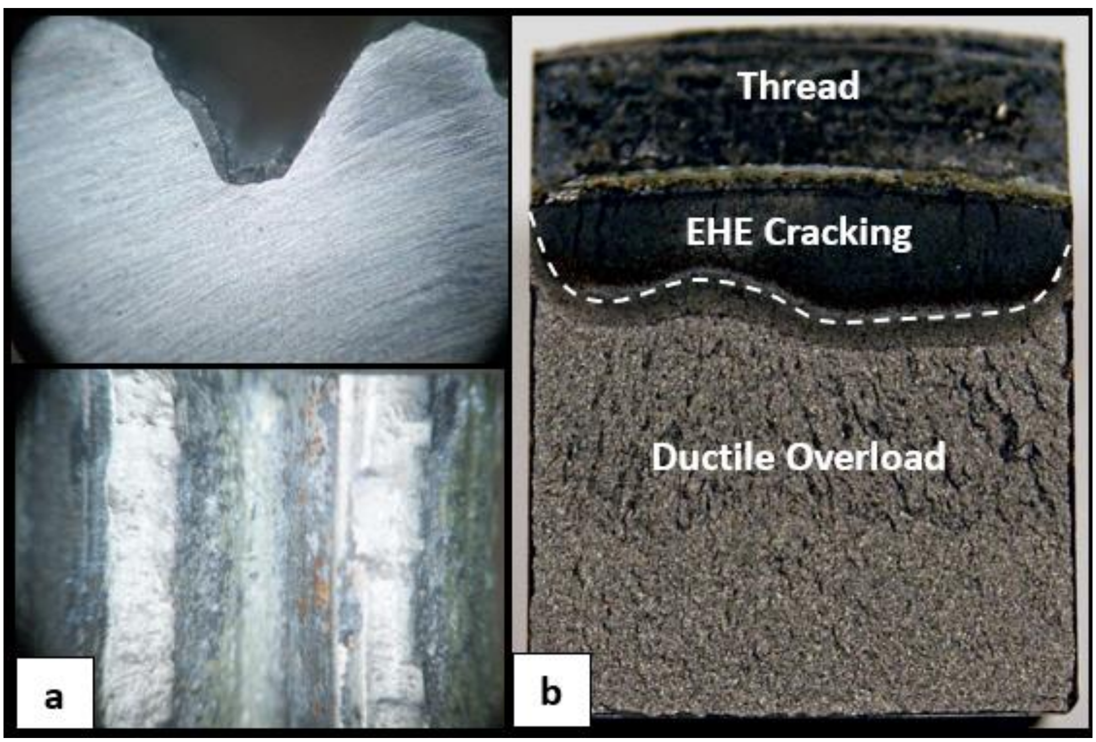


Figure K.6-7: Rod 12-V-E109 Thd 5 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix L: Rod 18-V-1

L.1 Description of Sample

Rod 18-V-1 was a non-galvanized replacement rod manufactured in 2013 from the same heat of material that was tested in Test Rigs 16 and 17 in Test IV. It was made from 4340 steel to ASTM A354 Grade BD with additional requirements on hardness and CVN. The bolts are 3 inches in diameter with machined threads.

L.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 18-V-1 and can be seen versus time in **Figure L**.2-1. The final OCP recorded for Rod 18-V-1 was Vsce=-0.685 V.

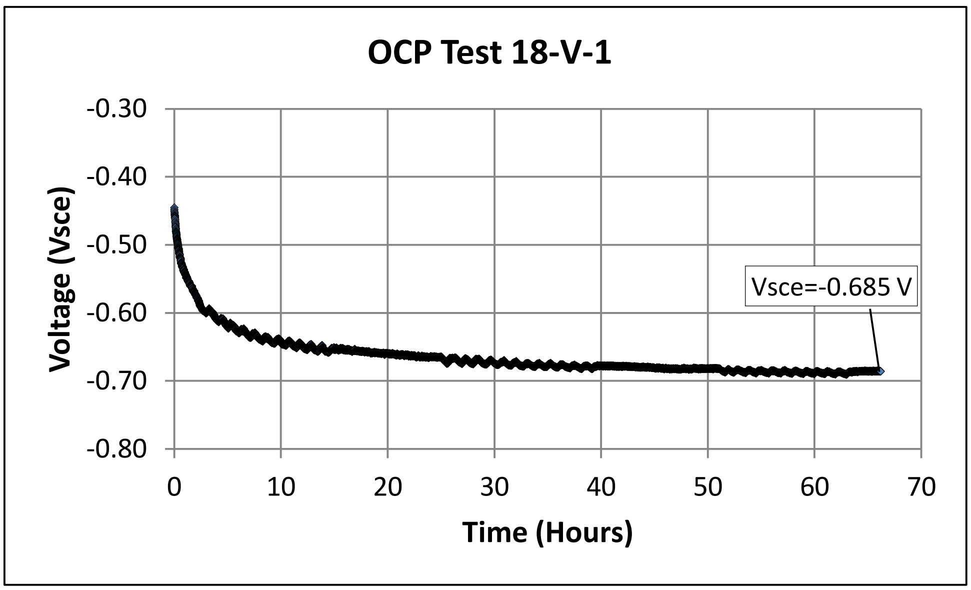


Figure L.2-1: Open Circuit Potential for Rod 18-V-1

L.3 Hardness

The hardness data and profile for sample 18-V-1 are shown in **Table L.3-1** and **Figure L.3-1**.

Table L.3-1: Hardness Data of Rod 18-V-1 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	33.5	33.5
MR 1, FFS	35.5	35.2
MR 3, EHE	35.5	
MR 4, EHE	34.5	
OD 1, FFS	35.5	35.4
OD 3, EHE	35.0	
OD 4, EHE	35.5	
Thd 1, FFS	35.5	
Thd 2, IHE	35.5	
Thd 3, EHE	35.5	
Thd 4, EHE	35.5	

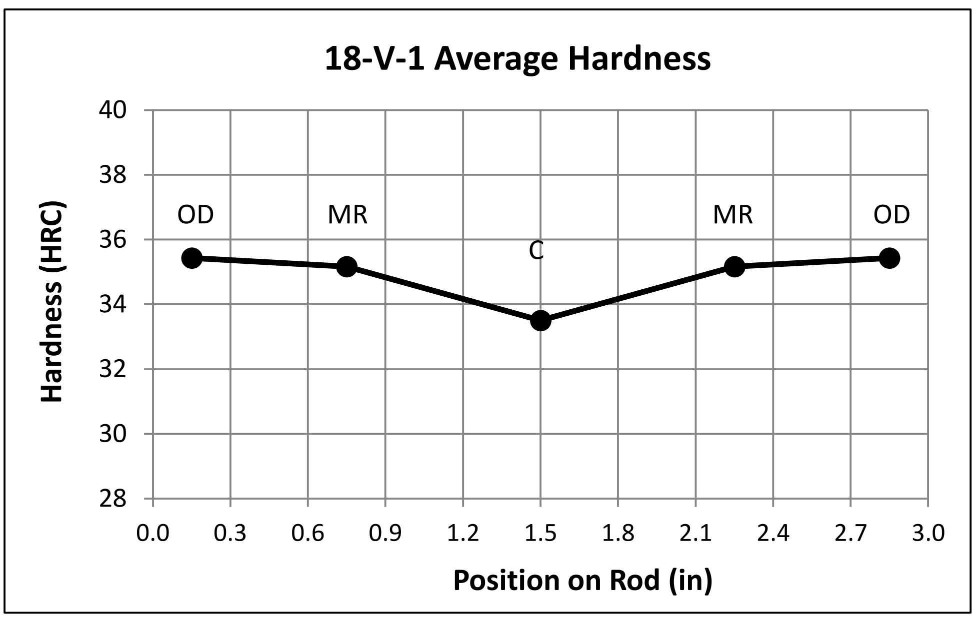


Figure L.3-1: Hardness Profile of Rod 18-V-1

L.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

L.4.1 Fatigue Pre-crack Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 18-V-1						
LRA Job No.:	**TYL130901**	**Structural Component:** Pier E2 **Comments**: Non-Galvanized; 2013 Machined Threads Same Heat as Test Rigs #16 and 17 in Test IV				
Rod#:	**18-V-1**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**35.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	91.1 0.57 1.03 7700		
	OD 3, EHE	**35.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			44.6 0.28 0.50 2.2
	OD 4, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			42.9 0.27 0.48 1.8
	MR 1, FFS	**35.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	88.8 0.56 1.00 8000		
	MR 3, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			43.2 0.27 0.49 2.1
	MR 4, EHE	**34.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			47.9 0.31 0.54 1.9
	Center 1, FFS	**33.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	84.9 0.56 0.96 8400		

L.4.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 18-V-1						
LRA Job No.:	**TYL130901**	**Structural Component:** Pier E2 **Comments**: Non-Galvanized; 2013 Machined Threads Same Heat as Test Rigs #16 and 17 in Test IV				
Rod#:	**18-V-1**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.5**	Pmax* (lbs) Fu Rsb Strain Rate (x10^{-8} in/in/sec)	343.0 1.13 1.6 1800		
	Thd 2, IHE	**35.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate (x10^{-8} in/in/sec)		340.6 1.12 1.5 1.0	
	Thd 3, EHE	**35.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate (x10^{-8} in/in/sec)			314.5 1.04 1.4 1.1
	Thd 4, EHE	**35.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate (x10^{-8} in/in/sec)			313.8 1.03 1.4 0.5

L.4.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 18-V-1
RSL™ (B) 4-pt Bend Test

LRA Job No.:	TYL130901
Rod #:	18-V-1
Product Form:	1e
Rod OD:	3"

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	35.5	159	102.2	102.2	102.2	100.0%	91.1	0.57	309.3	1.9	7700	0.2107	145.0	50lb/min		1.03	
	OD 3, EHE	3.5% NaCl @ -1.106V	35.0	157	62.0	55.8	49.6	49.0%	44.6	0.28	152.1	1.0	2.2	0.2120		10/5/2,4		0.50	
	OD 4, EHE	3.5% NaCl @ -1.106V	35.5	159	55.0	55.0	49.4	47.1%	42.9	0.27	144.4	0.9	1.8	0.2066		10/5/2,4		0.48	
	MR 1, FFS	Air	35.5	159	98.9	98.9	98.9	100.0%	88.8	0.56	301.8	1.9	8000	0.2115	149.0	50lb/min		1.00	
	MR 3, EHE	3.5% NaCl @ -1.106V	35.5	159	62.0	58.9	49.5	48.6%	43.2	0.27	145.2	0.9	2.1	0.2070		10/5/2,4		0.49	
	MR 4, EHE	3.5% NaCl @ -1.106V	34.5	155	55.0	63.3	54.8	53.9%	47.9	0.31	161.3	1.0	1.9	0.2076		10/5/2,4		0.54	
	Center 1, FFS	Air	33.5	151	90.8	90.8	90.8	100.0%	84.9	0.56	291.5	1.9	8400	0.2198	143.5	50lb/min		0.96	
Threaded	Thd 1, FFS	Air	35.5	159	346.1	346.1	346.1	100.0%	100.0	0.63	248.0	1.6	1800	N/A	N/A	0.4 in/min	343.0	1.13	
	Thd 2, IHE	Air	35.5	159	265.7	348.1	345.5	99.3%	99.3	0.62	246.0	1.5	1.0	N/A	N/A	10/5/1,8	340.6	1.12	
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.5	159	265.7	322.7	318.1	91.7%	91.7	0.58	227.2	1.4	1.1	N/A	N/A	10/5/1,8	314.5	1.04	Cracked in Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	35.5	159	265.7	323.0	317.8	91.5%	91.5	0.57	226.7	1.4	0.5	N/A	N/A	13/5/1,16	313.8	1.03	No Holiday

L.5 Fatigue Pre-cracked Specimen Test Results

L.5.1 OD 1, FFS:

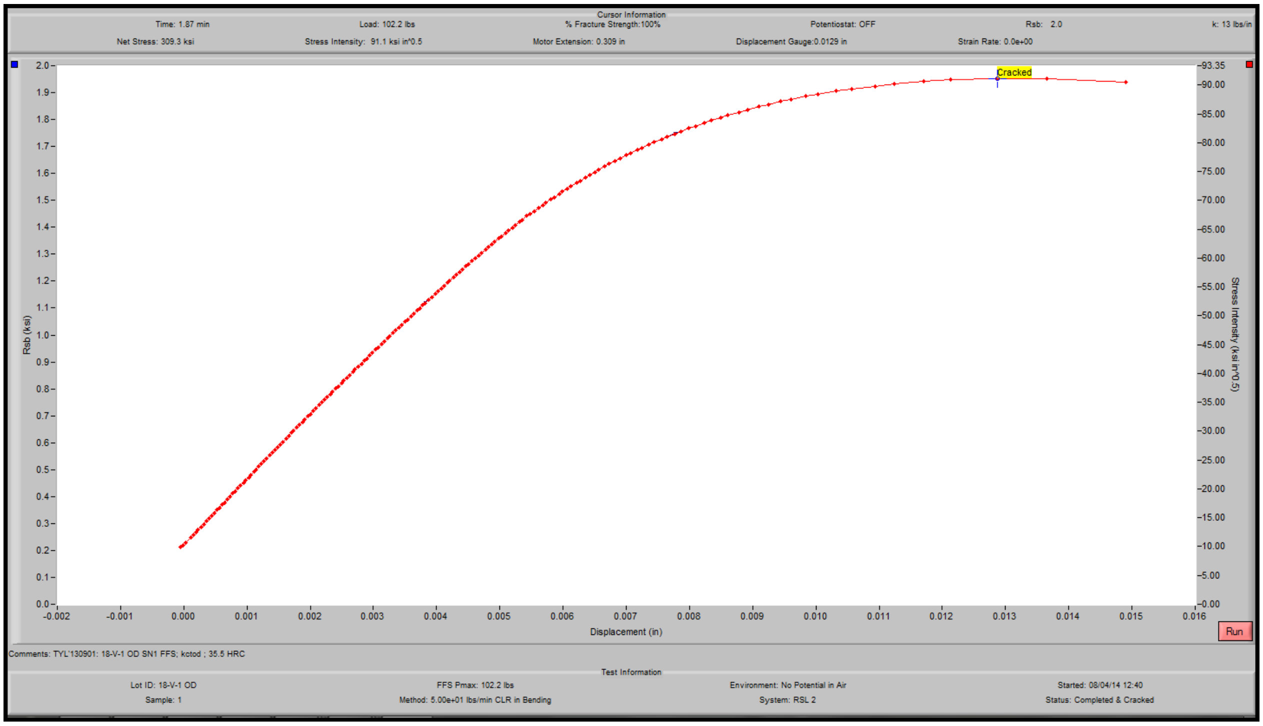


Figure L.5-1: Rod 18-V-1 OD 1, Graphical FFS Results

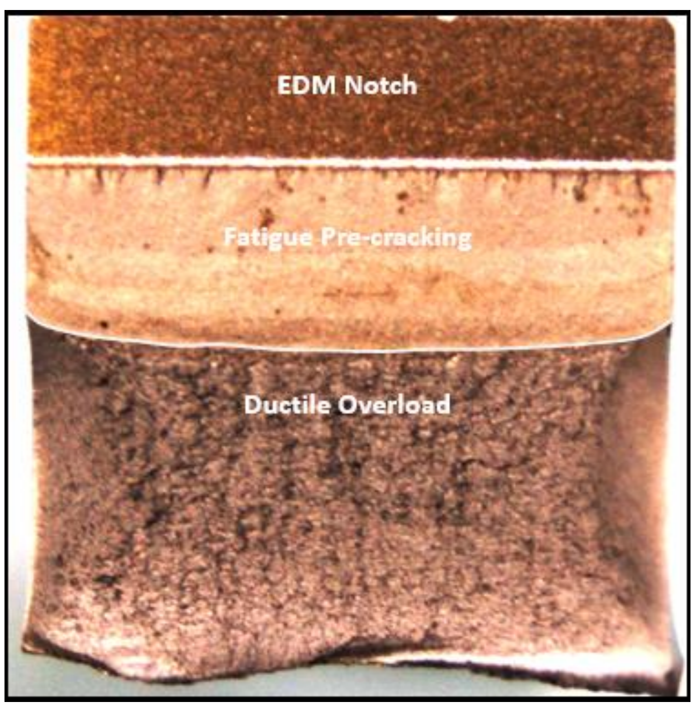


Figure L.5-2: Fracture Face of Rod 18-V-1 OD 1, FFS

L.5.2 OD 3, EHE:

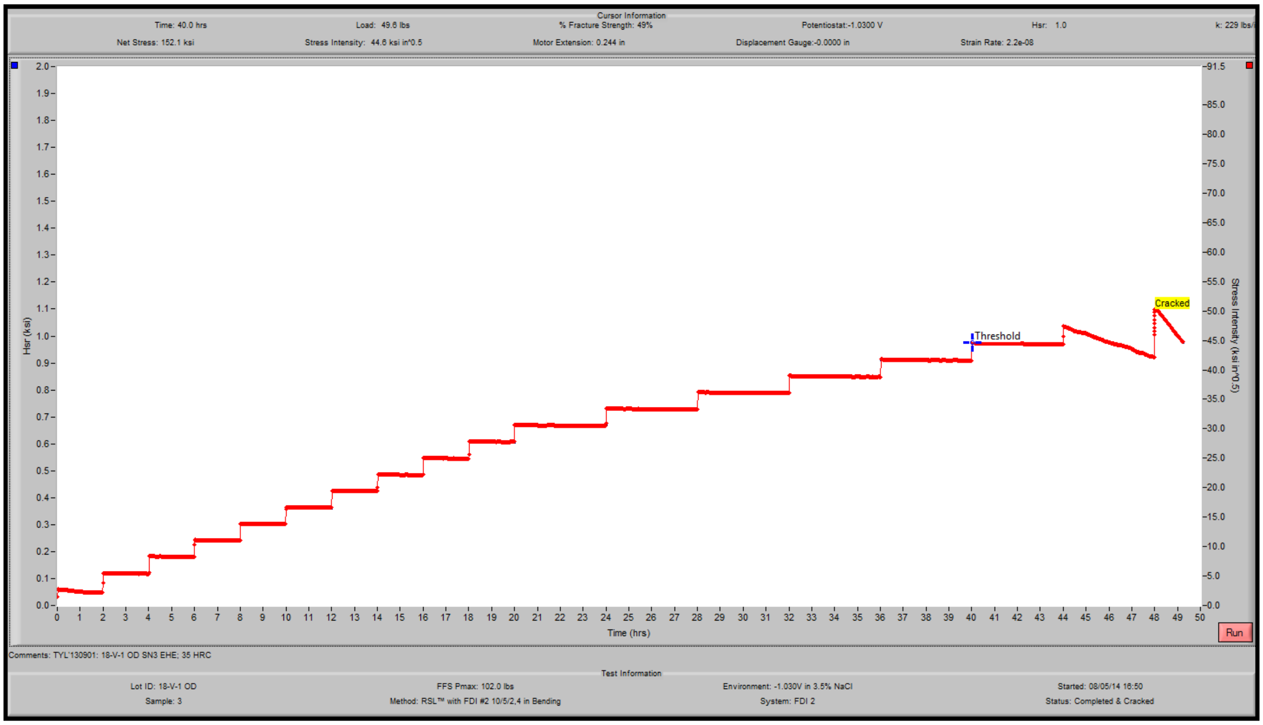


Figure L.5-3: Rod 18-V-1 OD 3, Graphical EHE Results

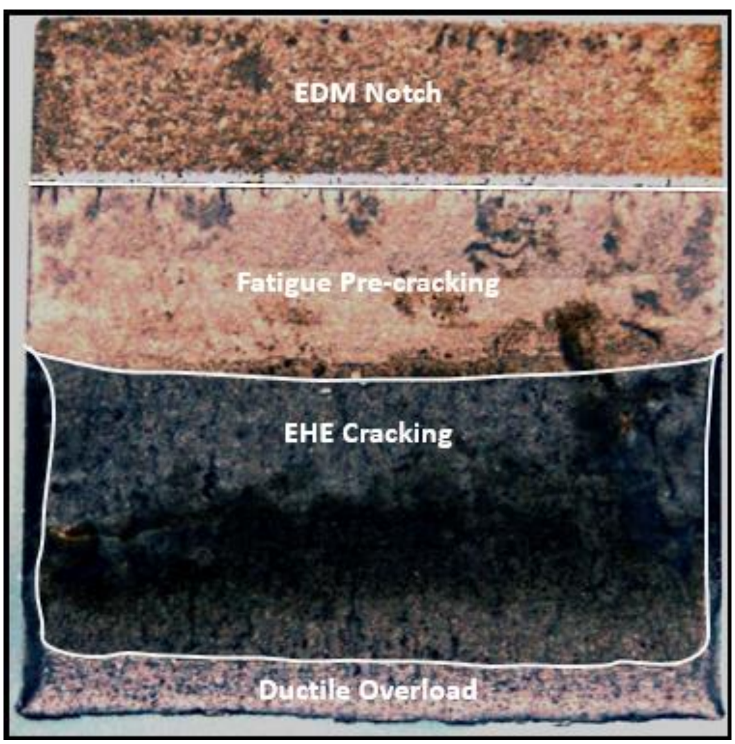


Figure L.5-4: Fracture Face of Rod 18-V-1 OD 3, EHE

L.5.3 OD 4, EHE:

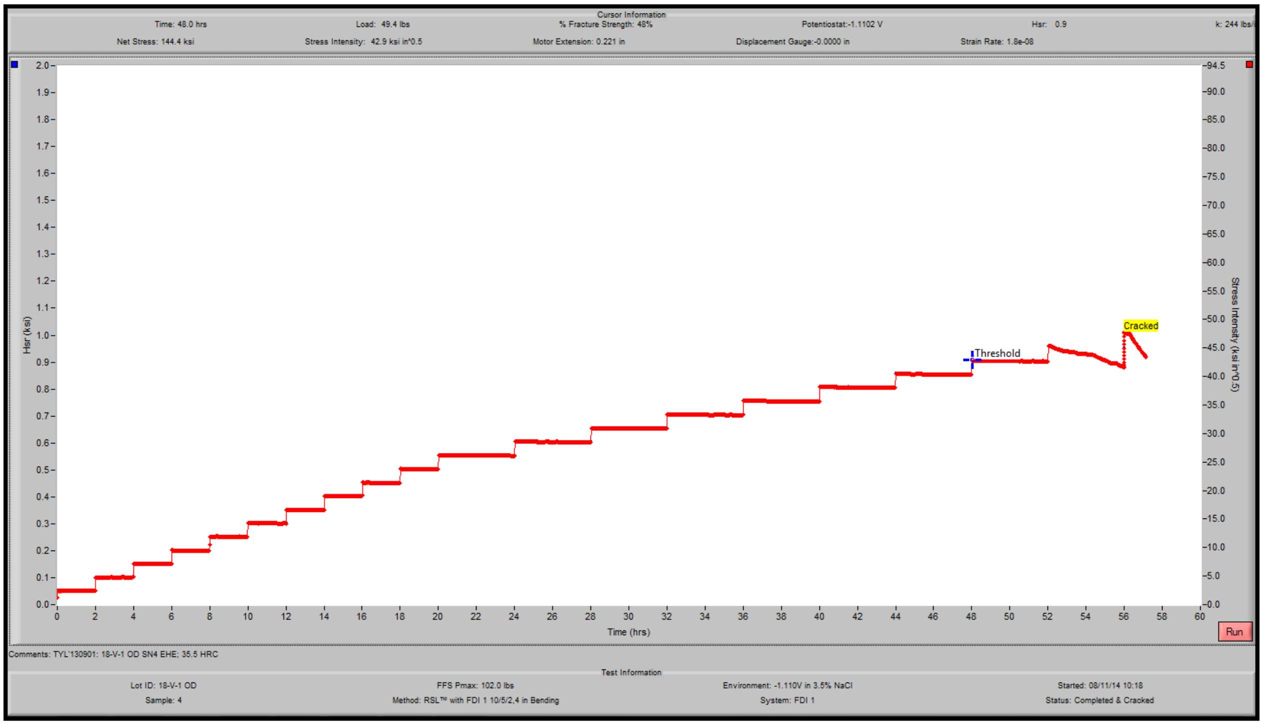


Figure L.5-5: Rod 18-V-1 OD 4, Graphical EHE Results

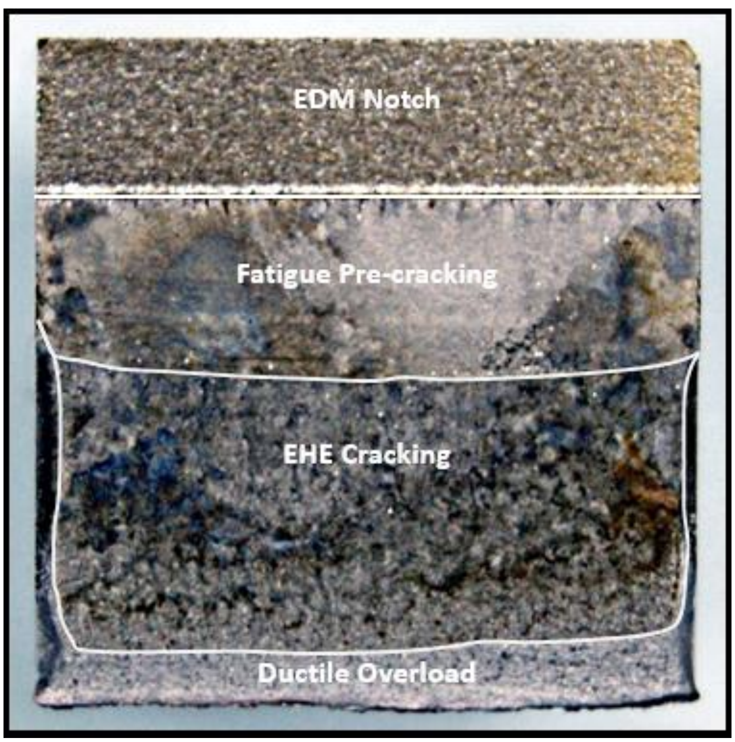


Figure L.5-6: Fracture Face of Rod 18-V-1 OD 4, EHE

L.5.4 MR 1, FFS:

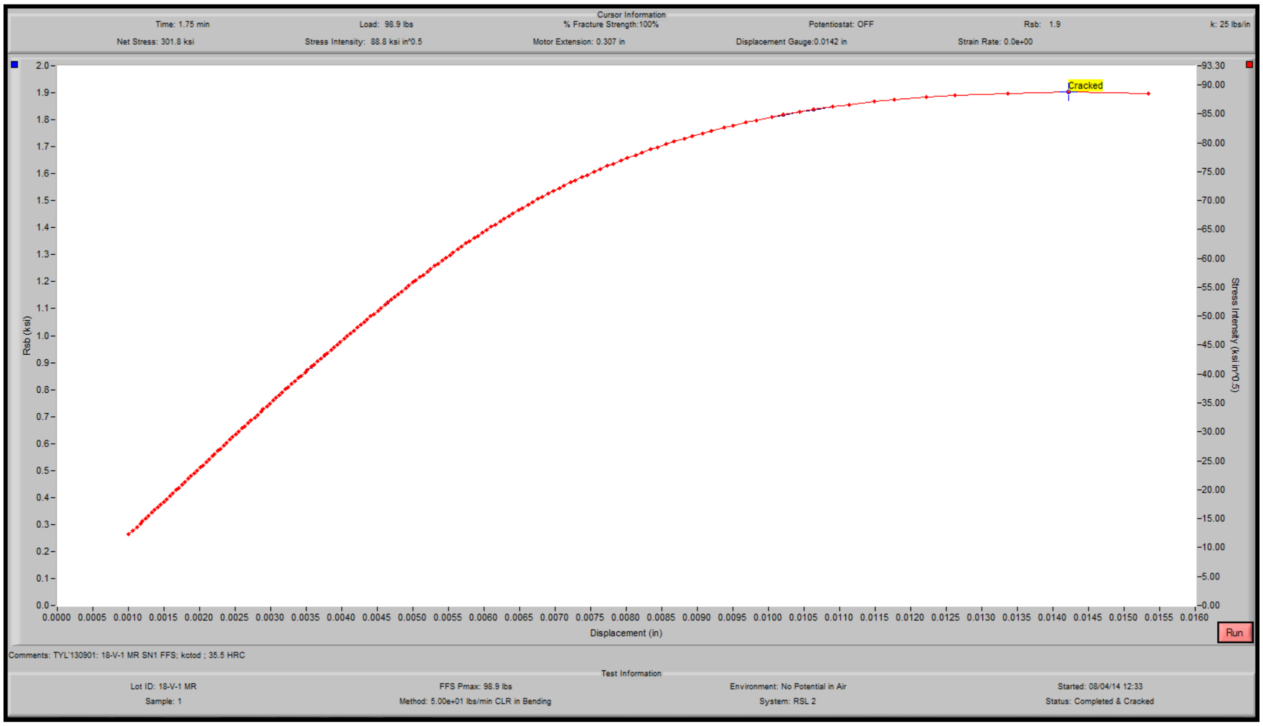


Figure L.5-7: Rod 18-V-1 MR 1, Graphical FFS Results

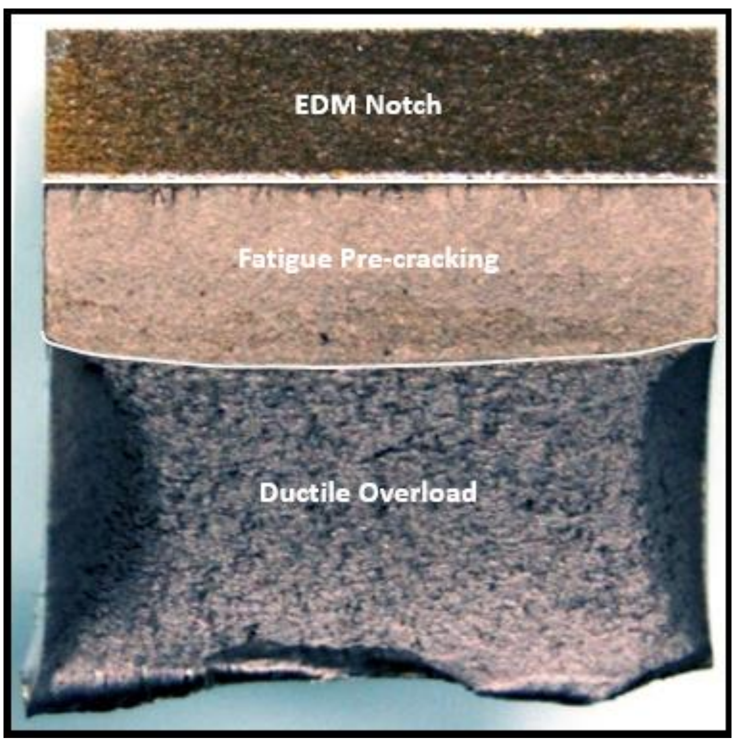


Figure L.5-8: Fracture Face of Rod 18-V-1 MR 1, FFS

L.5.5 MR 3, EHE:

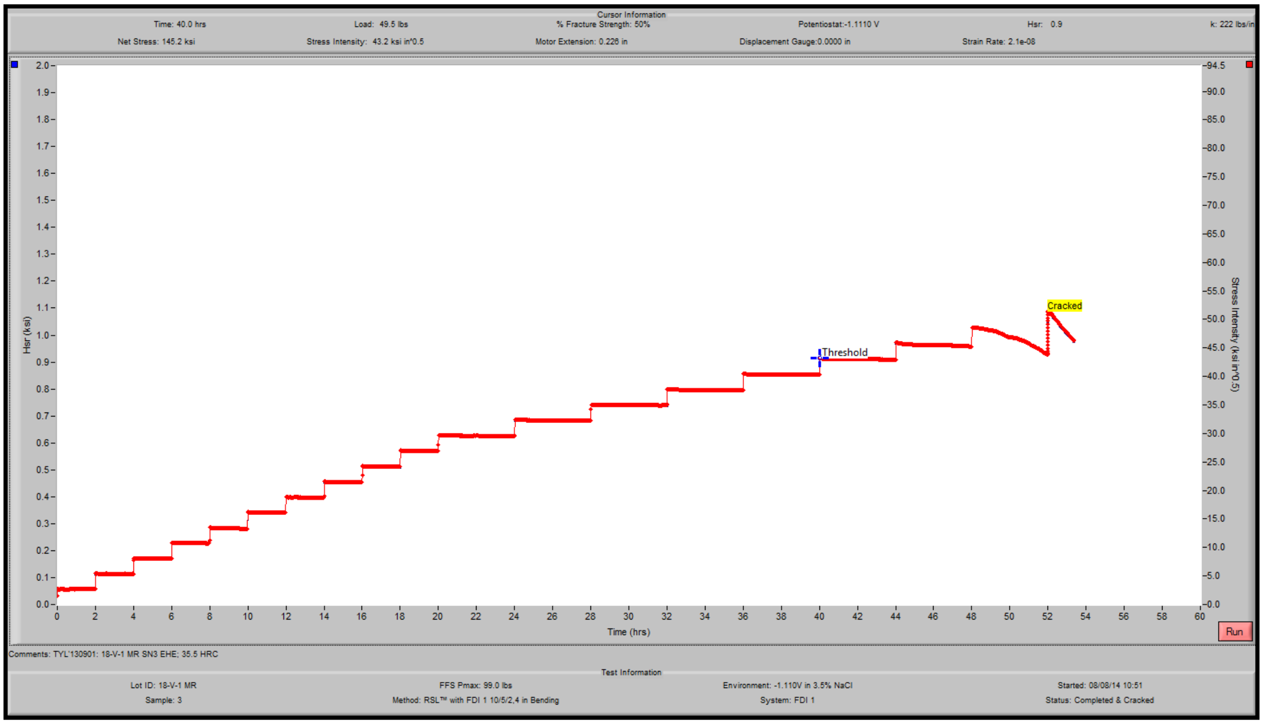


Figure L.5-9: Rod 18-V-1 MR 3, Graphical EHE Results

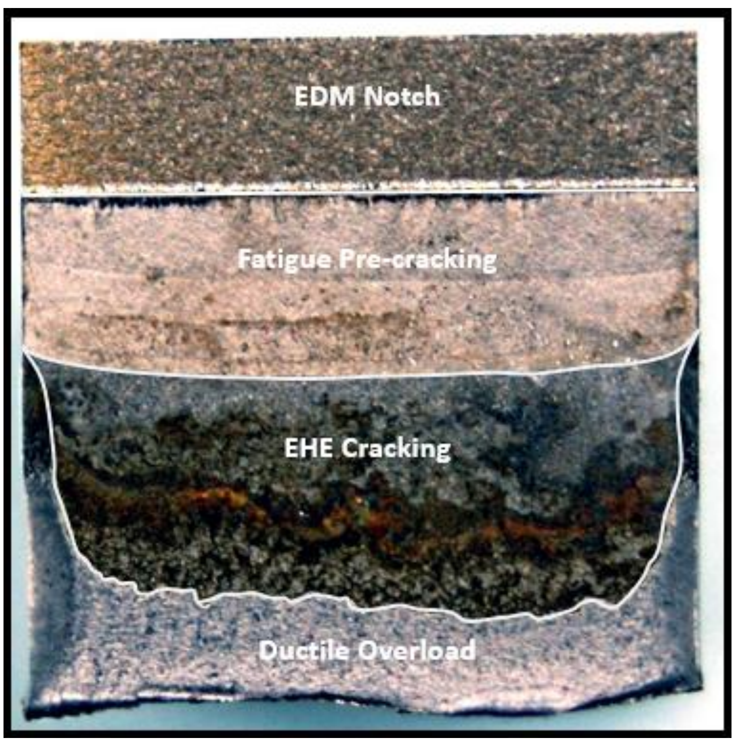


Figure L.5-10: Fracture Face of Rod 18-V-1 MR 3, EHE

L.5.6 MR 4, EHE:

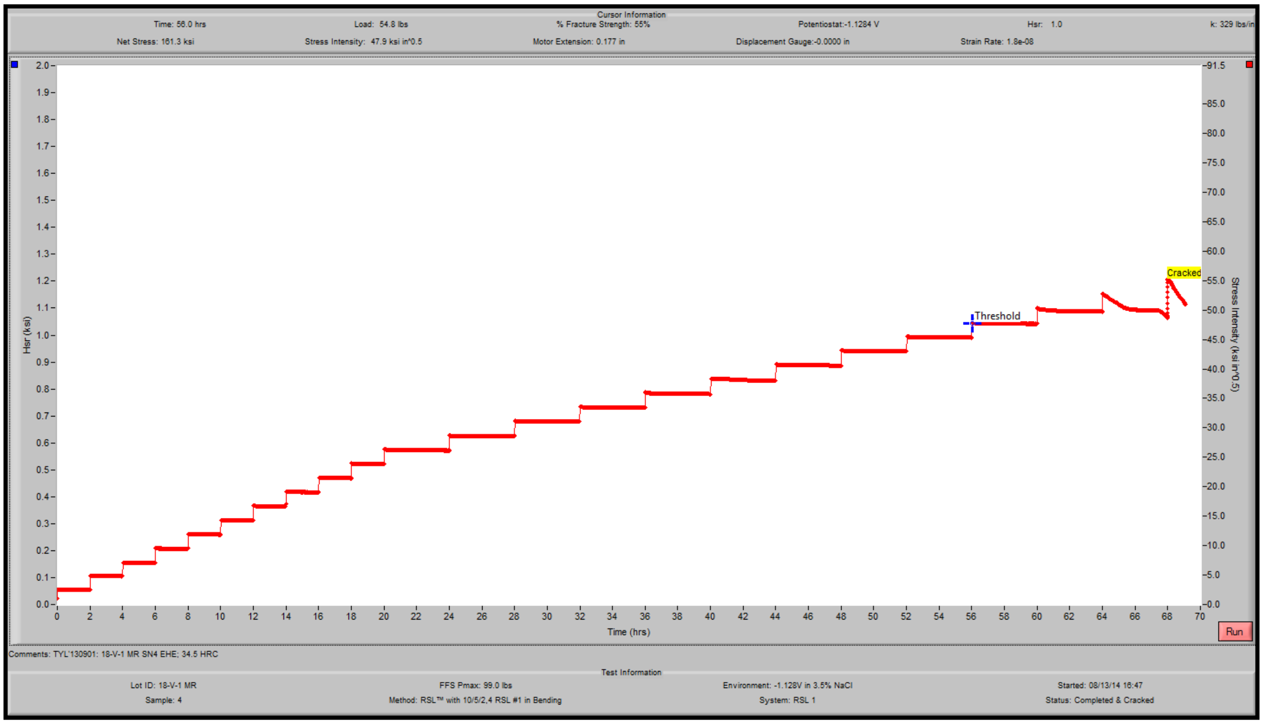


Figure L.5-11: Rod 18-V-1 MR 4, Graphical EHE Results

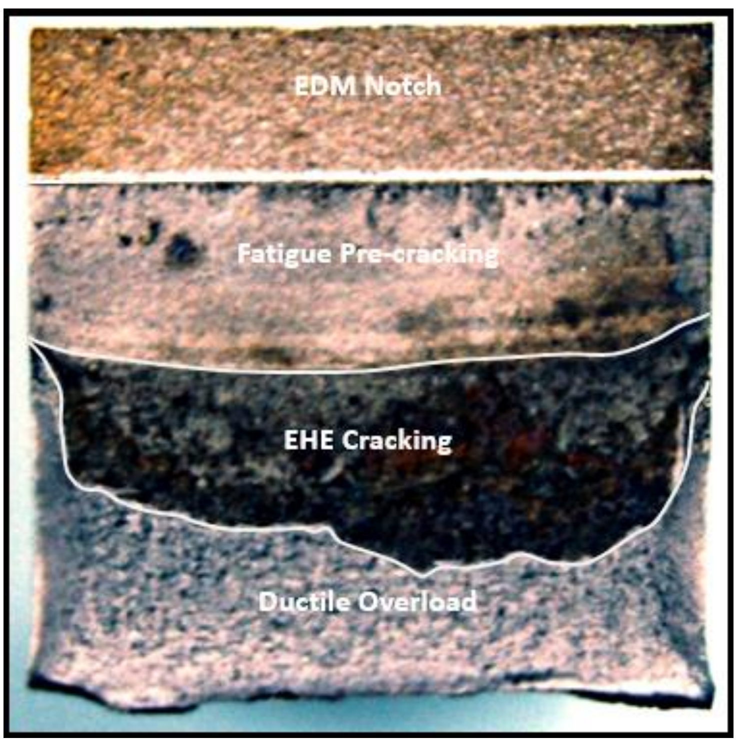


Figure L.5-12: Fracture Face of Rod 18-V-1 MR 4, EHE

L.5.7 Center 1, FFS:

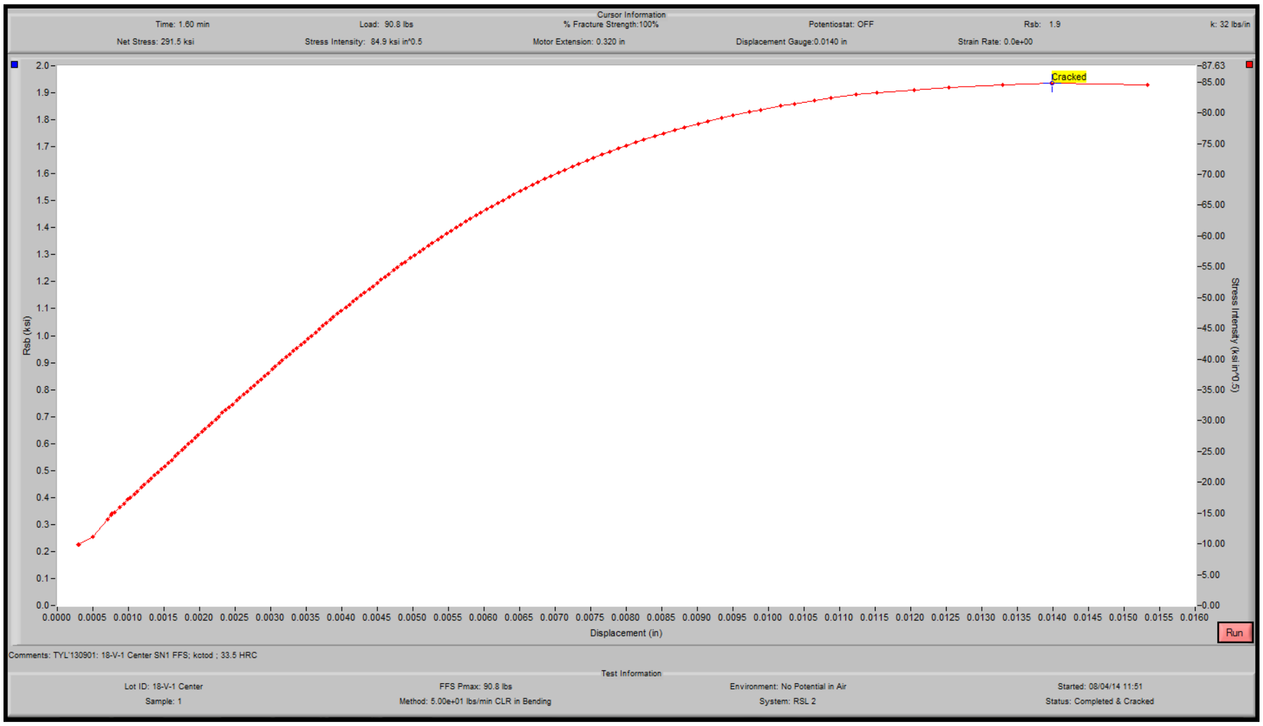


Figure L.5-13: Rod 18-V-1 Center 1, Graphical FFS Results

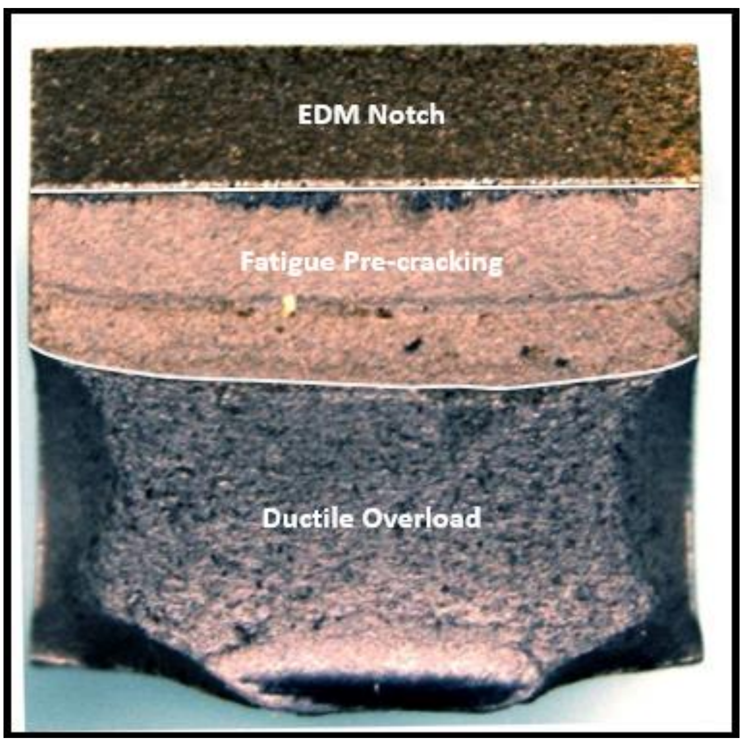


Figure L.5-14: Fracture Face of Rod 18-V-1 Center 1, FFS

L.6 Threaded Specimen Test Results

L.6.1 Thd 1, FFS:

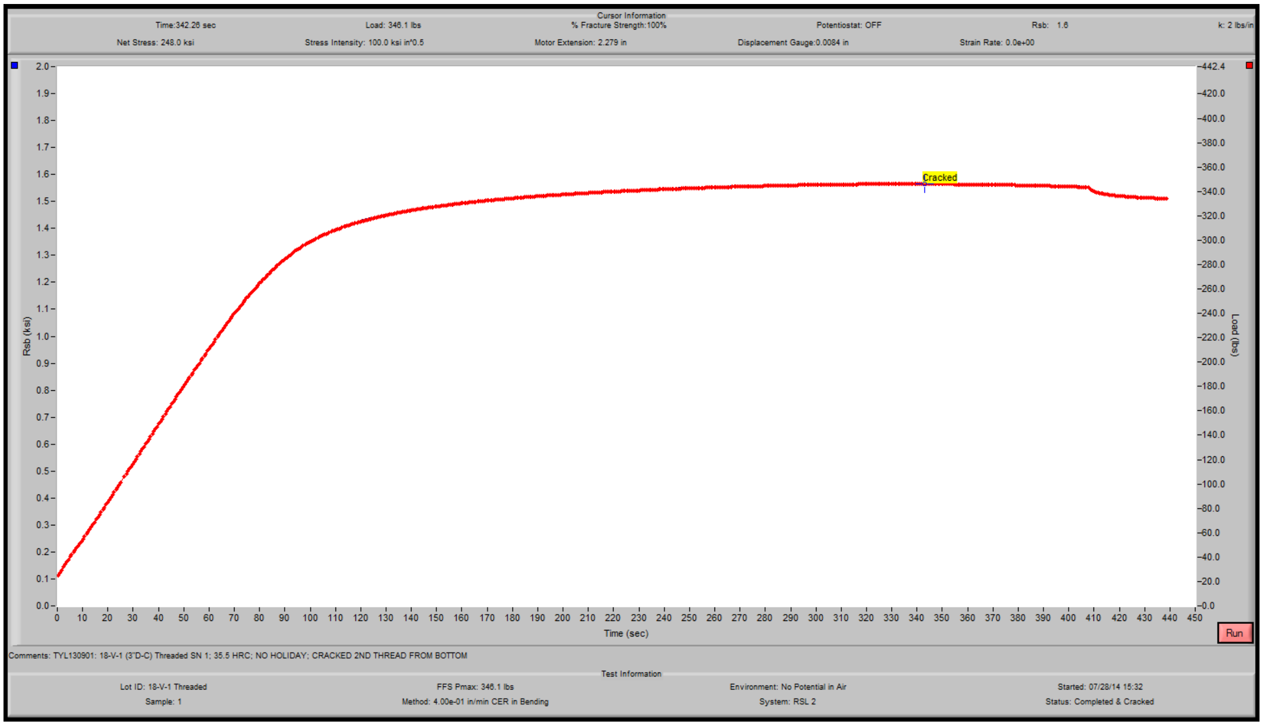


Figure L.6-1: Rod 18-V-1 Thd 1, Graphical FFS Results

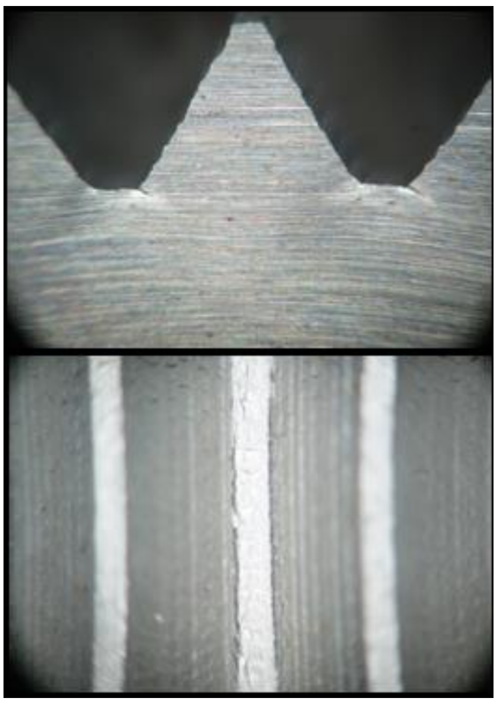


Figure L.6-2: Rod 18-V-1 Thd 1 FFS Fracture Face

L.6.2 Thd 2, IHE:

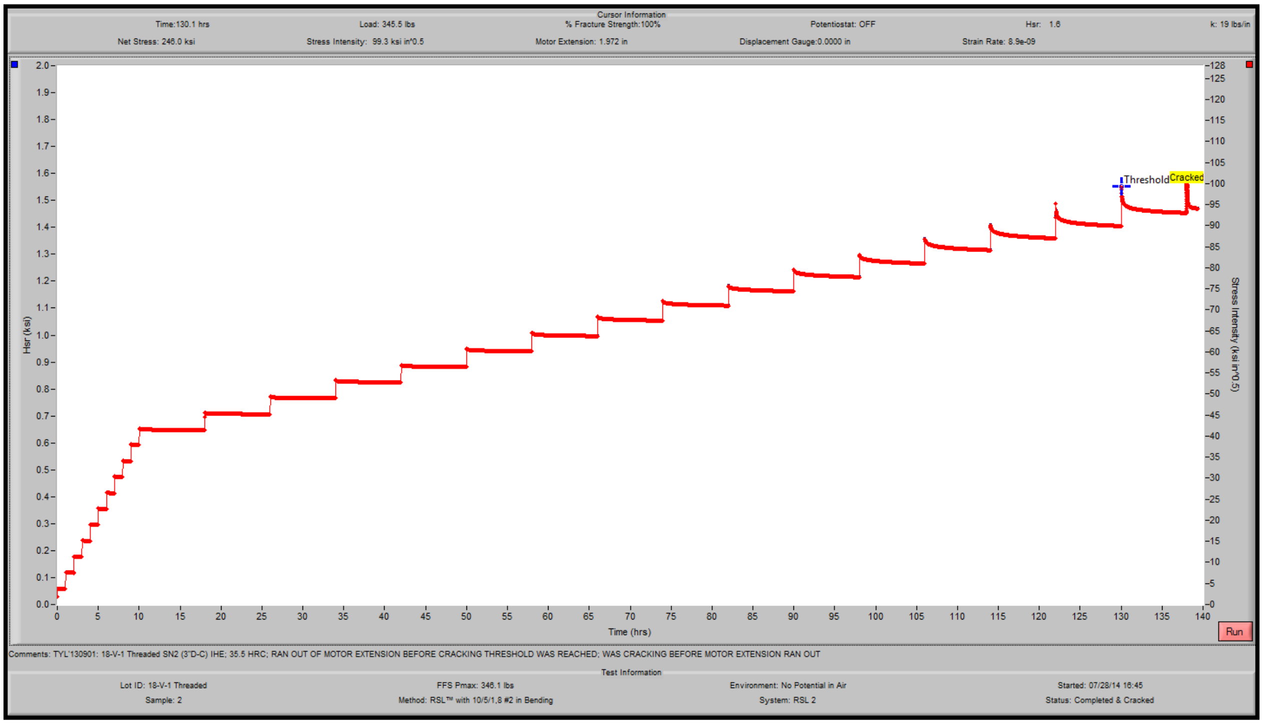


Figure L.6-3: Rod 18-V-1 Thd 2, Graphical IHE Results

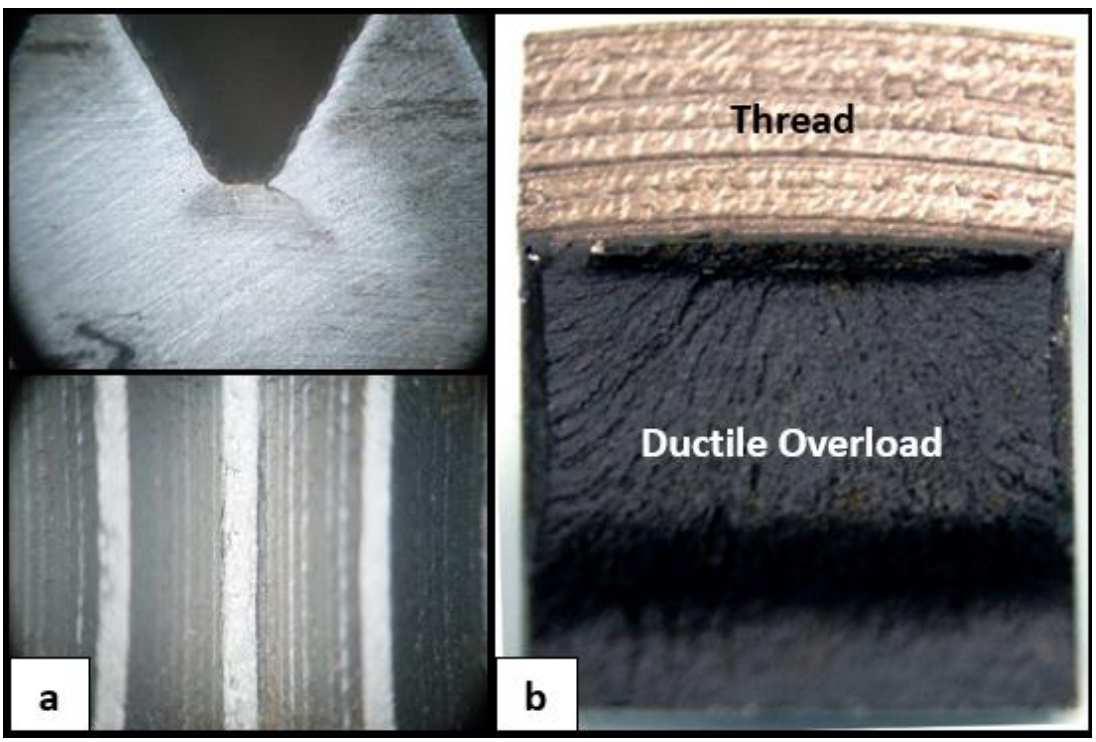


Figure L.6-4: Rod 18-V-1 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

L.6.3 Thd 3, EHE:

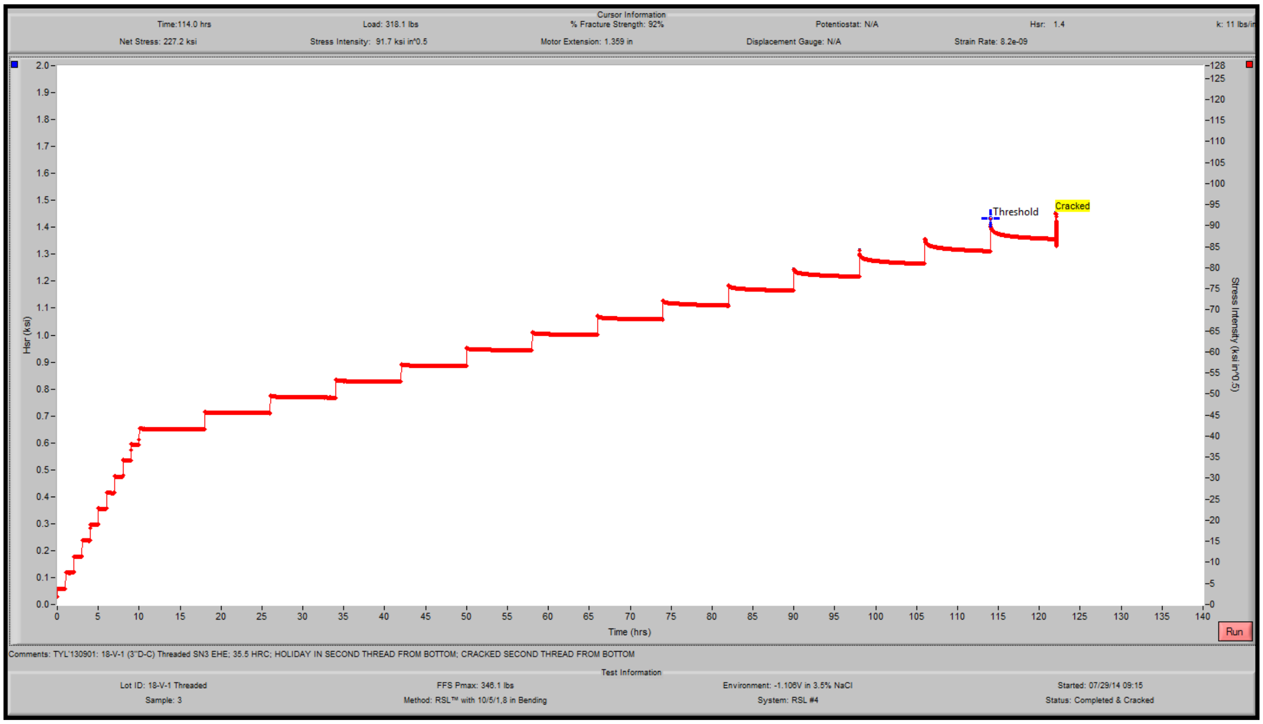


Figure L.6-5: Rod 18-V-1 Thd 3 Graphical EHE Results

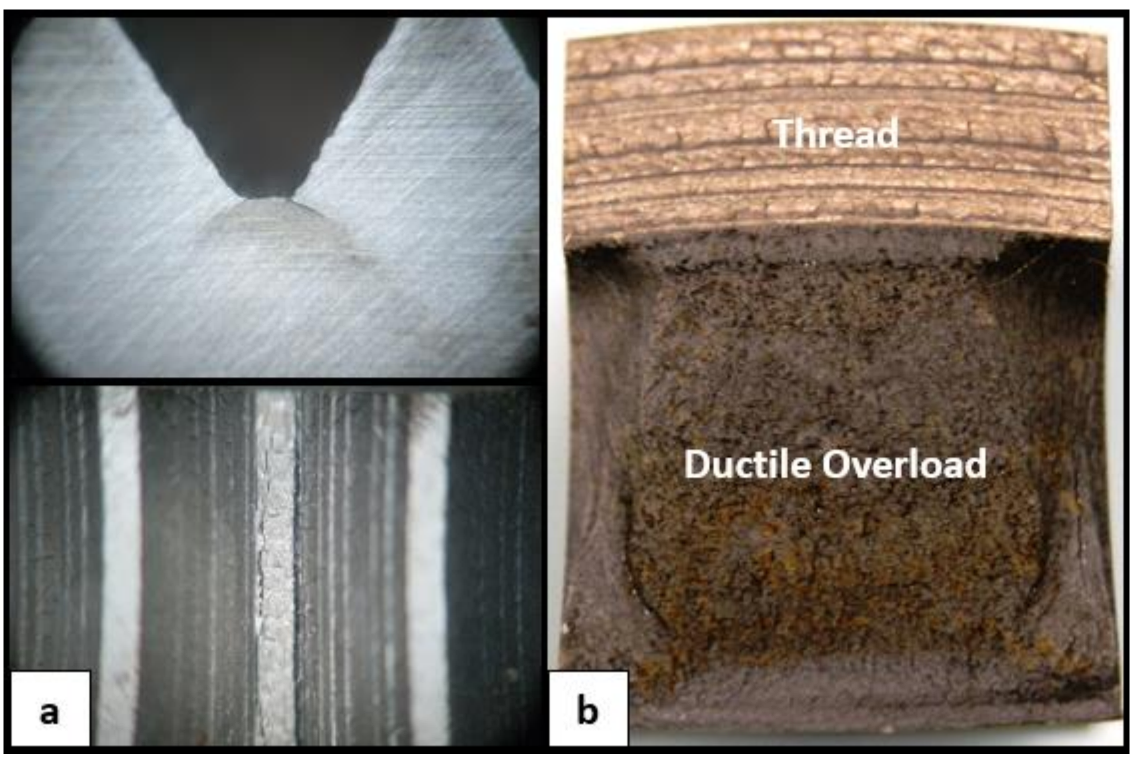


Figure L.6-6: Rod 18-V-1 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

L.6.4 Thd 4, EHE:

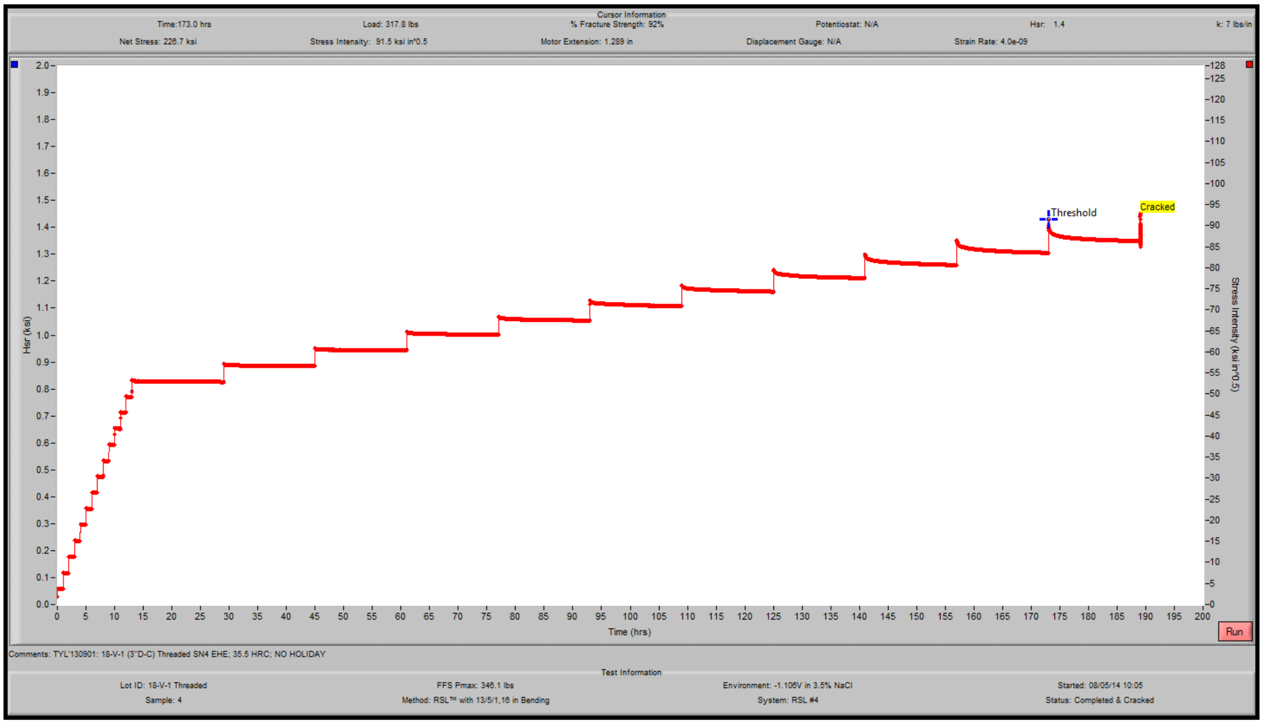


Figure L.6-7: Rod 18-V-1 Thd 4 Graphical EHE Results

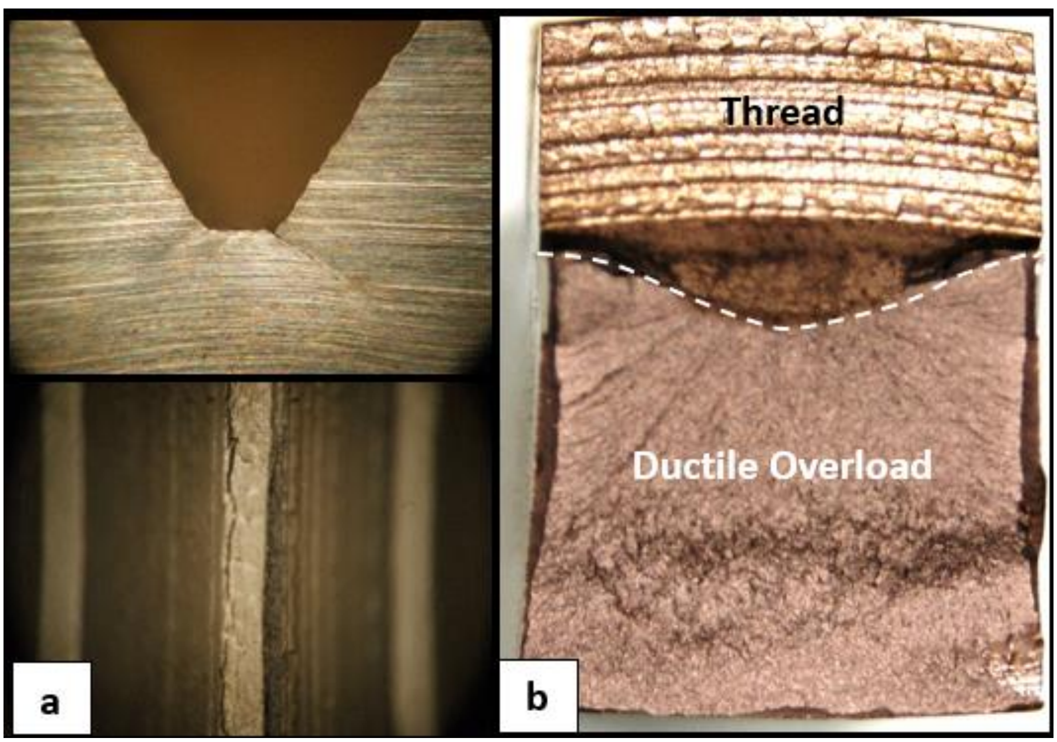


Figure L.6-8: Rod 18-V-1 Thd 4 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Appendix M: Rod 18-V-2

M.1 Description of Sample

Rod 18-V-2 was a galvanized replacement rod manufactured in 2013 from the same heat of material that was tested in Test Rigs 14, 15, 16 and 17 in Test IV. It was made from 4340 steel to ASTM A354 Grade BD with additional requirements on hardness and CVN. The bolts are 3 inches in diameter with machined threads.

M.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 18-V-2 and can be seen versus time in **Figure M**.2-1. The final OCP recorded for Rod 18-V-2 was Vsce = -1.021 V.

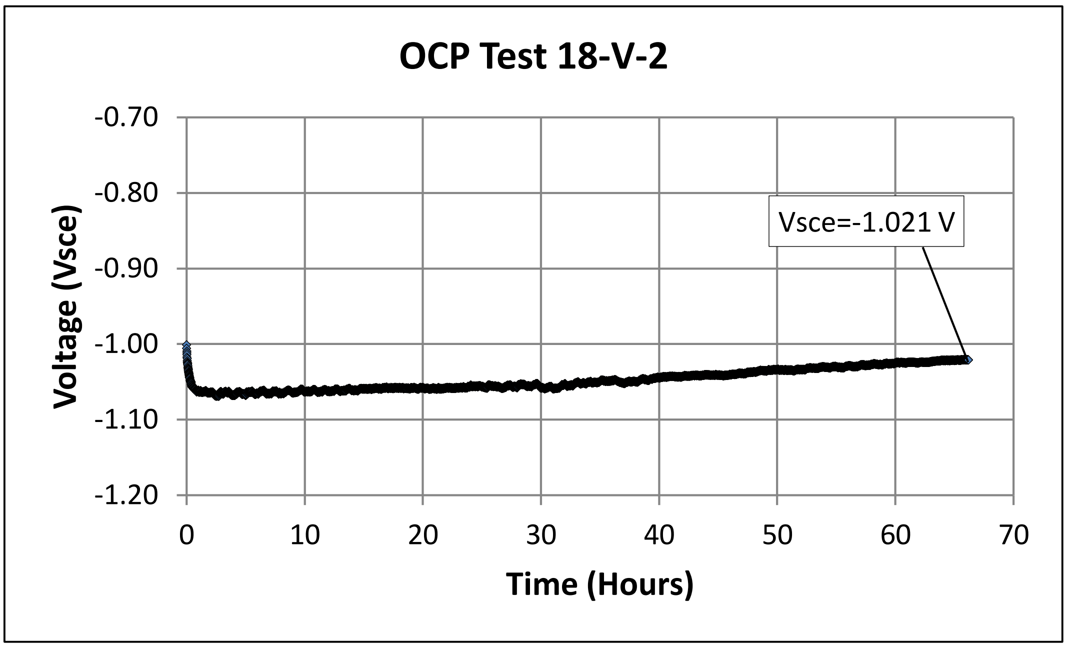


Figure M.2-1: Open Circuit Potential for Rod 18-V-2

M.3 Hardness

The hardness data and profile for sample 18-V-2 are shown in **Table M.3-1** and **Figure M.3-1**.

Table M.3-1: Hardness Data of Rod 18-V-2 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	33.0	33.0
MR 1, FFS	35.0	34.7
MR 3, EHE	35.0	
MR 4, EHE	34.0	
OD 1, FFS	35.0	35.5
OD 3, EHE	35.5	
OD 4, EHE	36.0	
Thd 1, FFS	35.5	
Thd 2, IHE	35.5	
Thd 3, EHE	35.5	
Thd 4, EHE	35.5	

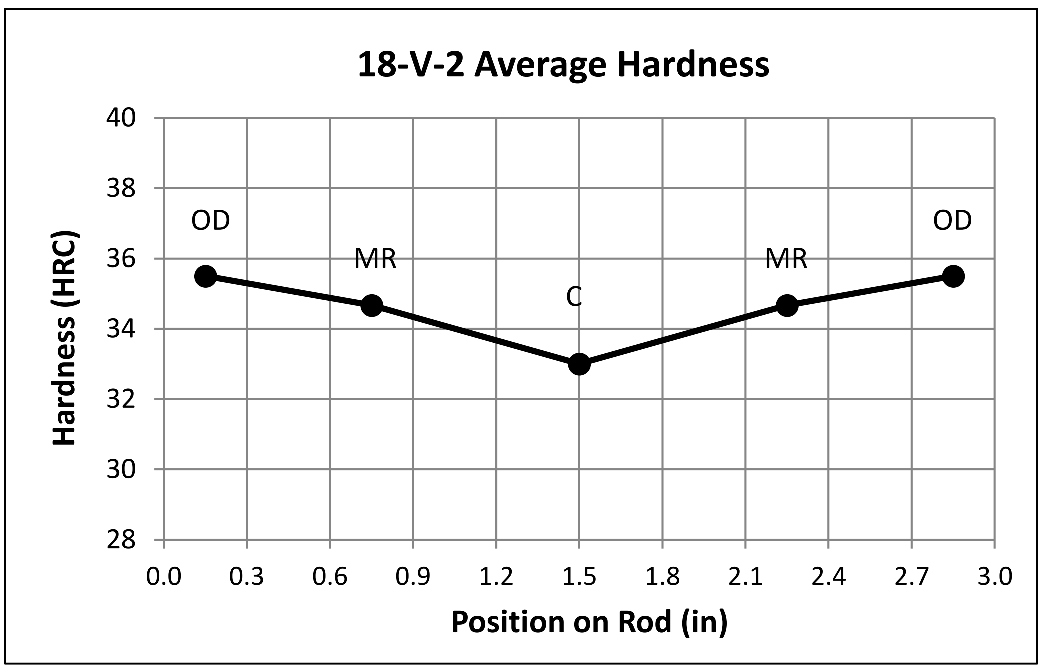


Figure M.3-1: Hardness Profile of Rod 18-V-2

M.4 Summary

Detailed data are listed in the summary table. The results from this table are summarized in "checker board" tables.

M.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 18-V-2						
LRA Job No.:	**TYL130901**	**Structural Component:** Pier E2 **Comments**: Galvanized; 2013 Machined Threads Same Heat as Test Rigs #14 and 15 in Test IV				
Rod#:	**18-V-2**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**35.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	91.4 0.58 1.03 7800		
	OD 3, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			42.7 0.27 0.48 2.1
	OD 4, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			44.1 0.27 0.50 1.8
	MR 1, FFS	**35.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	88.5 0.56 1.00 8000		
	MR 3, EHE	**35.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			44.4 0.28 0.50 2.2
	MR 4, EHE	**34.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			49.6 0.32 0.56 1.8
	Center 1, FFS	**33.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	87.0 0.58 0.98 8400		

M.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 18-V-2						
LRA Job No.:	**TYL130901**	**Structural Component:** Pier E2 **Comments**: Galvanized; 2013 Machined Threads Same Heat as Test Rigs #14 and 15 in Test IV				
Rod#:	**18-V-2**					
Product Form:	**1e**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.5**	Pmax* (lbs)	332.0		
			Fu	1.09		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	1800		
	Thd 2, IHE	**35.5**	$P_{threshold}$* (lbs)		334.0	
			Fu		1.10	
			Hsr		1.5	
			Strain Rate ($x10^{-8}$ in/in/sec)		1.0	
	Thd 3, EHE	**35.5**	$P_{threshold}$* (lbs)			300.8
			Fu			0.99
			Hsr			1.4
			Strain Rate ($x10^{-8}$ in/in/sec)			1.0
	Thd 4, EHE	**35.5**	$P_{threshold}$* (lbs)			297.3
			Fu			0.98
			Hsr			1.3
			Strain Rate ($x10^{-8}$ in/in/sec)			0.5

M.4.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 18-V-2
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**18-V-2**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	35.0	157	100.6	100.6	100.6	100.0%	91.4	0.58	311.5	2.0	7800	0.2121	149.6	50lb/min		1.03	
	OD 3, EHE	3.5% NaCl @ -1.106V	35.5	159	60.0	57.0	47.9	46.7%	42.7	0.27	144.6	0.9	2.1	0.2102		10/5/2,4		0.48	
	OD 4, EHE	3.5% NaCl @ -1.106V	36.0	162	52.0	57.2	49.3	48.2%	44.1	0.27	150.1	0.9	1.8	0.2100		10/5/2,4		0.50	
	MR 1, FFS	Air	35.0	157	97.3	97.3	97.3	100.0%	88.5	0.56	301.5	1.9	8000	0.2131	149.0	50lb/min		1.00	
	MR 3, EHE	3.5% NaCl @ -1.106V	35.0	157	60.0	57.0	47.8	50.2%	44.4	0.28	152.4	1.0	2.2			10/5/2,4		0.50	
	MR 4, EHE	3.5% NaCl @ -1.106V	34.0	153	52.0	65.1	57.0	56.0%	49.6	0.32	166.5	1.1	1.8			10/5/2,4		0.56	Stiffness shows threshold as one step lower - WRC
	Center 1, FFS	Air	33.0	149	96.1	96.1	96.1	100.0%	87.0	0.58	296.0	2.0	8400	0.2148	146.8	50lb/min		0.98	
Threaded	Thd 1, FFS	Air	35.5	159	336.7	336.7	336.7	100.0%	96.8	0.61	239.6	1.5	1800	N/A	N/A	0.4 in/min	332.0	1.09	
	Thd 2, IHE	Air	35.5	159	266.7	351.7	351.7	100.6%	97.4	0.61	238.3	1.5	1	N/A	N/A	10/5/1,8	334.0	1.10	
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.5	159	266.7	330.2	316.9	90.6%	87.7	0.55	215.4	1.4	1	N/A	N/A	10/5/1,8	300.8	0.99	Cracked in Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	35.5	159	270.0	324.0	304.8	89.6%	86.7	0.54	213.9	1.3	0.5	N/A	N/A	13/5/1,16	297.3	0.98	Cracked in Holiday

M.5 Fatigue Pre-cracked Specimen Test Results

M.5.1 OD 1, FFS:

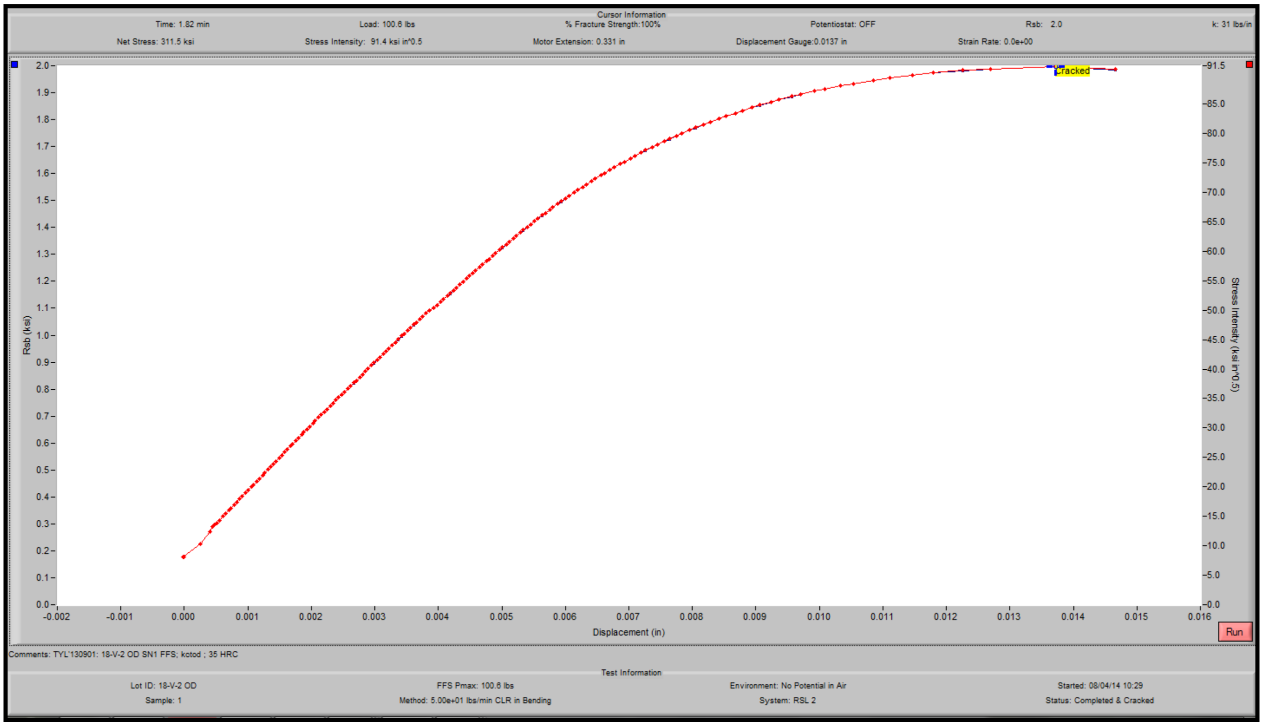


Figure M.5-1: Rod 18-V-2 OD 1, Graphical FFS Results

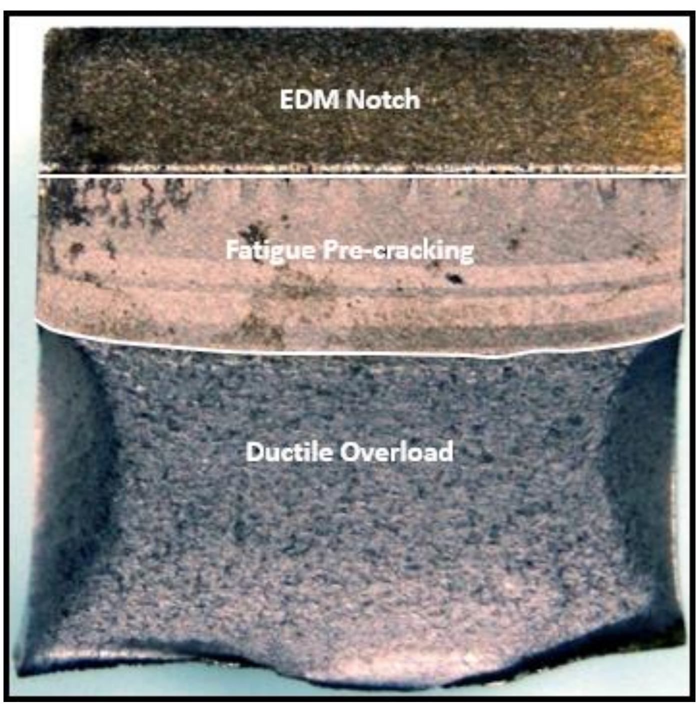


Figure M.5-2: Fracture Face of Rod 18-V-2 OD 1, FFS

M.5.2 OD 3, EHE:

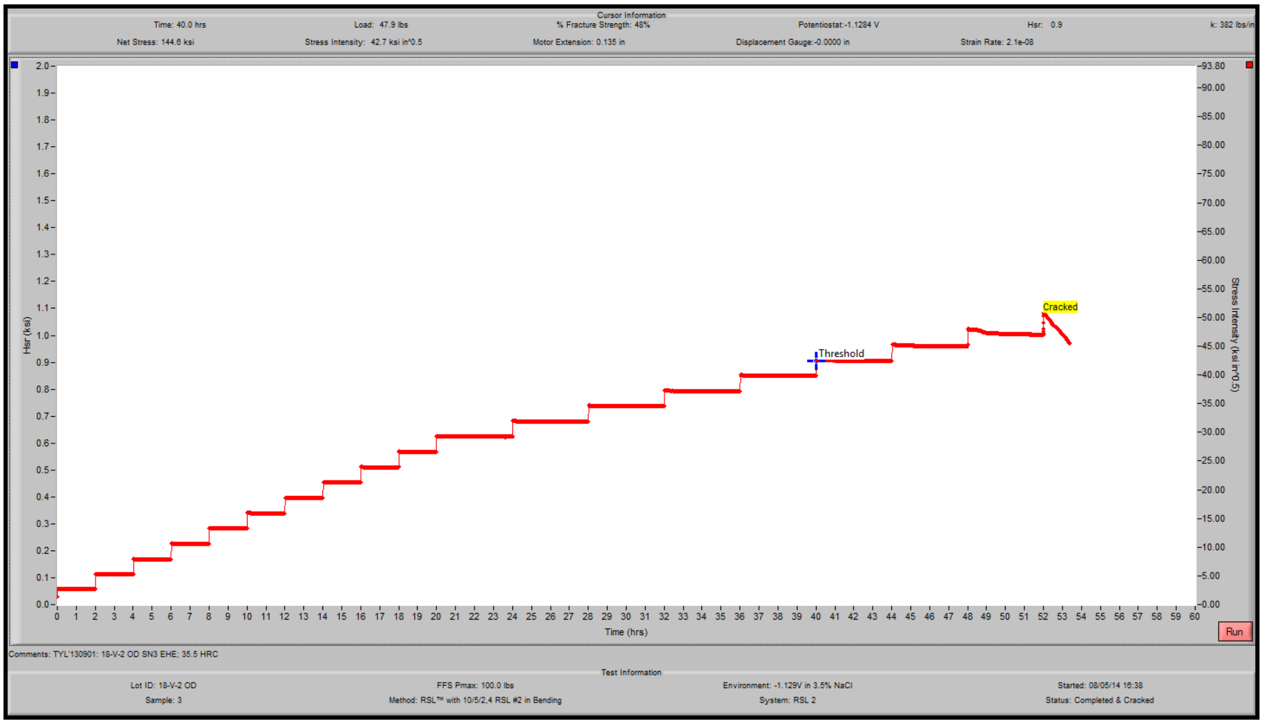


Figure M.5-3: Rod 18-V-2 OD 3, Graphical EHE Results

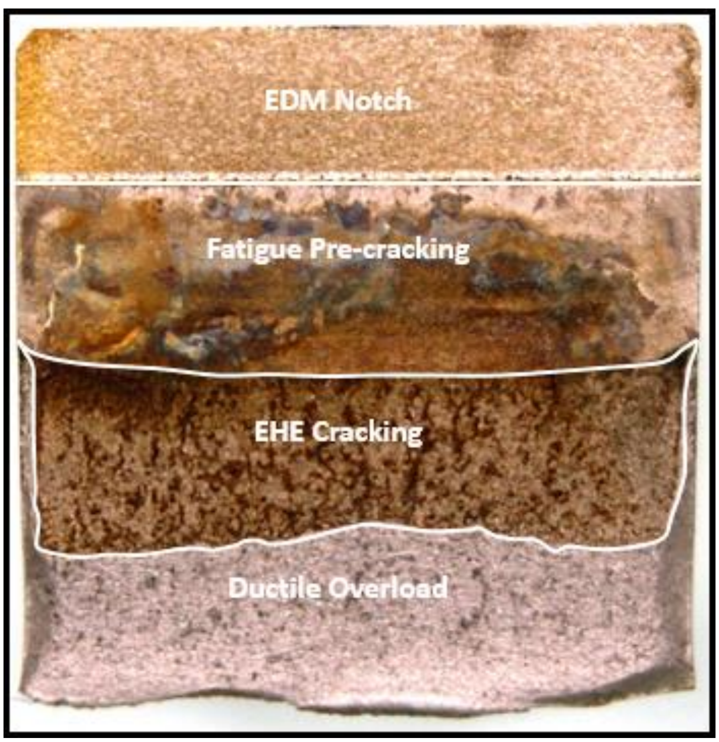


Figure M.5-4: Fracture Face of Rod 18-V-2 OD 3, EHE

M.5.3 OD 4, EHE:

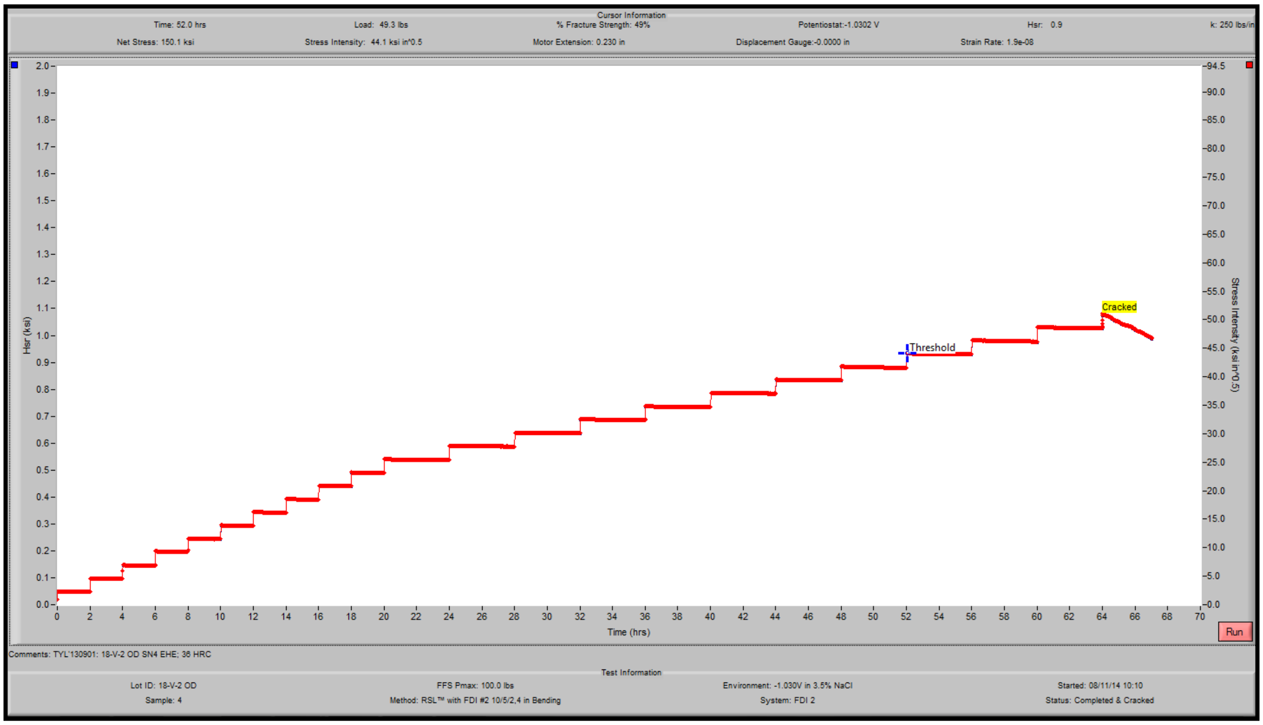


Figure M.5-5: Rod 18-V-2 OD 4, Graphical EHE Results

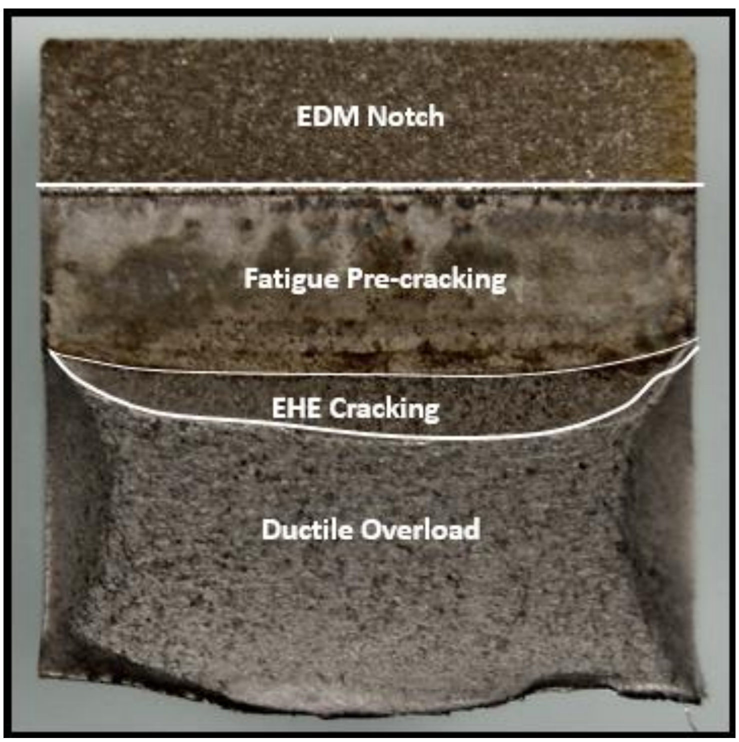


Figure M.5-6: Fracture Face of Rod 18-V-2 OD 4, EHE

M.5.4 MR 1, FFS:

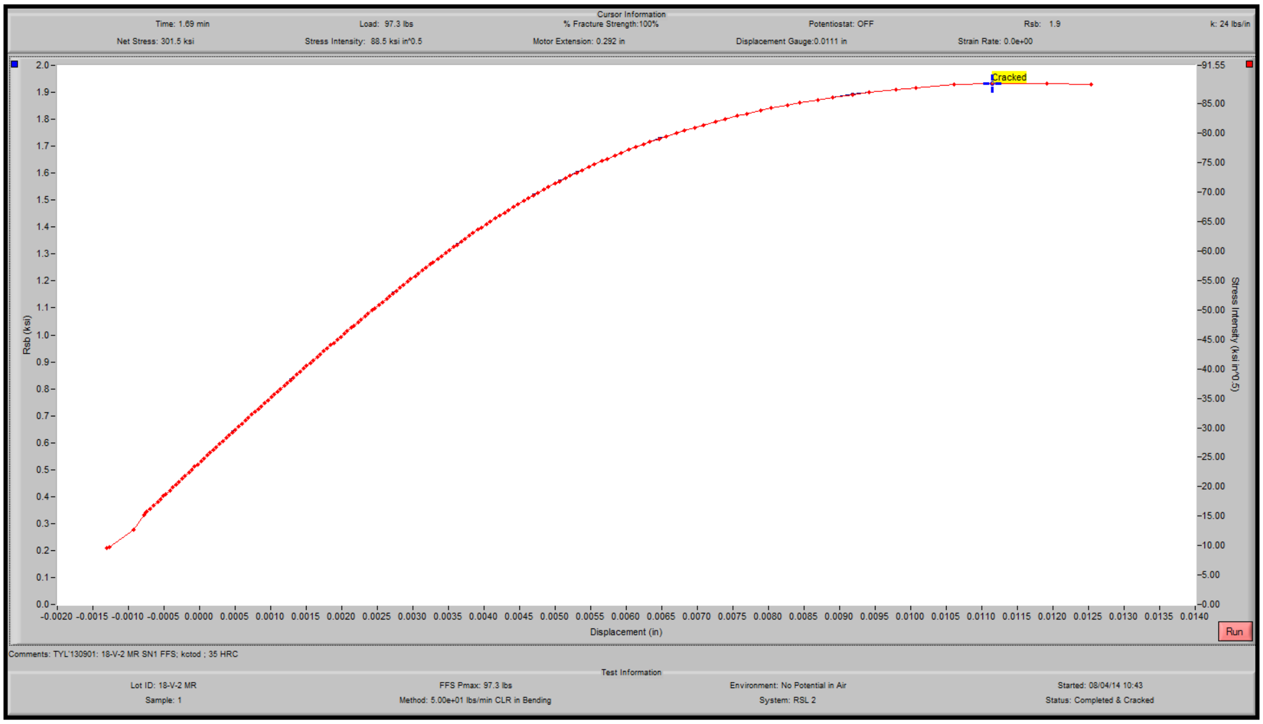


Figure M.5-7: Rod 18-V-2 MR 1, Graphical FFS Results

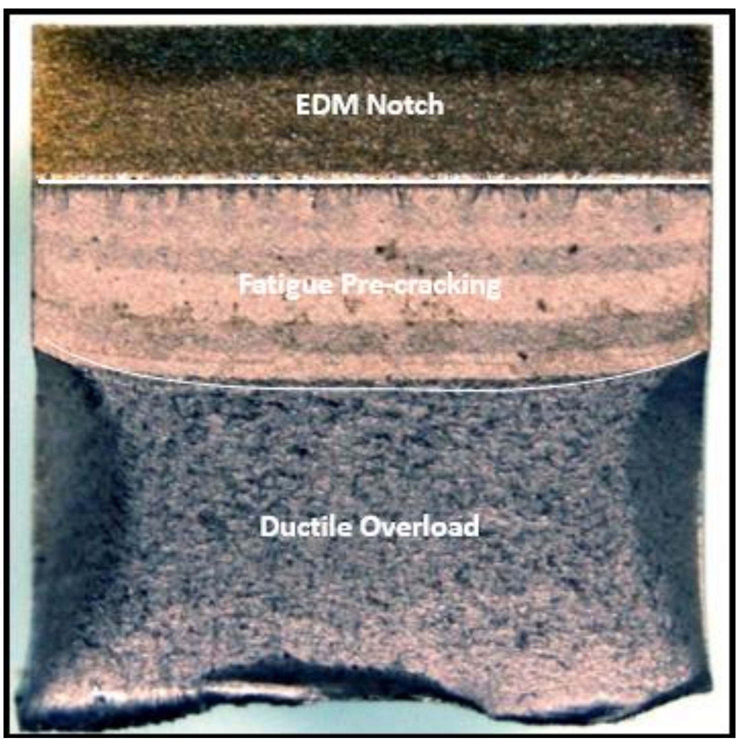


Figure M.5-8: Fracture Face of Rod 18-V-2 MR 1, FFS

M.5.5 MR 3, EHE:

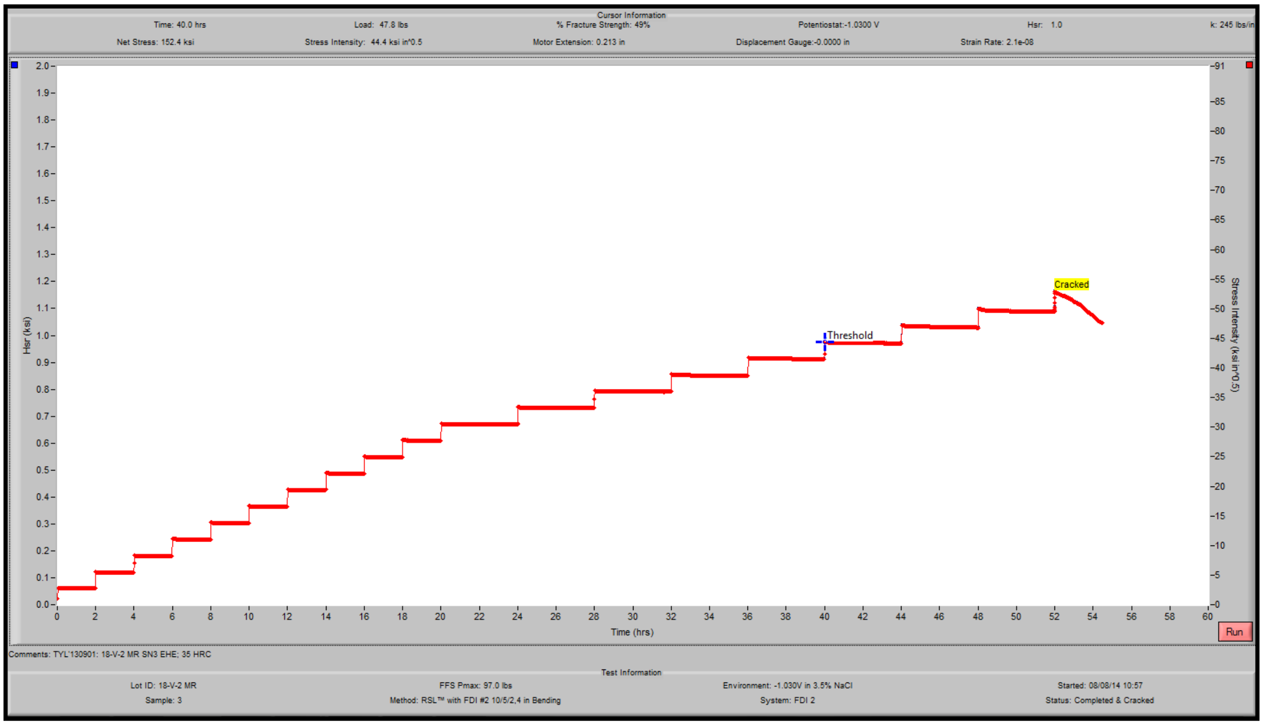


Figure M.5-9: Rod 18-V-2 MR 3, Graphical EHE Results

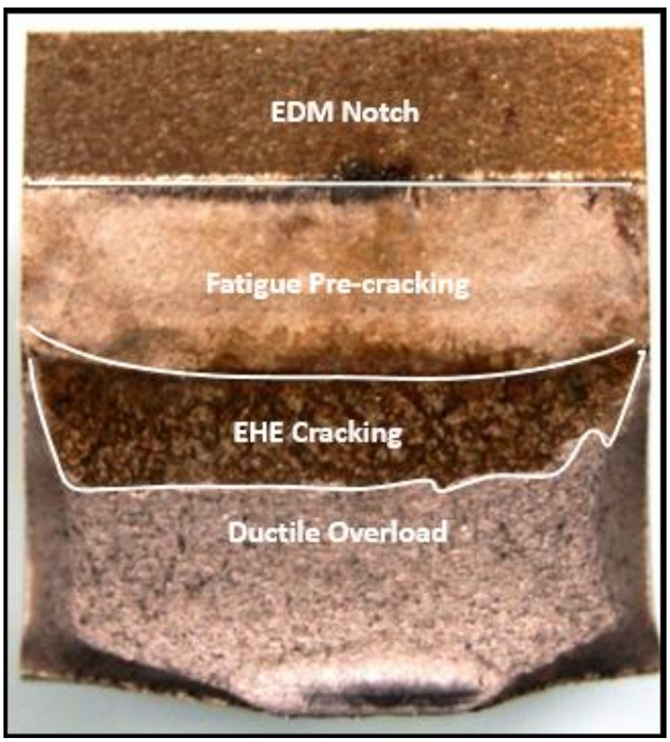


Figure M.5-10: Fracture Face of Rod 18-V-2 MR 3, EHE

M.5.6 MR 4, EHE:

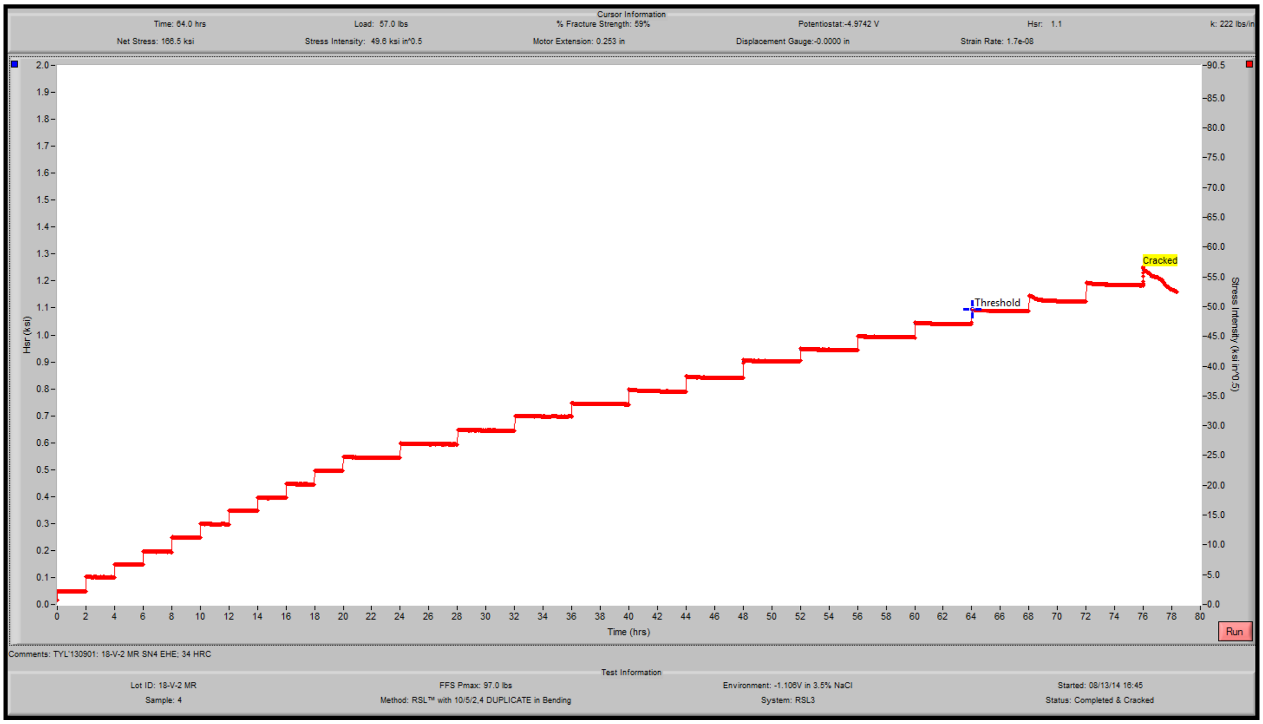


Figure M.5-11: Rod 18-V-2 MR 4, Graphical EHE Results

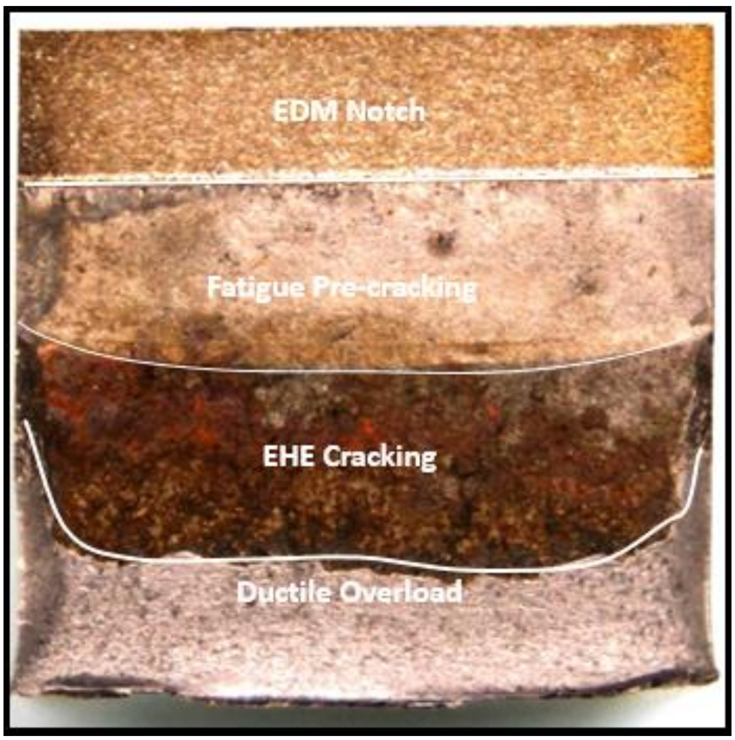


Figure M.5-12: Fracture Face of Rod 18-V-2 MR 4, EHE

M.5.7 Center 1, FFS:

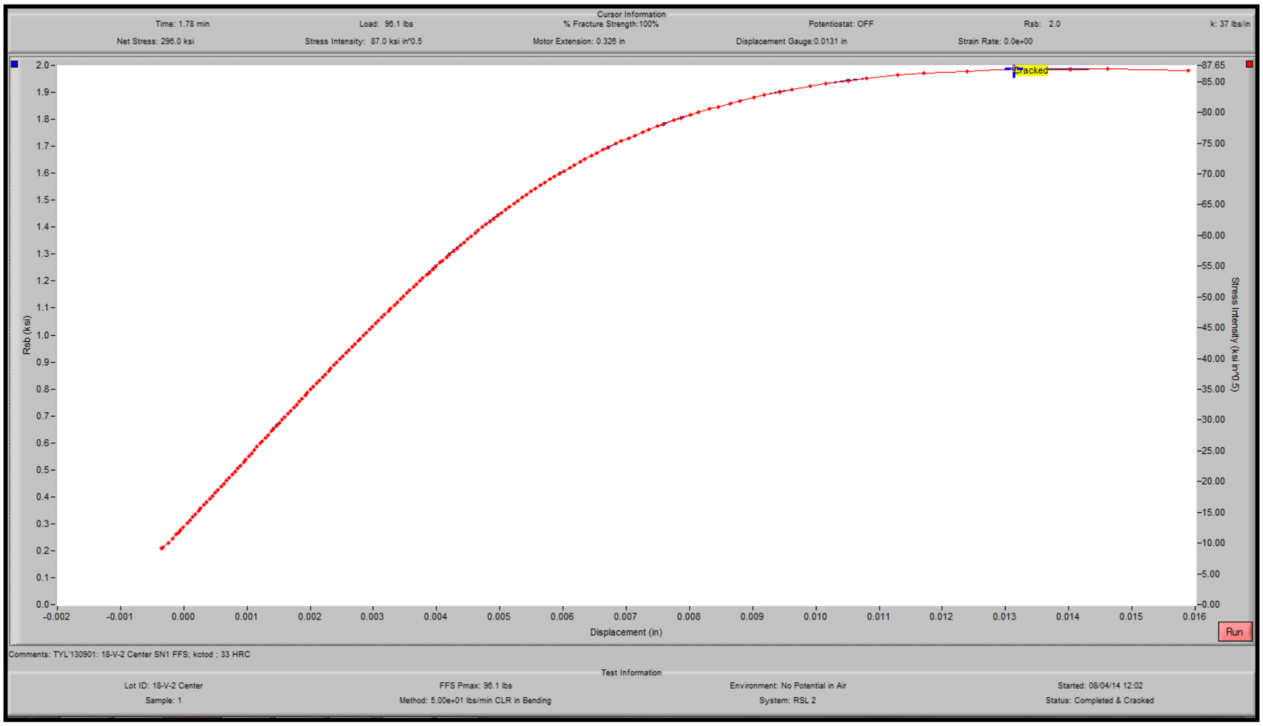


Figure M.5-13: Rod 18-V-2 Center 1, Graphical FFS Results

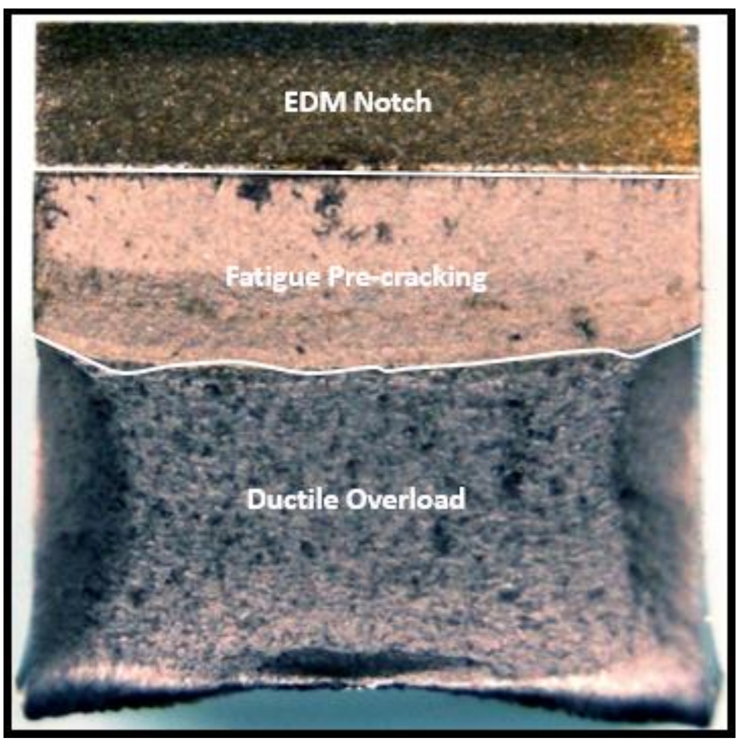


Figure M.5-14: Fracture Face of Rod 18-V-2 Center 1, FFS

M.6 Threaded Specimen Test Results

M.6.1 Thd 1, FFS:

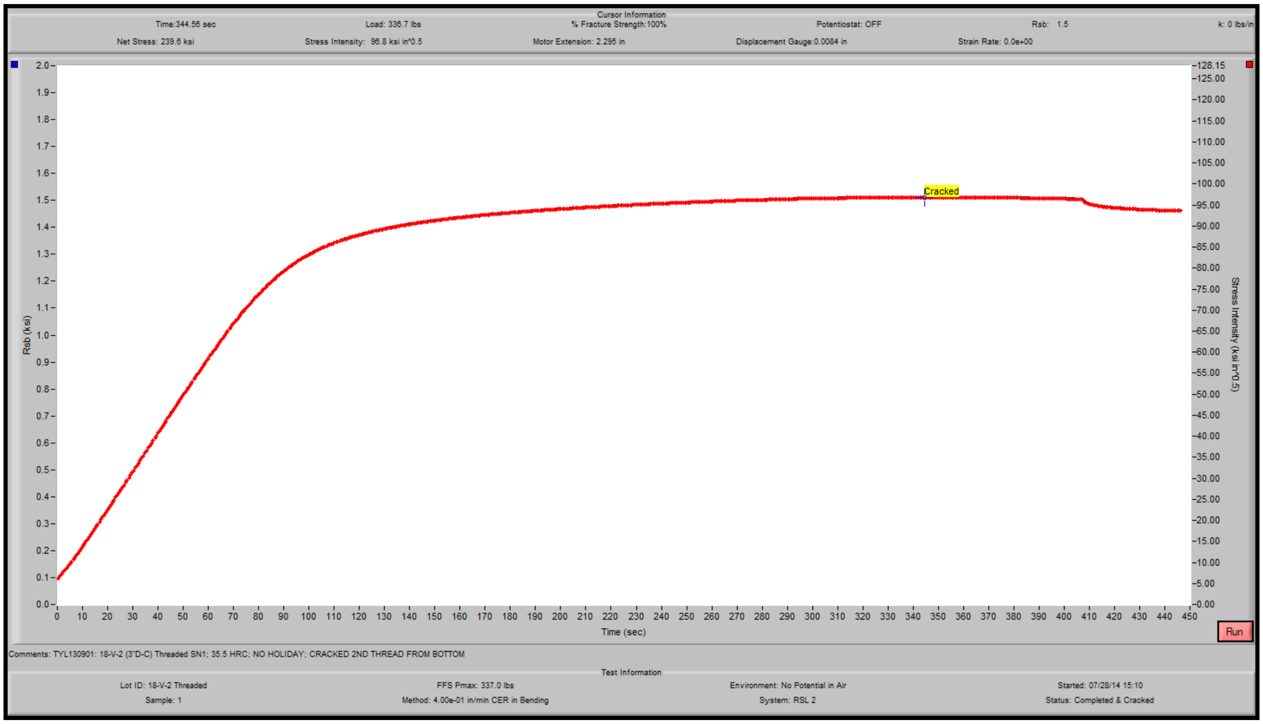


Figure M.6-1: Rod 18-V-2 Thd 1, Graphical FFS Results

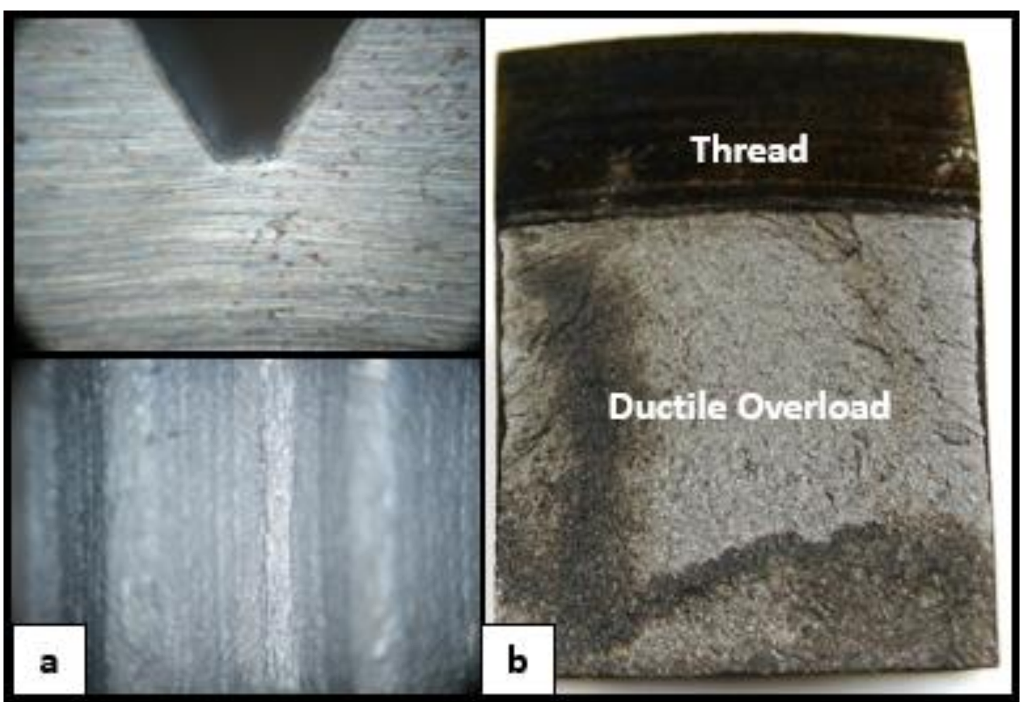


Figure M.6-2: Rod 18-V-2 Thd 1 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

M.6.2 Thd 2, IHE:

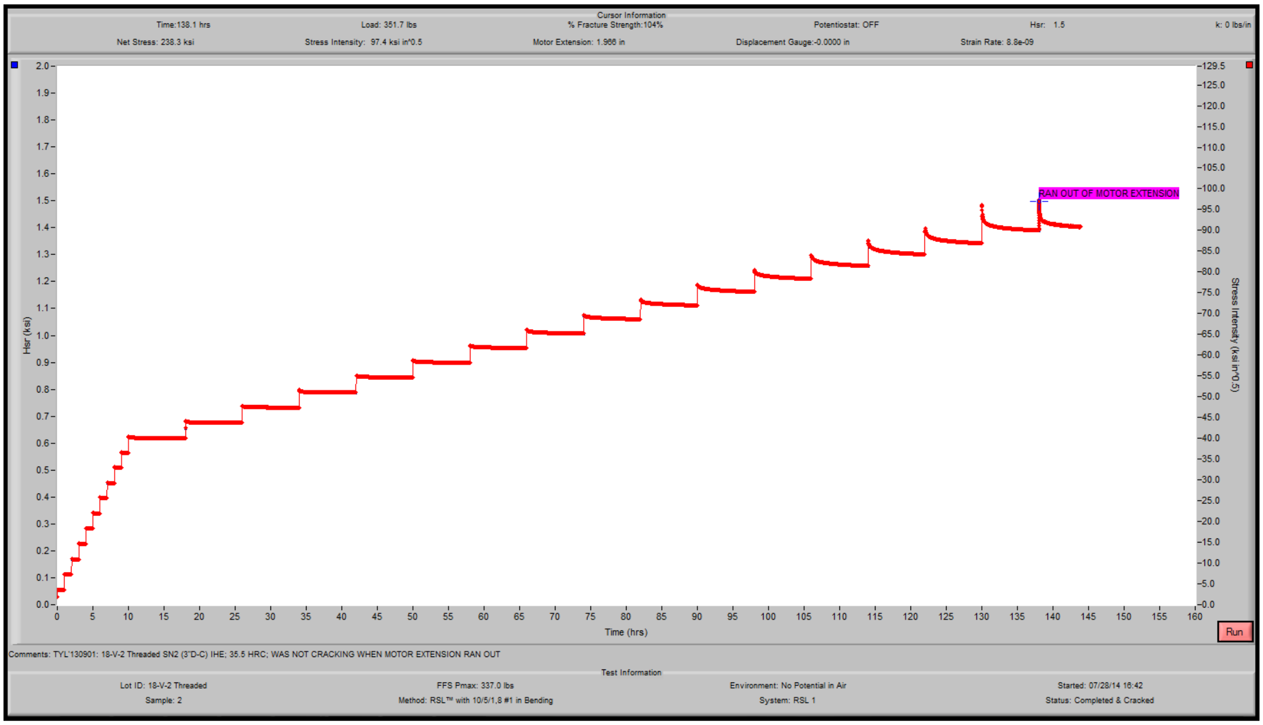


Figure M.6-3: Rod 18-V-2 Thd 2, Graphical IHE Results

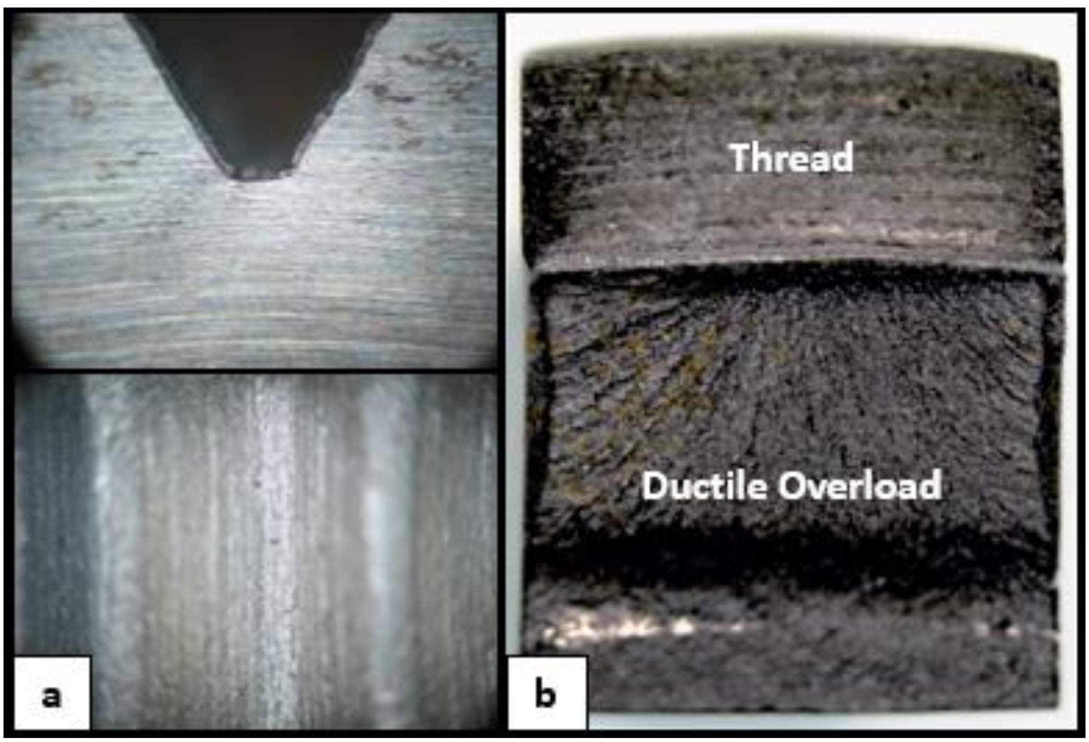


Figure M.6-4: Rod 18-V-2 Thd 2 a) Thread Root from Side and Normal Views Post IHE Test and b) IHE Fracture Face

M.6.3 Thd 3, EHE:

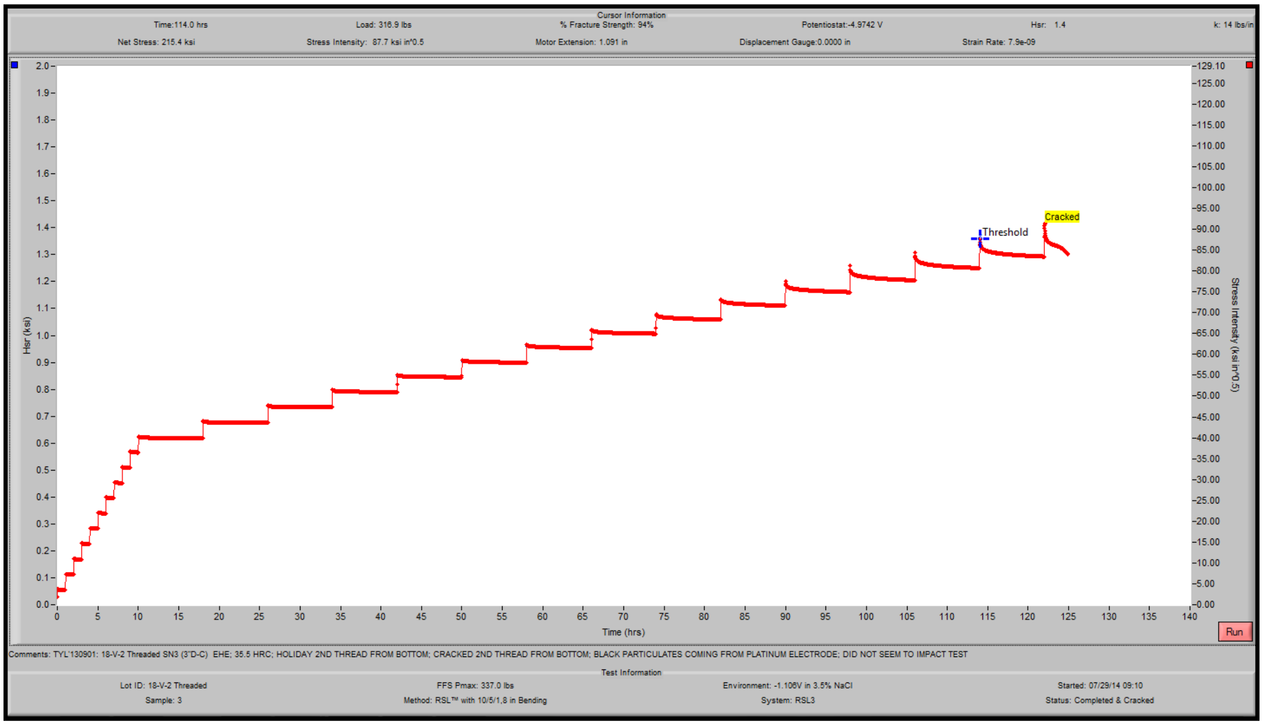


Figure M.6-5: Rod 18-V-2 Thd 3 Graphical EHE Results

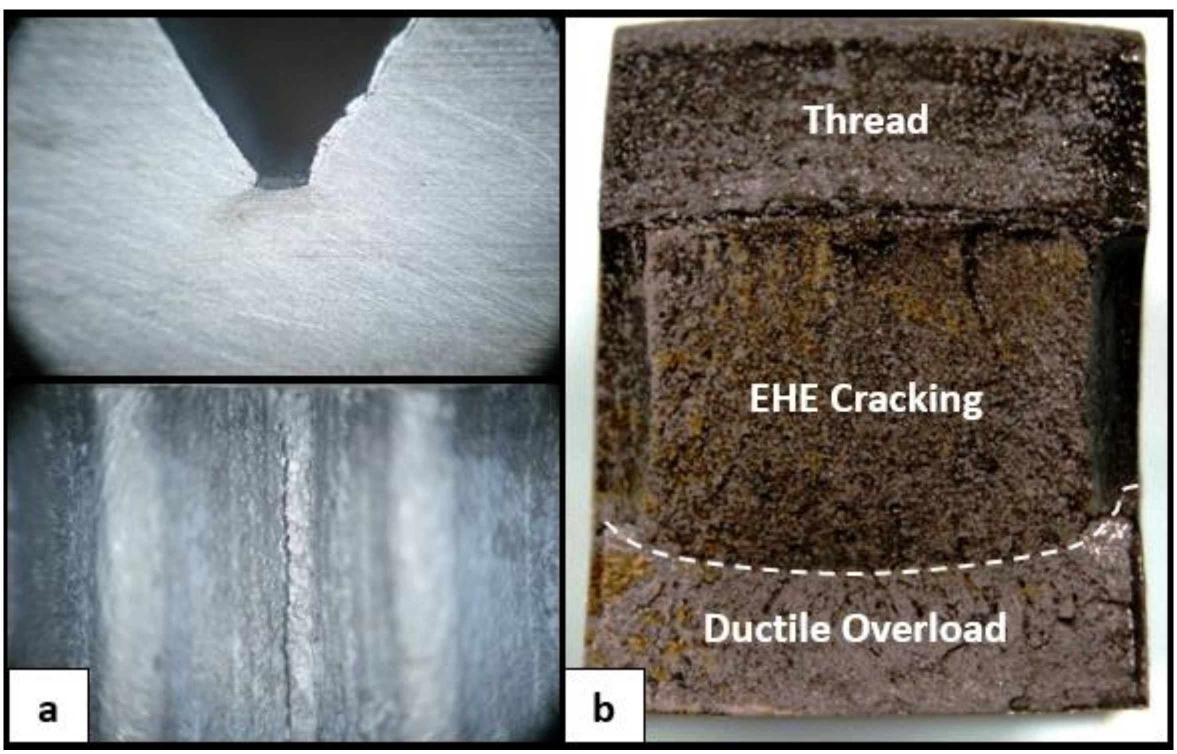


Figure M.6-6: Rod 18-V-2 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

M.6.4 Thd 4, EHE:

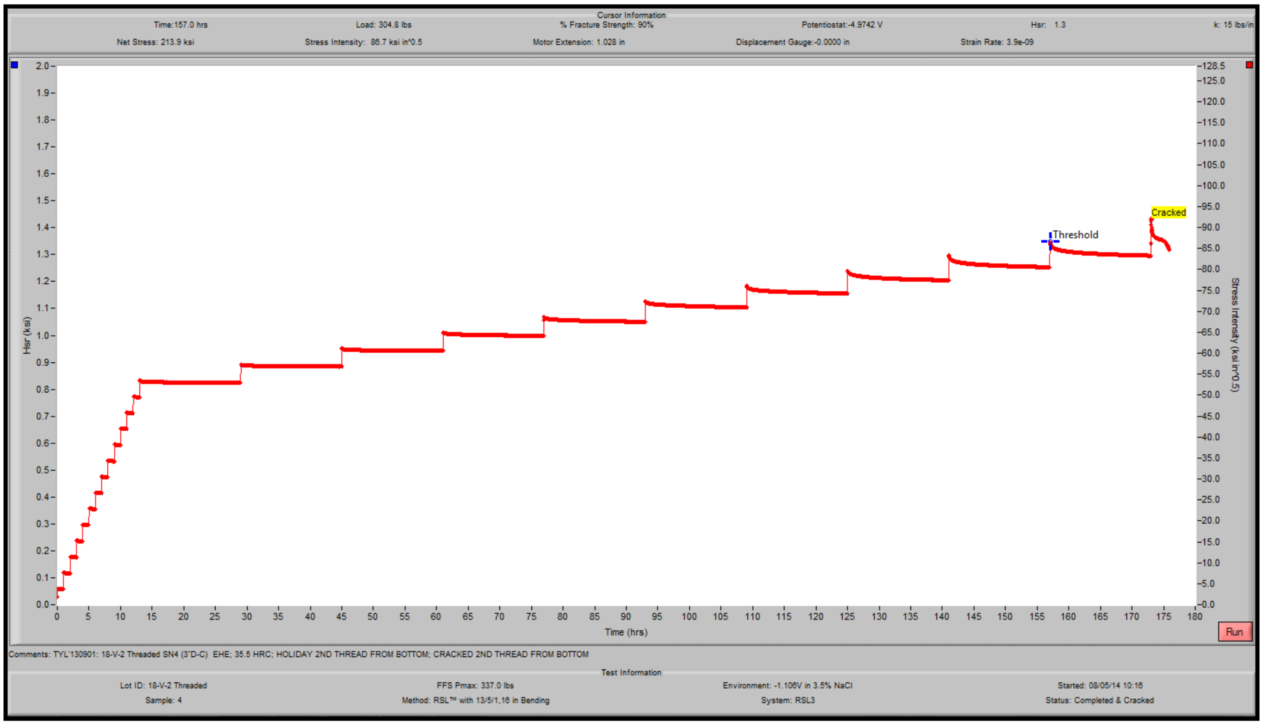


Figure M.6-7: Rod 18-V-2 Thd 4 Graphical EHE Results

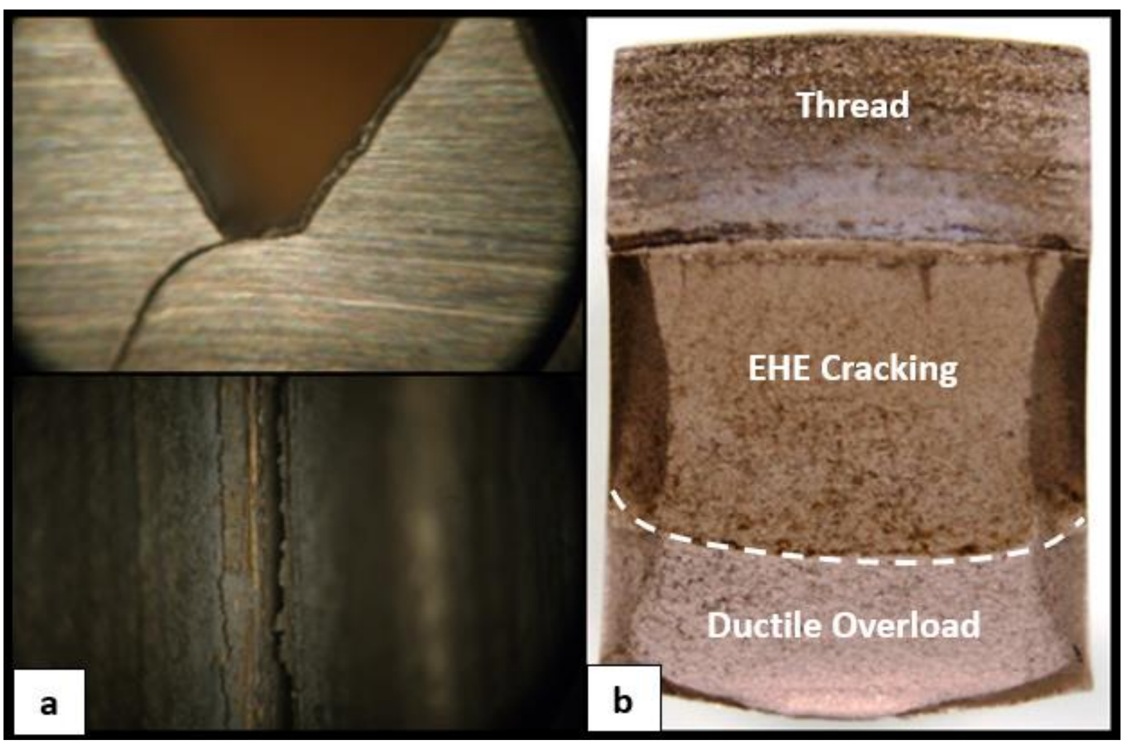


Figure M.6-8: Rod 18-V-2 Thd 4 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Appendix N: Rod 7-V-E012

N.1 Description of Sample

Rod 7-V-E012 was a PWS Strand Anchor Rod located at the anchorage location above Pier E2 from the same heat of rod as Test Rigs #9 and #10 in tested in Test IV and Rod 7-V-E027 in Test V. It was made from 4140 steel to ASTM A354 Grade BD. Rod 7-V-E012 is 3.5 inches in diameter with machined threads. The segment from one of the rod pieces provided to LRA is shown in **Figure N.1-1**.

Figure N.1-1: Pier E2 Anchorage PWS Strand Anchor, Rod 7-V-E012

N.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 7-V-E012 and can be seen versus time in **Figure N**.2-1. The final OCP recorded for Rod 7-V-E012 was Vsce=-0.940 V.

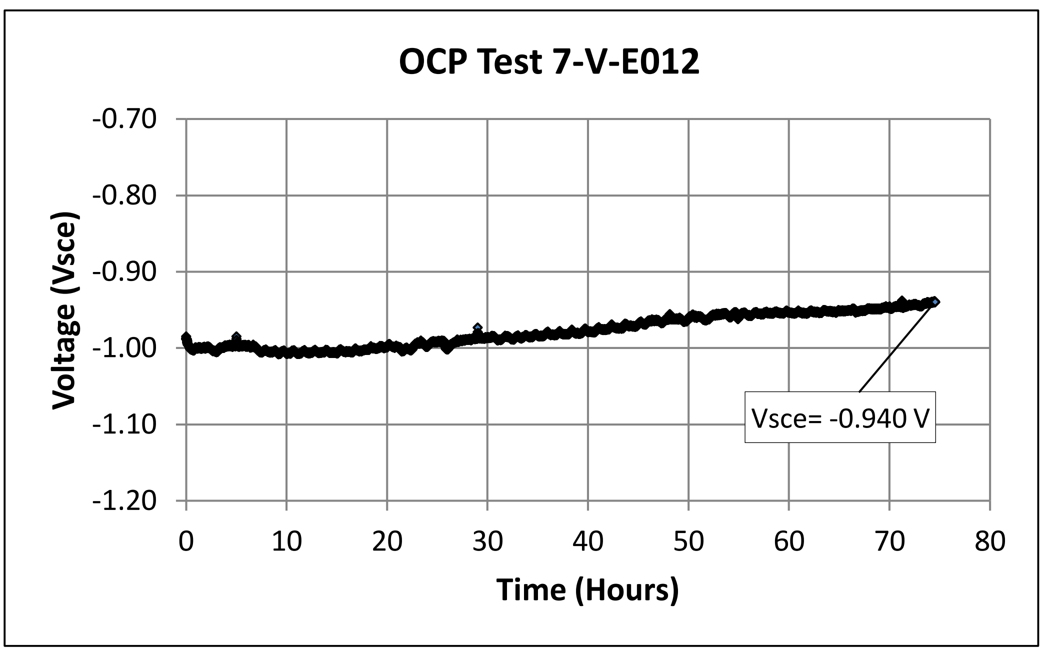


Figure N.2-1: Open Circuit Potential for Rod 7-V-E012

LRA@LouRaymond.com
Phone: 949 474-0218

N.3 Hardness

The hardness data and profile for sample 7-V-E012 are shown in **Table N.3-1** and **Figure N.3-1**.

Table N.3-1: Hardness Data of Rod 7-V-E012 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	28.5	28.5
MR 1, FFS	32.5	33.3
MR 3, EHE	34.0	
MR 4, EHE	33.5	
OD 1, FFS	38.0	37.9
OD 3, EHE	38.0	
OD 4, EHE	37.5	
Thd 1, FFS	38.0	
Thd 4, EHE	38.5	
Thd 7, EHE	38.0	
Thd 8, EHE	37.5	

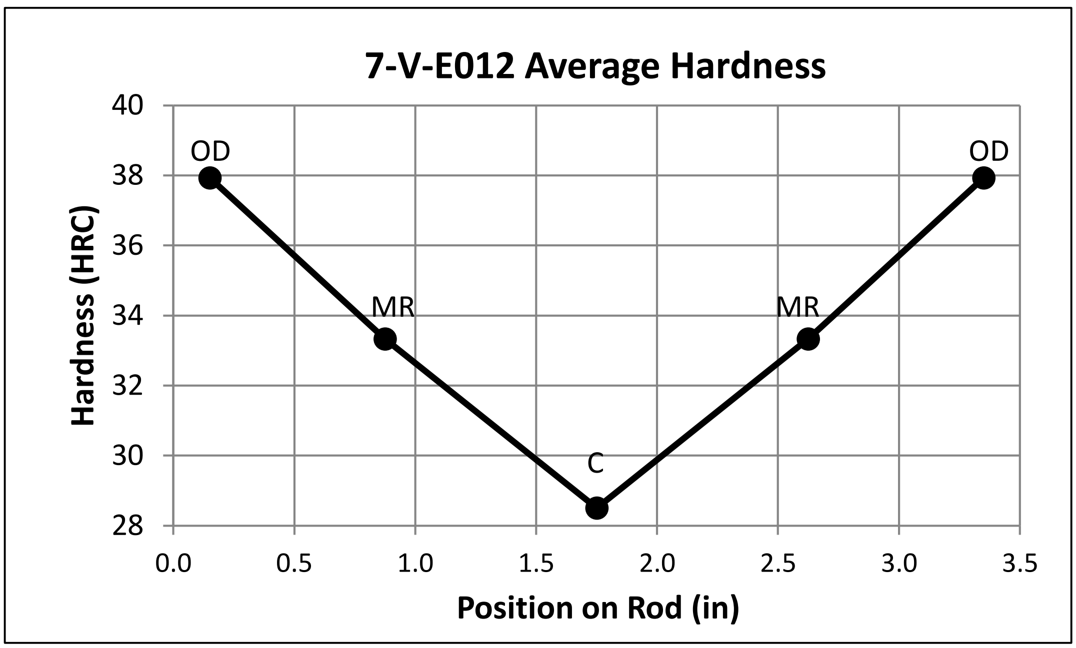


Figure N.3-1: Hardness Profile of Rod 7-V-E012

N.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

N.4.1 Fatigue Pre-crack Results

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E012						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)				
Rod#:	**7-V-E012**					
Product Form:	**1e**	**Comments**: 2010 Machined Threads				
Rod OD:	**3.5"**	Same Heat of Rod as Test Rigs #9 and #10 in Test IV				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**38.0**	K_{max} DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)	87.0 0.51 0.96 8300		
	OD 3, EHE	**38.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)			20.5 0.12 0.23 4.5
	OD 4, EHE	**37.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)			21.1 0.12 0.23 0.9
	MR 1, FFS	**32.5**	K_{max} DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)	78.6 0.54 0.87 8000		
	MR 3, EHE	**34.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)			28.4 0.19 0.31 1.9
	MR 4, EHE	**33.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)			32.6 0.22 0.36 1.3
	Center 1, FFS	**28.5**	K_{max} DTI_{th} Fu Strain Rate (x10^{-8} in/in/sec)	77.6 0.59 0.86 8200		

N.4.2 Threaded Results

Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-E012

LRA Job No.:	**TYL130523**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)
Rod#:	**7-V-E012**	
Product Form:	**1e**	**Comments**: 2010 Machined Threads
Rod OD:	**3.5"**	Same Heat of Rod as Test Rigs #9 and #10 in Test IV

	Sample #/ID	HRC		P-FFS	P-IHE	P-EHE
Threaded	**Thd 1, FFS**	**38.0**	Pmax* (lbs)	367.7		
			Fu	1.19		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	2950		
	Thd 4, EHE	**38.5**	$P_{threshold}$* (lbs)			194.1
			Fu			0.63
			Hsr			0.8
			Strain Rate ($x10^{-8}$ in/in/sec)			2.0
	Thd 7, EHE	**38.0**	$P_{threshold}$* (lbs)			196.5
			Fu			0.63
			Hsr			0.8
			Strain Rate ($x10^{-8}$ in/in/sec)			1.7
	Thd 8, EHE	**37.5**	$P_{threshold}$* (lbs)			178.7
			Fu			0.58
			Hsr			0.8
			Strain Rate ($x10^{-8}$ in/in/sec)			1.5

N.4.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-E012
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130523**
Rod #:	**7-V-E012**
Product Form:	**1e**
Rod OD:	**3.5"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	38.0	172	97.3	97.3	97.3	100.0%	87.0	0.51	295.5	1.7	8300	0.2110	138.3	50 lbs/min		0.96	
	OD 3, EHE	3.5% NaCl @ -1.106V	38.0	172	68.0	30.6	23.7	23.6%	20.5	0.12	69.0	0.4	4.5	0.2068		10/5/2,4		0.23	
	OD 4, EHE	3.5% NaCl @ -1.106V	37.5	169	26.0	27.3	23.3	24.3%	21.1	0.12	71.8	0.4	0.9	0.2111		10/5/2,4		0.23	
	MR 1, FFS	Air	32.5	147	89.6	89.6	89.6	100.0%	78.6	0.54	265.4	1.8	8000	0.2096	161.4	50 lbs/min		0.87	
	MR 3, EHE	3.5% NaCl @ -1.106V	34.0	153	60.0	45.0	32.9	36.1%	28.4	0.19	95.5	0.6	1.9	0.2077		10/5/2,4		0.31	
	MR 4, EHE	3.5% NaCl @ -1.106V	33.5	151	36.0	48.6	35.9	41.5%	32.6	0.22	111.4	0.7	1.3	0.2130		10/5/2,4		0.36	
	Center 1, FFS	Air	28.5	133	86.4	86.4	86.4	100.0%	77.6	0.59	263.9	2.0	8200	0.2126	152.0	50 lbs/min		0.86	
Threaded	Thd 1, FFS	Air	38.0	172	378.8	378.8	378.8	100.0%	107.2	0.62	264.7	1.5	2950	N/A		0.4 in/min	367.7	1.19	
	Thd 4, EHE	3.5% NaCl @ -1.106V	38.5	174	249.0	311.4	198.5	52.8%	56.6	0.32	140.1	0.8	2.0	N/A		10/5/2,4	194.1	0.63	Did not crack in Holiday.
	Thd 7, EHE	3.5% NaCl @ -1.106V	38.0	172	210.0	220.5	198.8	53.5%	57.3	0.33	142.0	0.8	1.7	N/A		10/5/2,4	196.5	0.63	Did not crack in Holiday.
	Thd 8, EHE	3.5% NaCl @ -1.106V	37.5	169	180.0	189.0	179.5	48.6%	52.1	0.31	128.6	0.8	1.5	N/A		10/5/2,4	178.7	0.58	Did not crack in Holiday.

N.5 Fatigue Pre-cracked Specimen Test Results

N.5.1 OD 1, FFS:

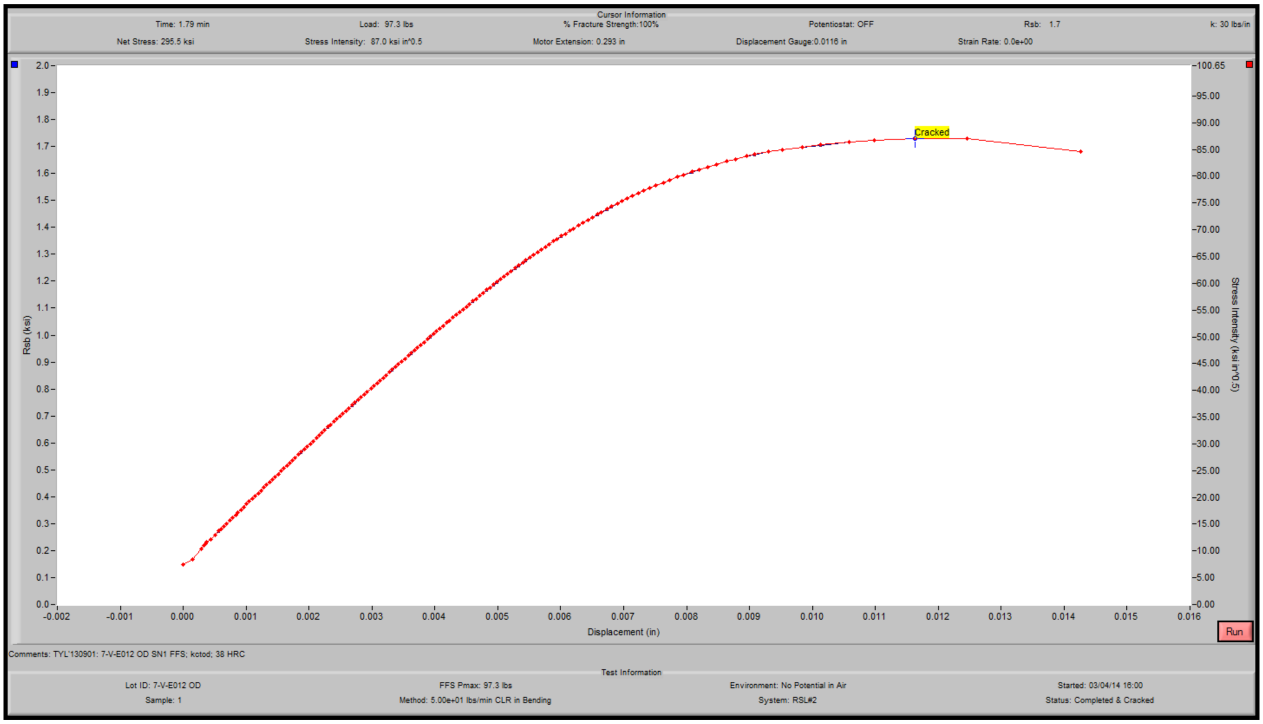


Figure N.5-1: Rod 7-V-E012 OD 1, Graphical FFS Results

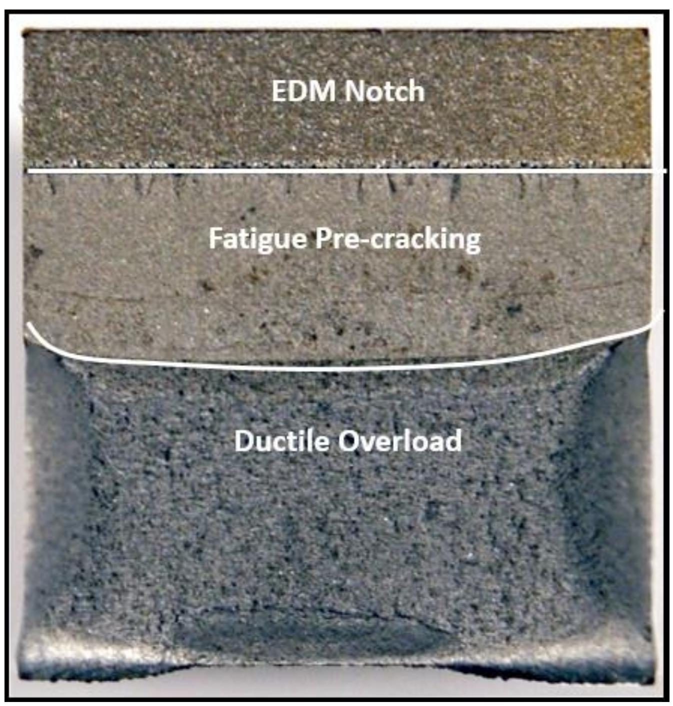


Figure N.5-2: Fracture Face of Rod 7-V-E012 OD 1, FFS

N.5.2 OD 3, EHE:

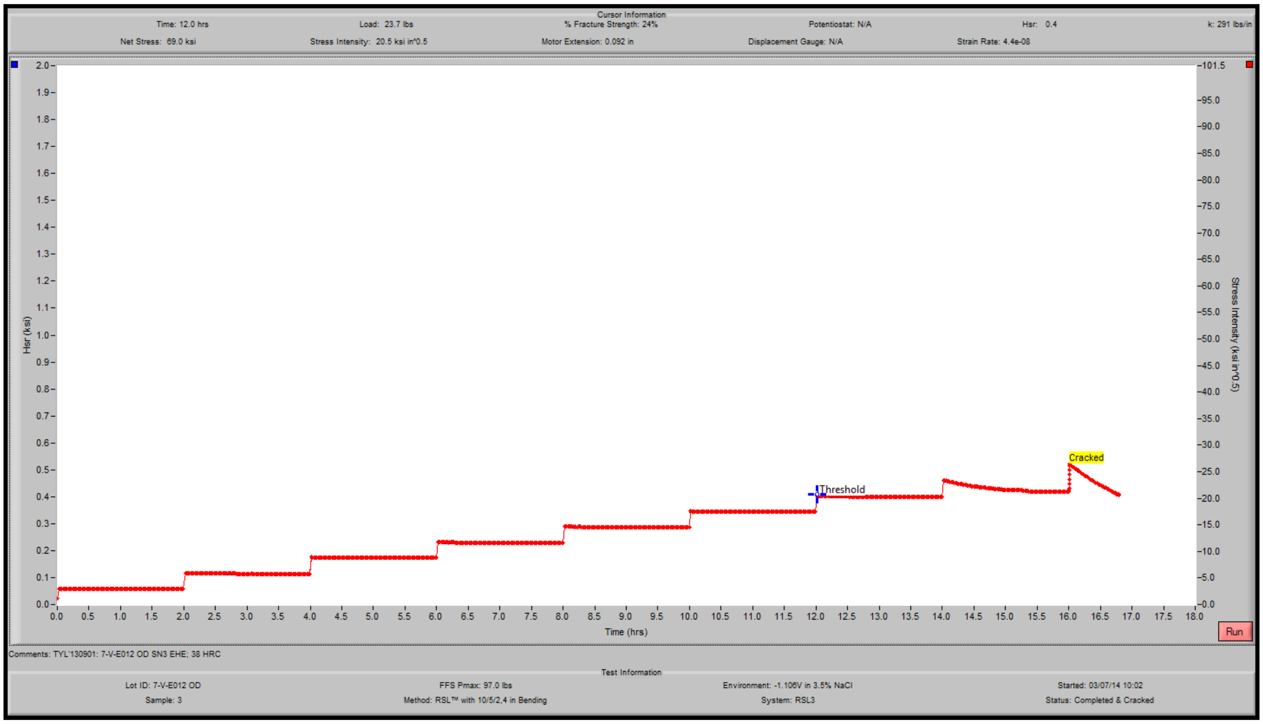


Figure N.5-3: Rod 7-V-E012 OD 3, Graphical EHE Results

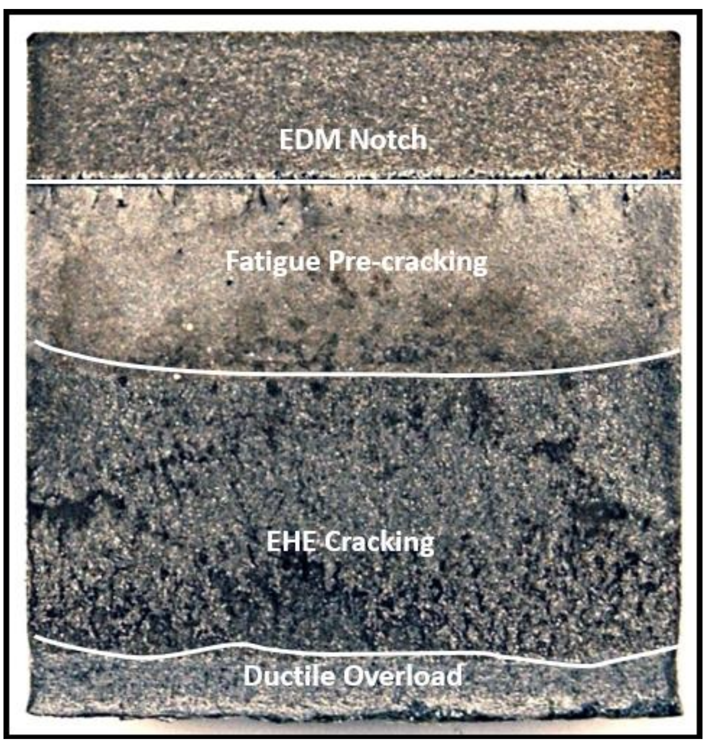


Figure N.5-4: Fracture Face of Rod 7-V-E012 OD 3, EHE

N.5.3 OD 4, EHE:

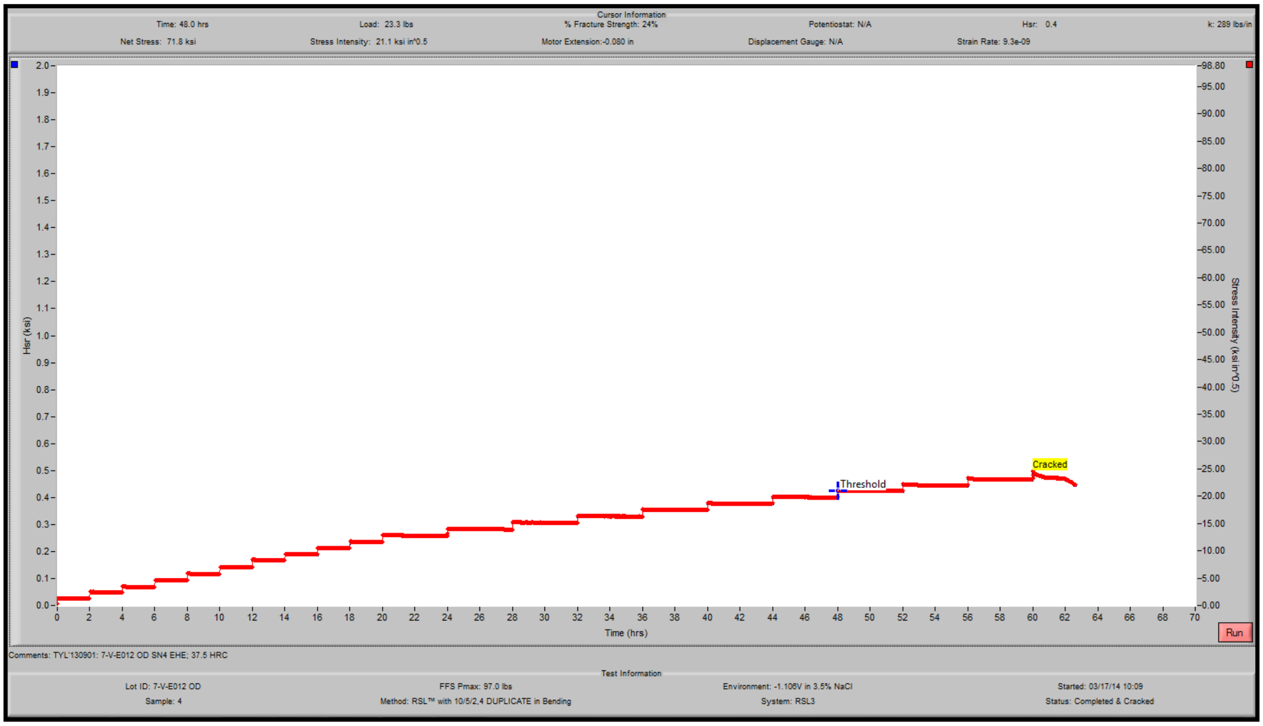


Figure N.5-5: Rod 7-V-E012 OD 4, Graphical EHE Results

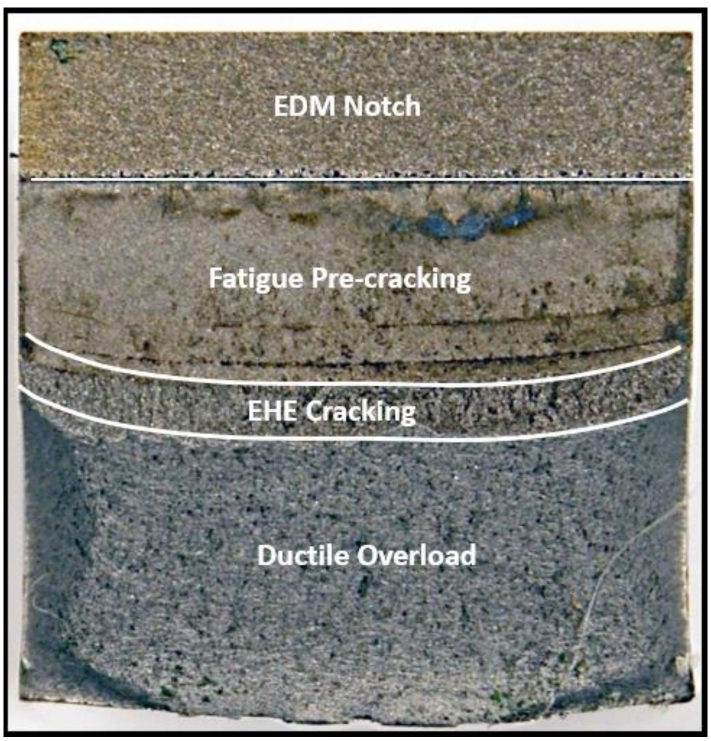


Figure N.5-6: Fracture Face of Rod 7-V-E012 OD 4, EHE

N.5.4 MR 1, FFS:

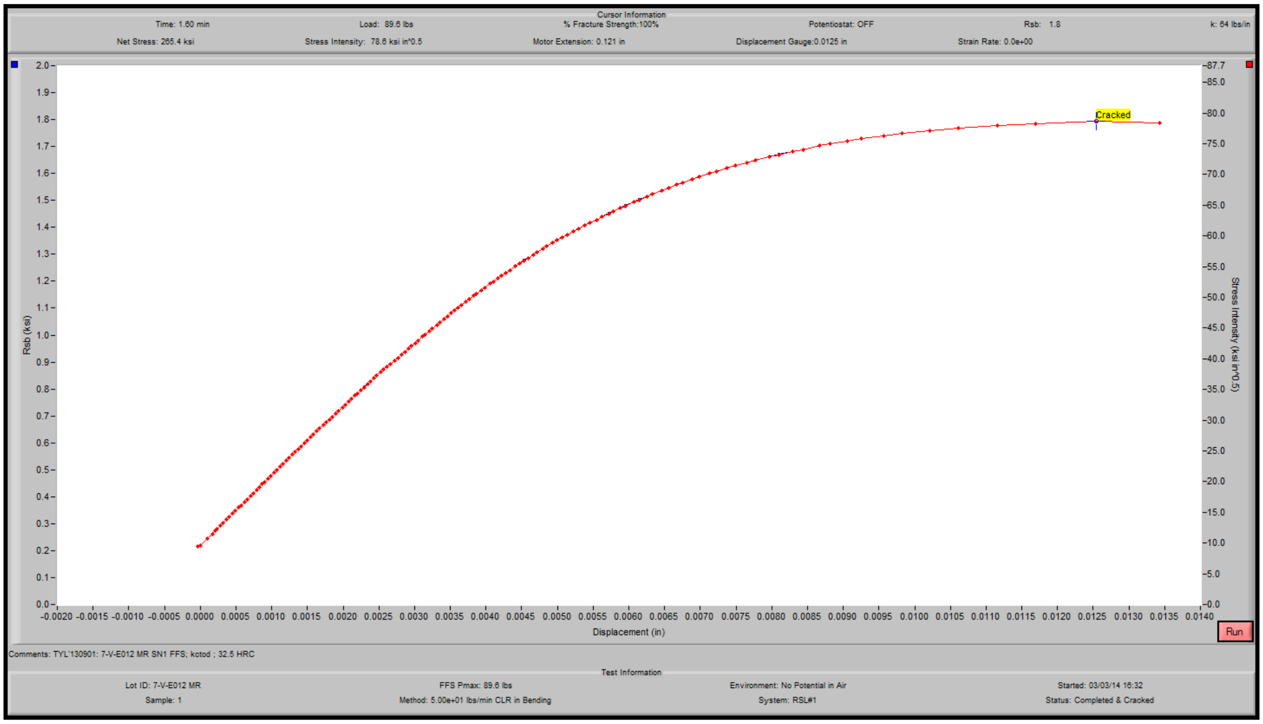


Figure N.5-7: Rod 7-V-E012 MR 1, Graphical FFS Results

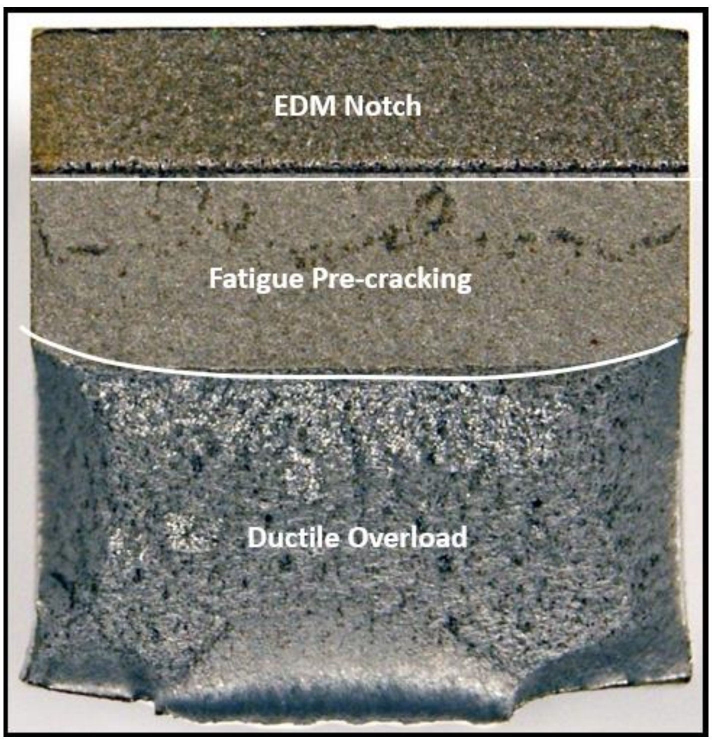


Figure N.5-8: Fracture Face of Rod 7-V-E012 MR 1, FFS

N.5.5 MR 3, EHE:

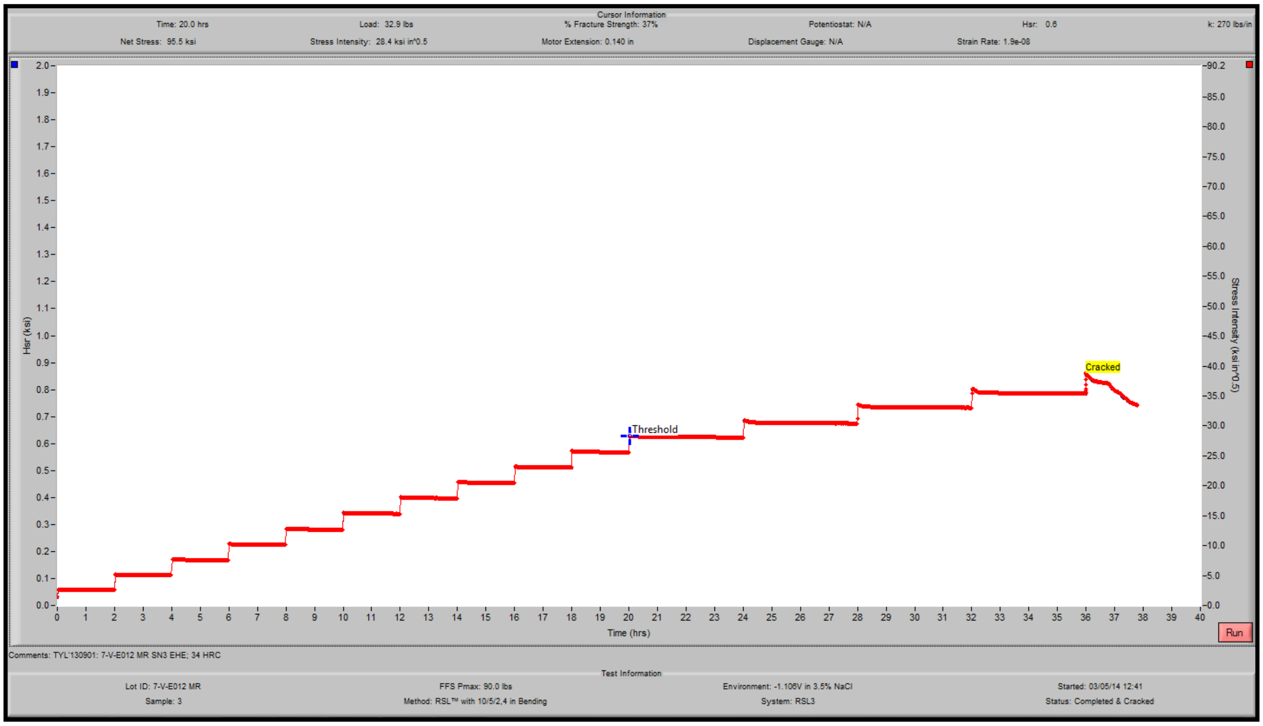


Figure N.5-9: Rod 7-V-E012 MR 3, Graphical EHE Results

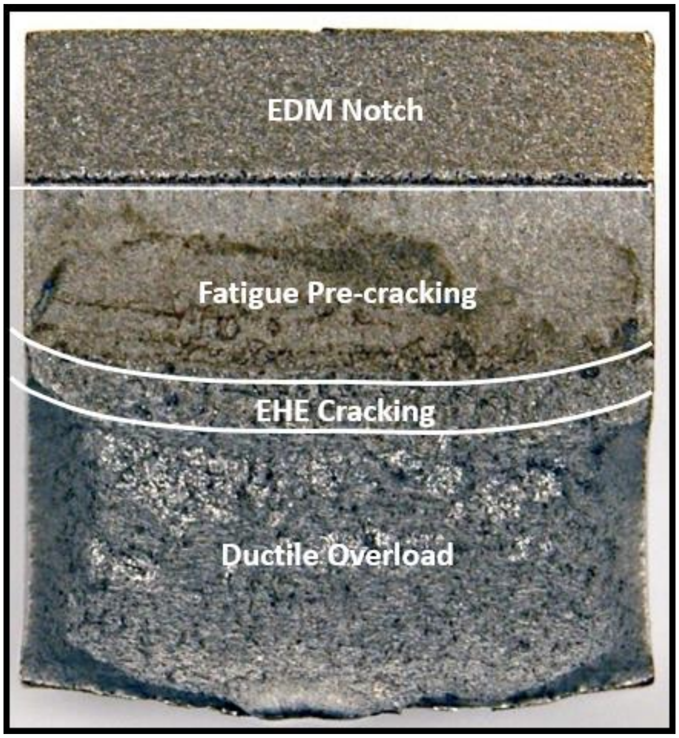


Figure N.5-10: Fracture Face of Rod 7-V-E012 MR 3, EHE

N.5.6 MR 4, EHE:

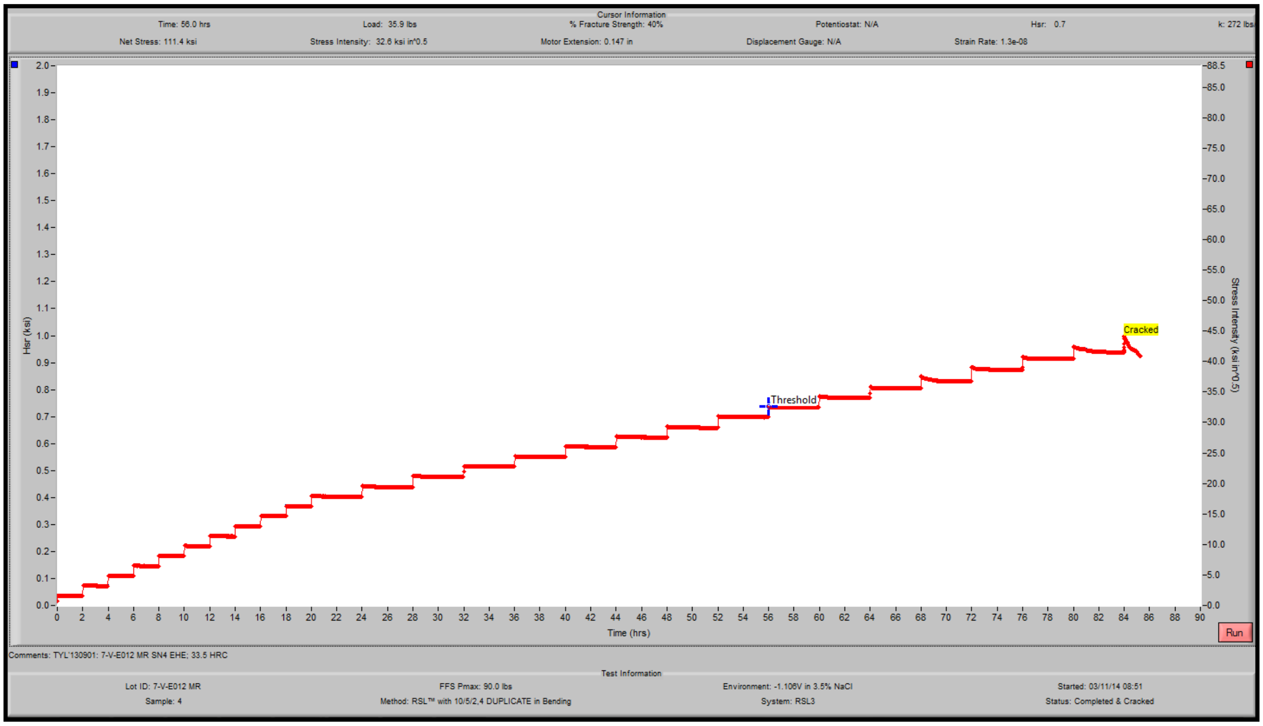


Figure N.5-11: Rod 7-V-E012 MR 4, Graphical EHE Results

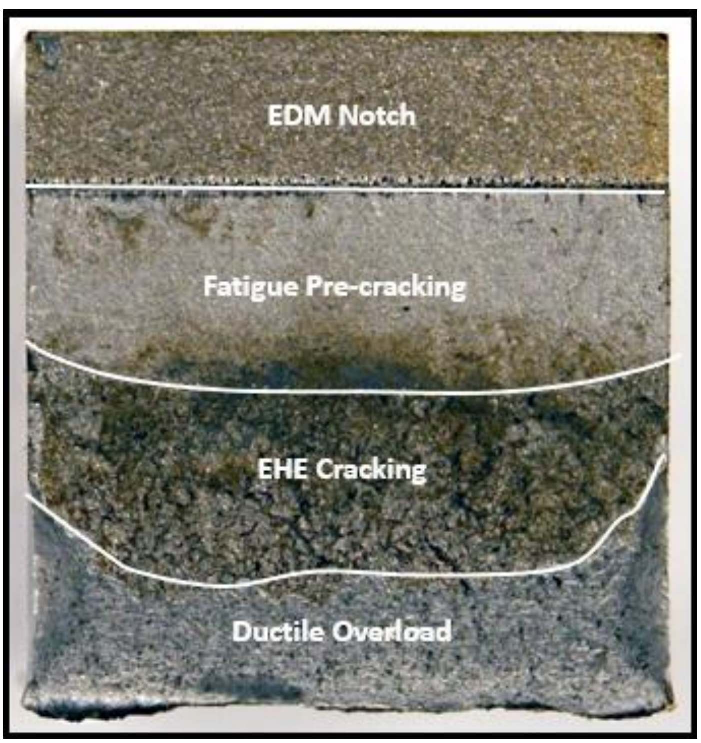


Figure N.5-12: Fracture Face of Rod 7-V-E012 MR 4, EHE

N.5.7 Center 1, FFS:

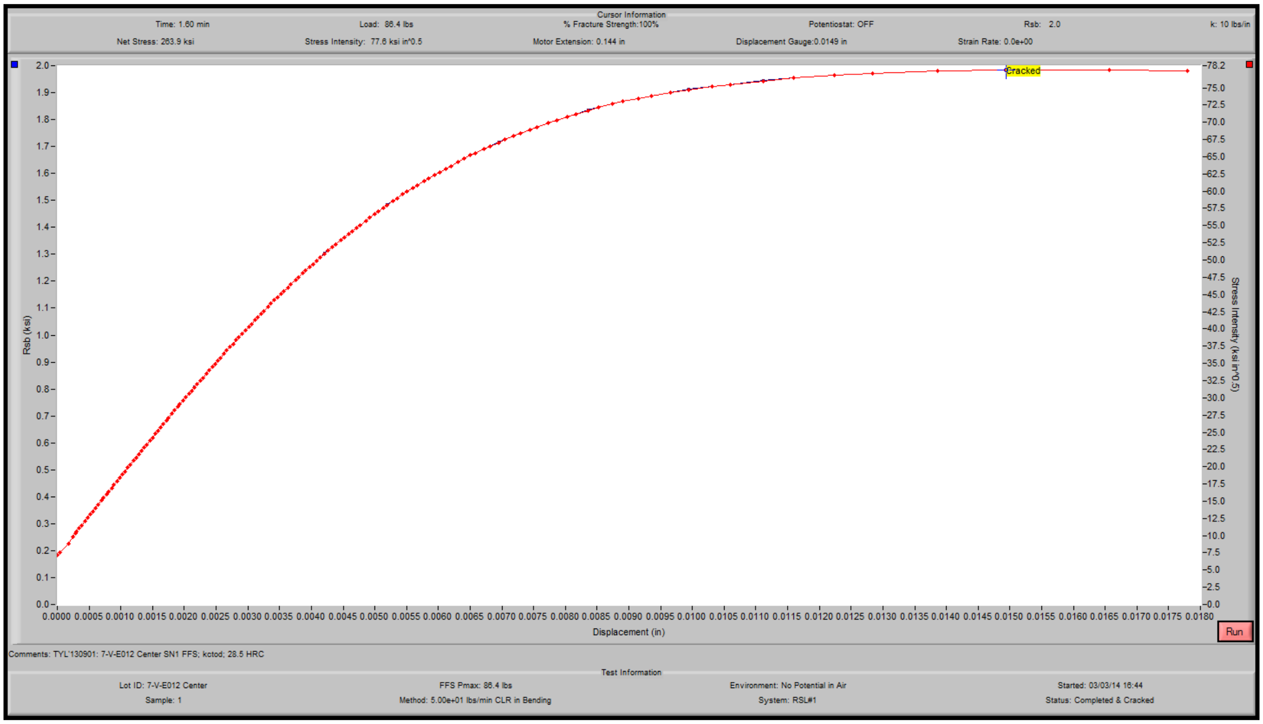


Figure N.5-13: Rod 7-V-E012 Center 1, Graphical FFS Results

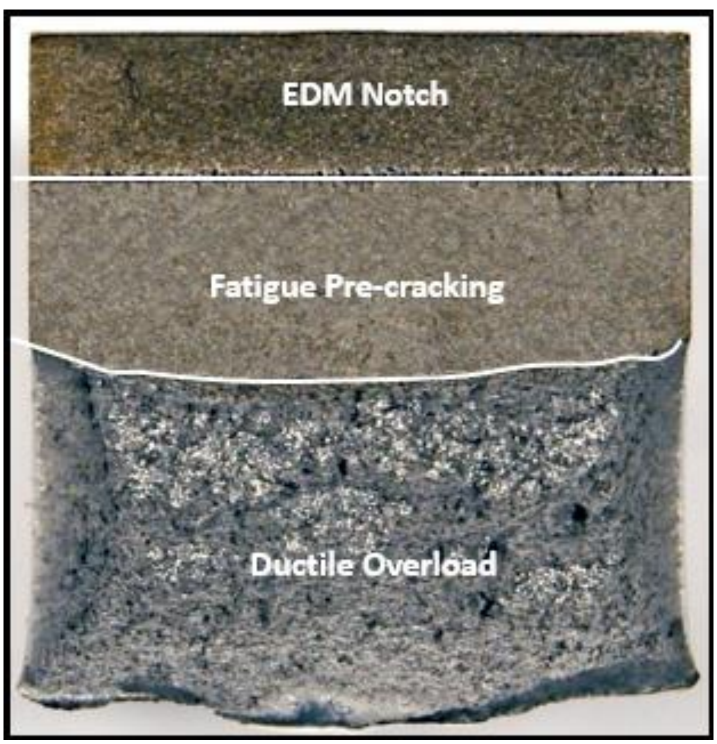


Figure N.5-14: Fracture Face of Rod 7-V-E012 Center 1, FFS

N.6 Threaded Specimen Test Results

N.6.1 Thd 1, FFS:

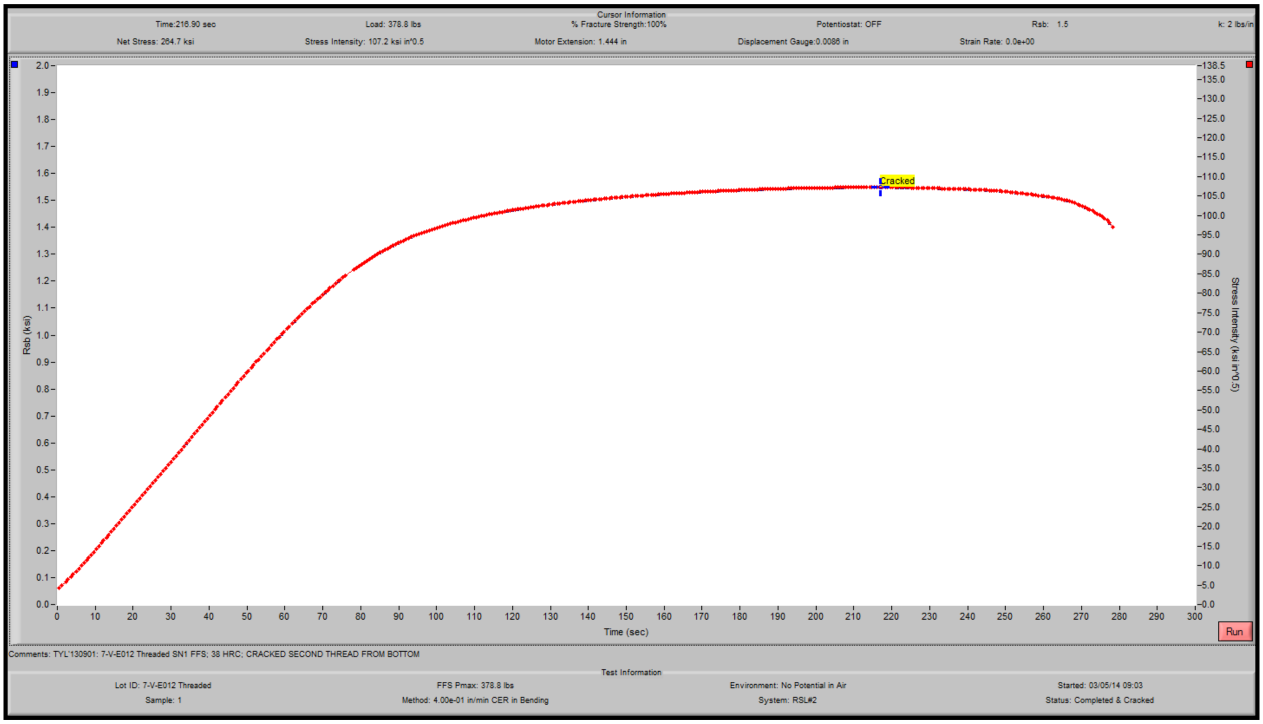


Figure N.6-1: Rod 7-V-E012 Thd 1, Graphical FFS Results

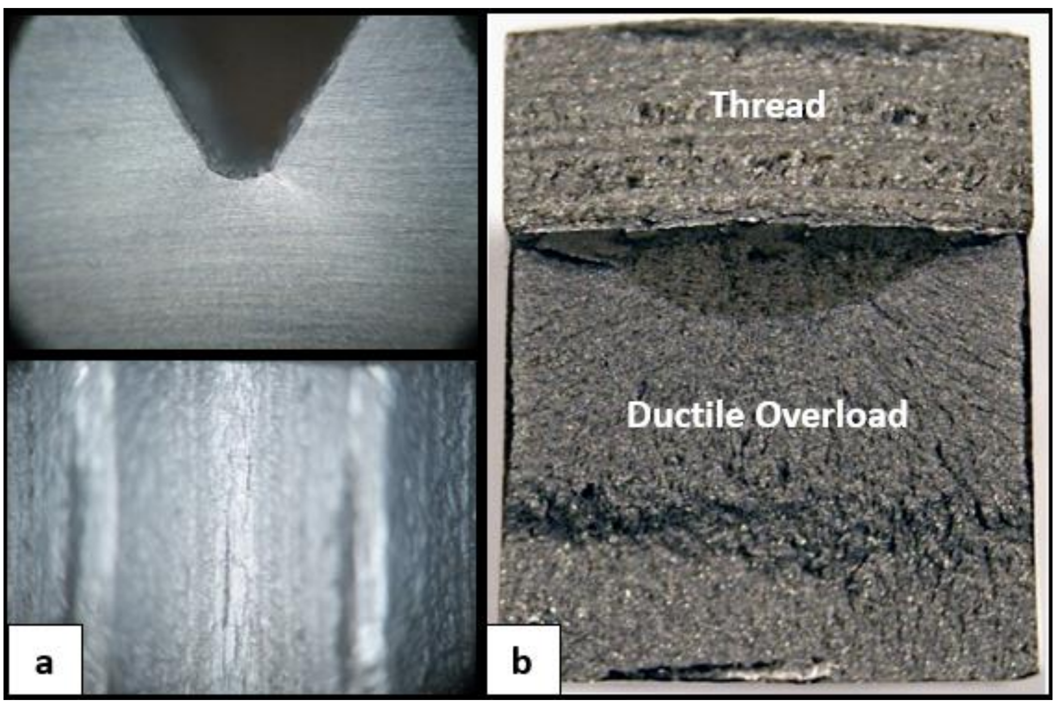


Figure N.6-2: Rod 7-V-E012 Thd 1 a)Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

N.6.2 Thd 4, EHE:

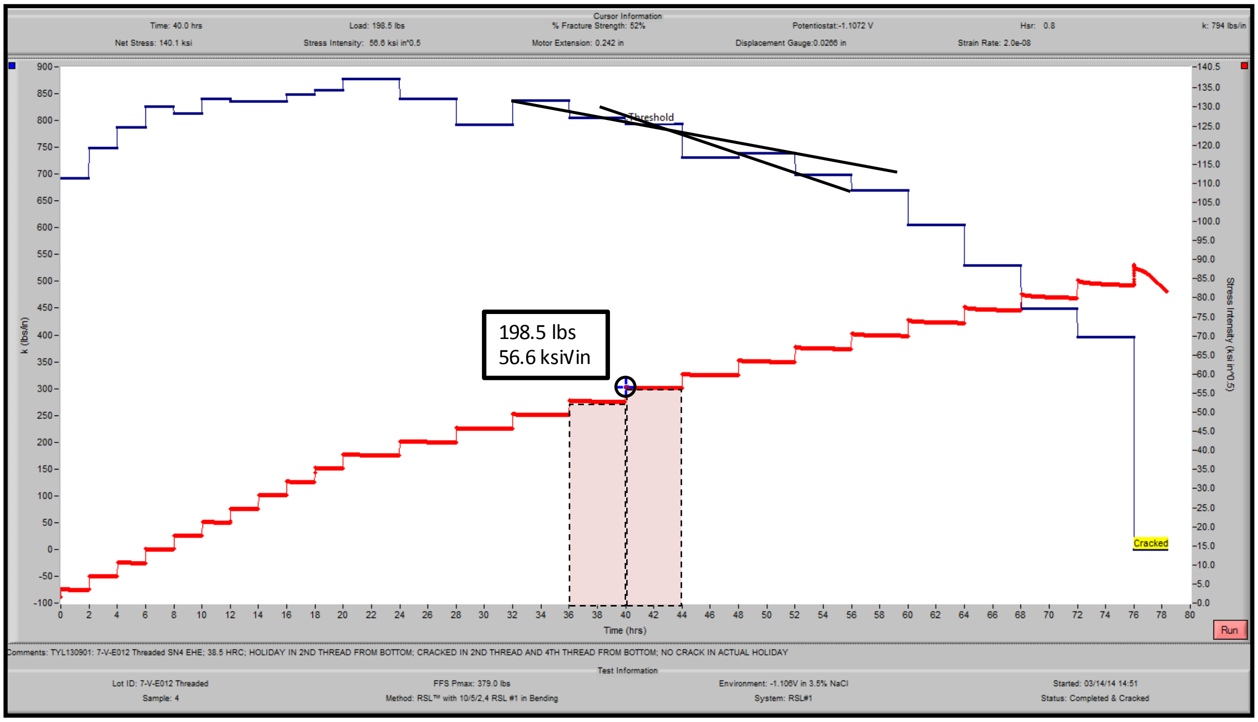


Figure N.6-3: Rod 7-V-E012 Thd 4, Graphical EHE Results

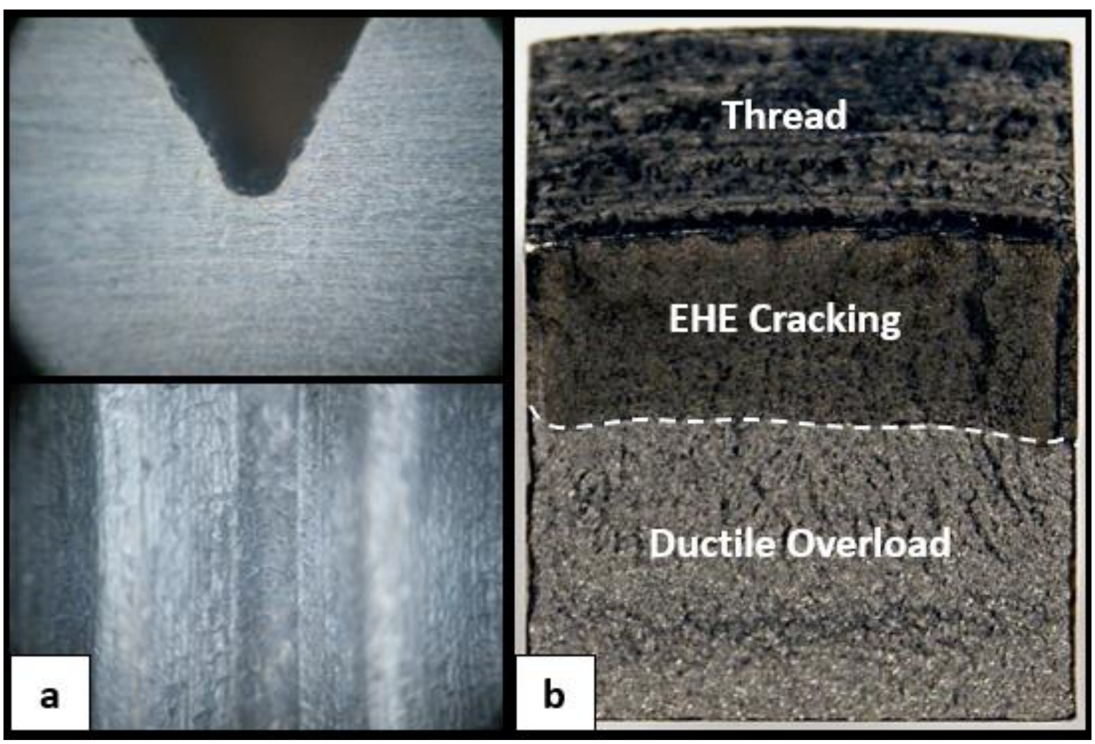


Figure N.6-4: Rod 7-V-E012 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

N.6.3 Thd 7, EHE:

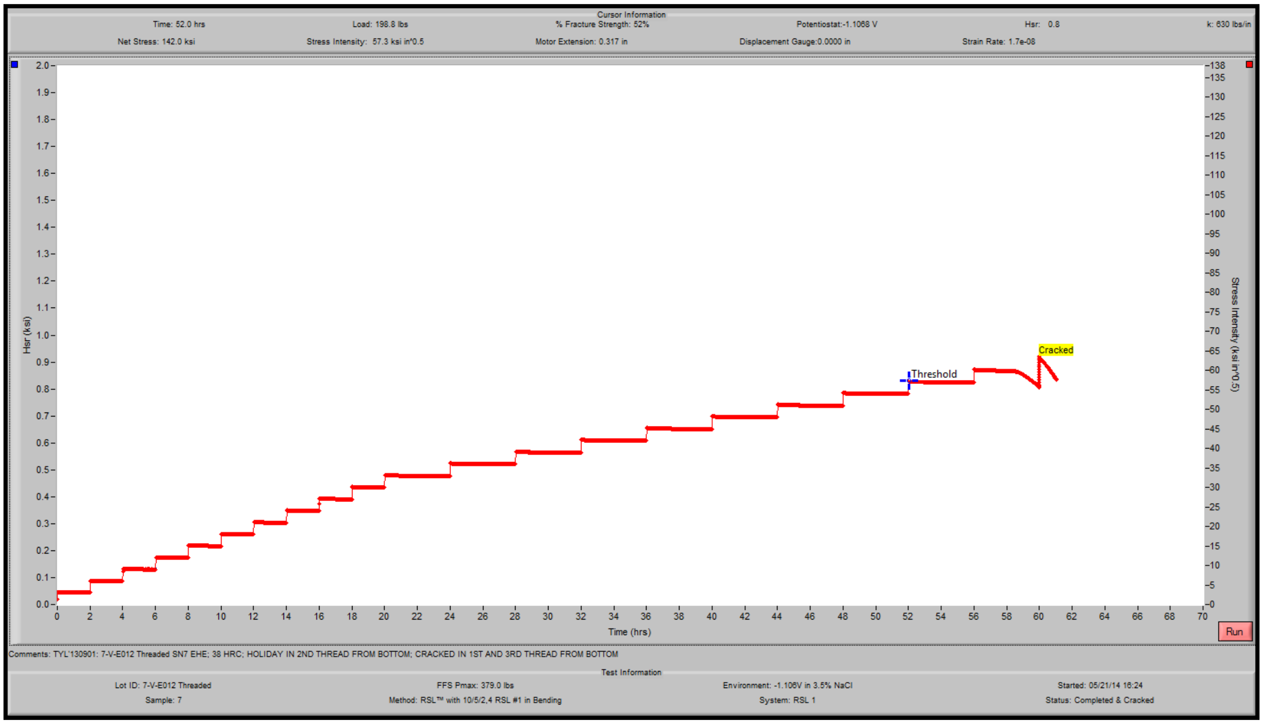


Figure N.6-5: Rod 7-V-E012 Thd 7, Graphical EHE Results

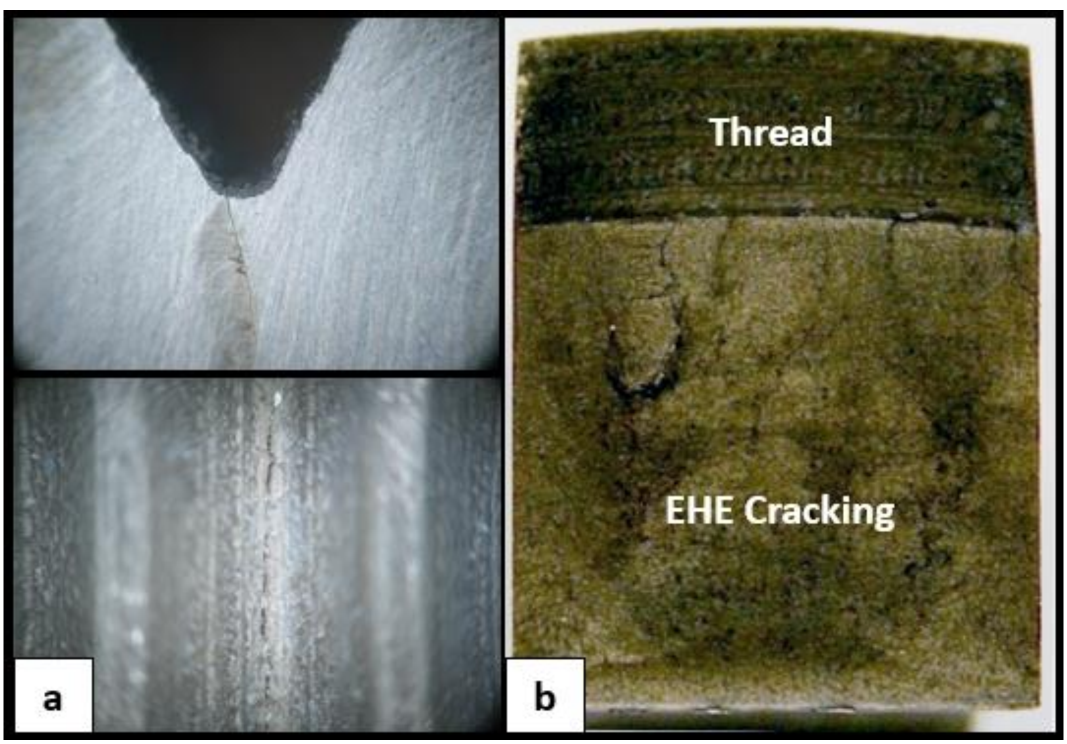


Figure N.6-6: Rod 7-V-E012 Thd 7 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

N.6.4 Thd 8, EHE:

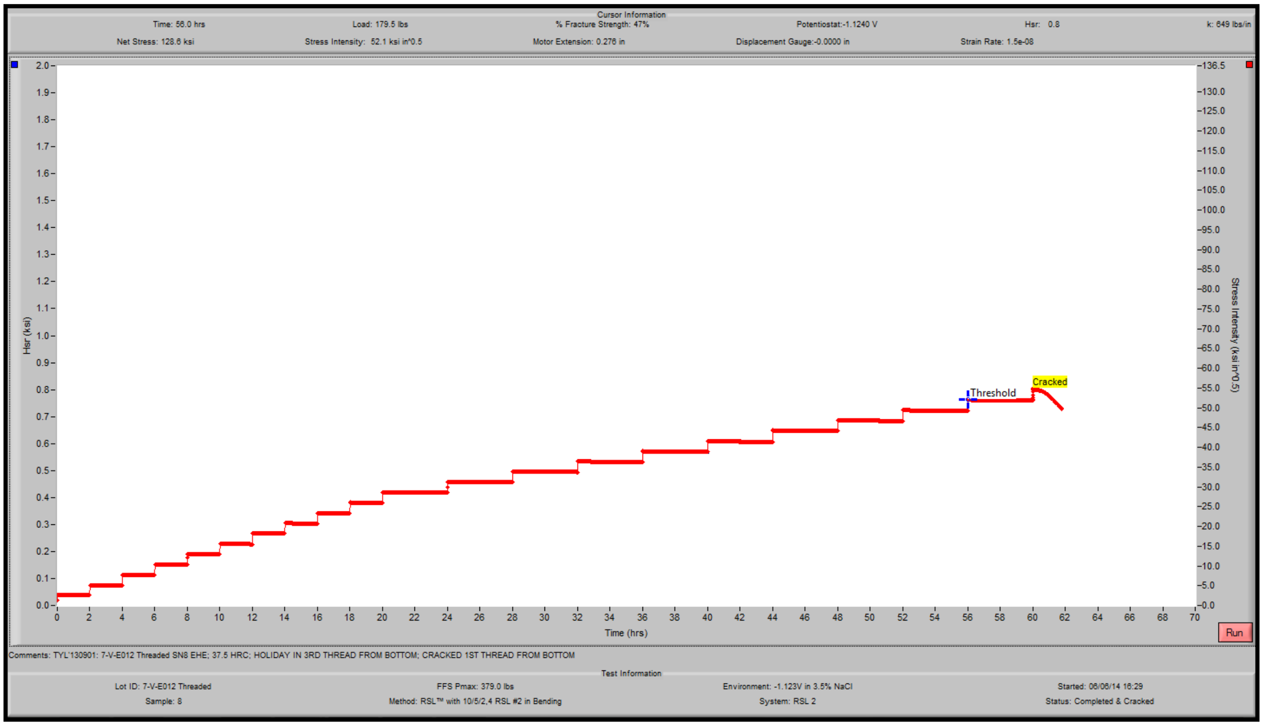


Figure N.6-7: Rod 7-V-E012 Thd 8, Graphical EHE Results

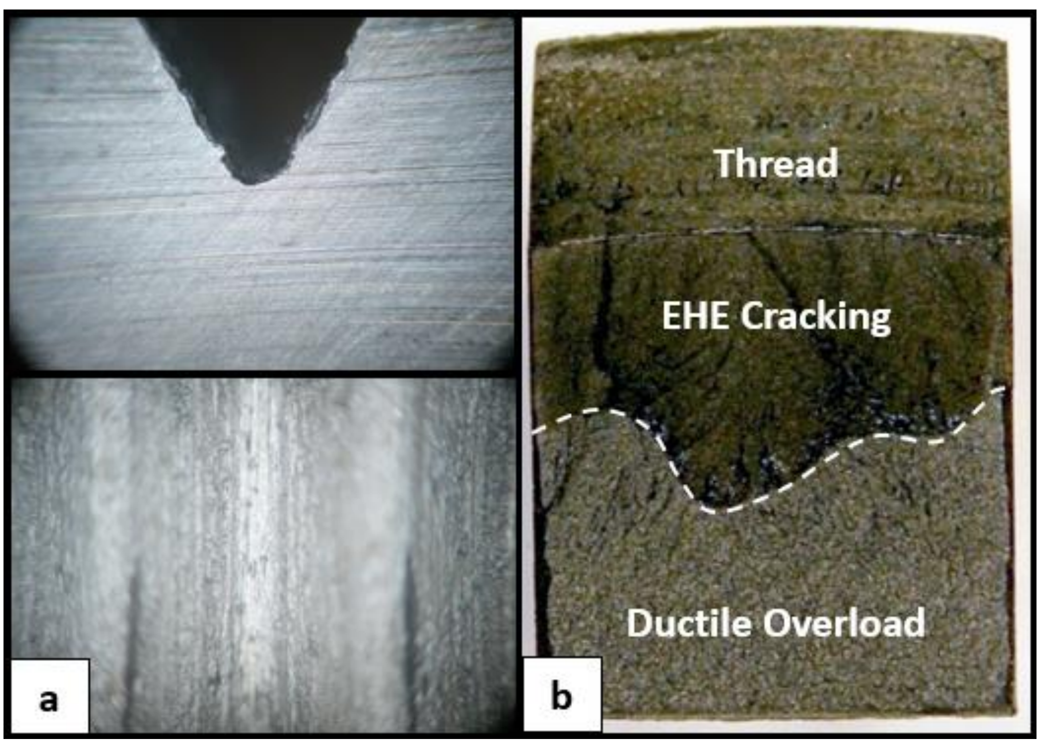
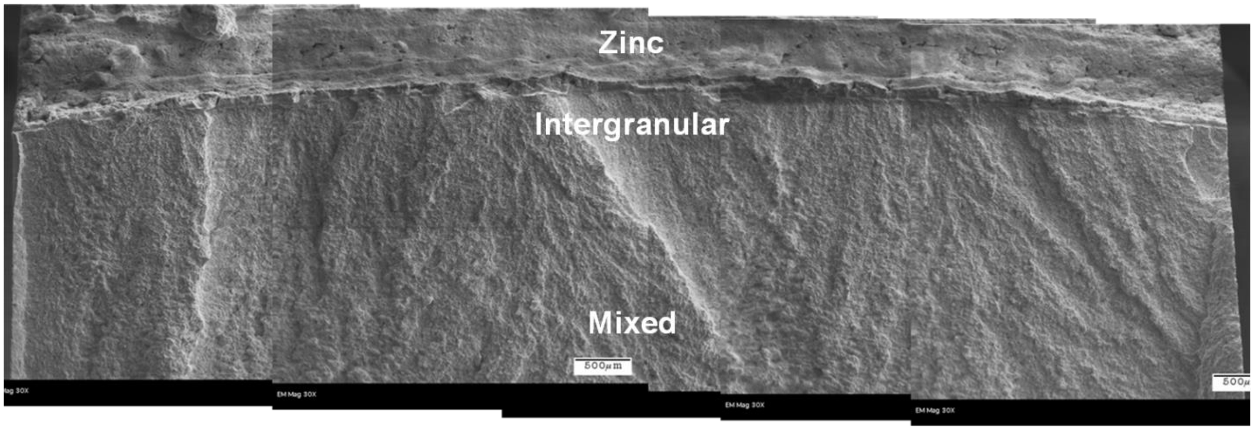
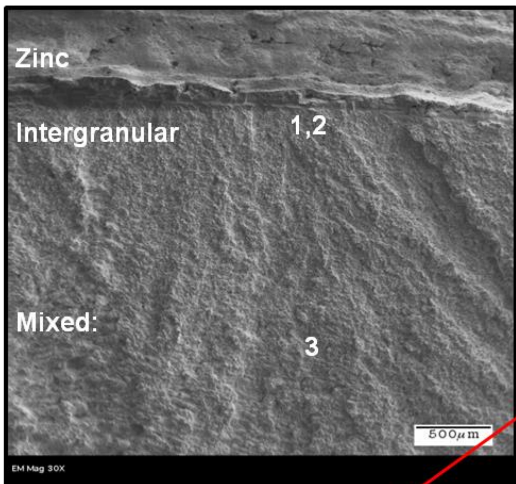


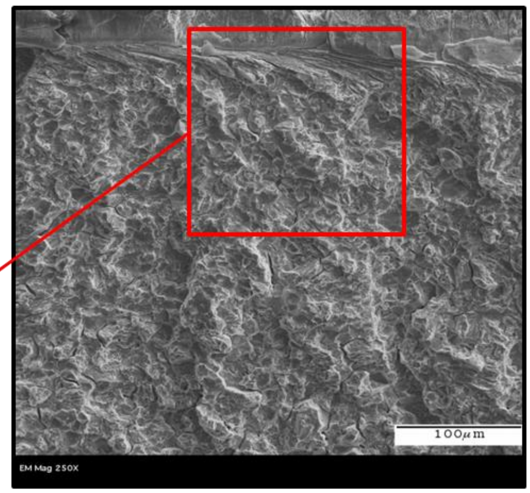
Figure N.6-8: Rod 7-V-E012 Thd 8 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure N.6-9: SEM of Rod 7-V-E012 Thd 8, EHE

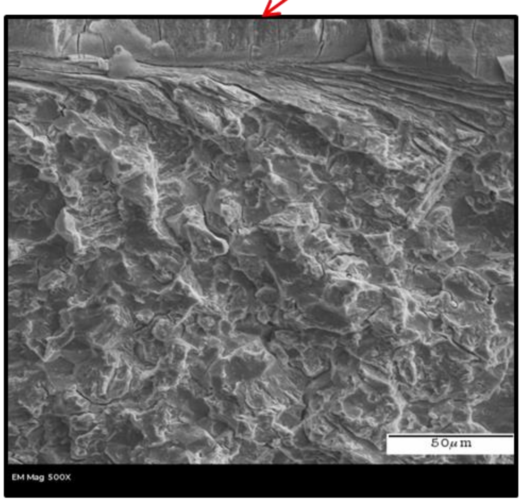




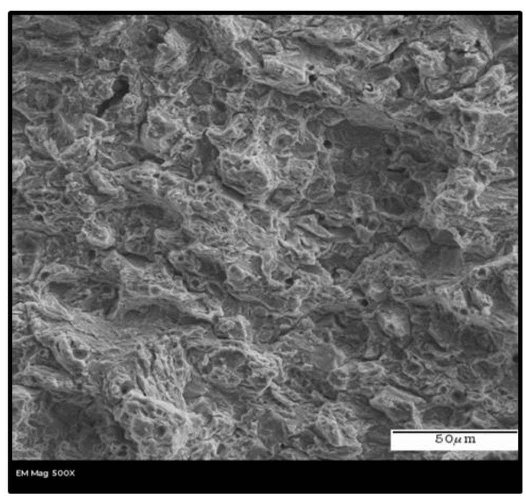
Thread Root 30X



1) Intergranular 250X



2) Intergranular 500X



3) Mixed: Ductile Overload, Intergranular 500X

Appendix O: Rod 7-V-E027

O.1 Description of Sample

Rod 7-V-E027 was a PWS Strand Anchor Rod located at the anchorage location above Pier E2 from the same heat of rod as Test Rigs #9 and #10 tested in Test IV and Rod 7-V-E012 in Test V. It was made from 4140 steel to ASTM A354 Grade BD. Rod 7-V-E027 is 3.5 inches in diameter with rolled threads. The segment from one of the rod pieces provided to LRA is shown in **Figure O.1-1**.

Figure O.1-1: Pier E2 Anchorage PWS Strand Anchor, Rod 7-V-E027

O.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 7-V-E027 and can be seen versus time in **Figure O**.2-1. The final OCP recorded for Rod 7-V-E027 was Vsce=-0.919 V.

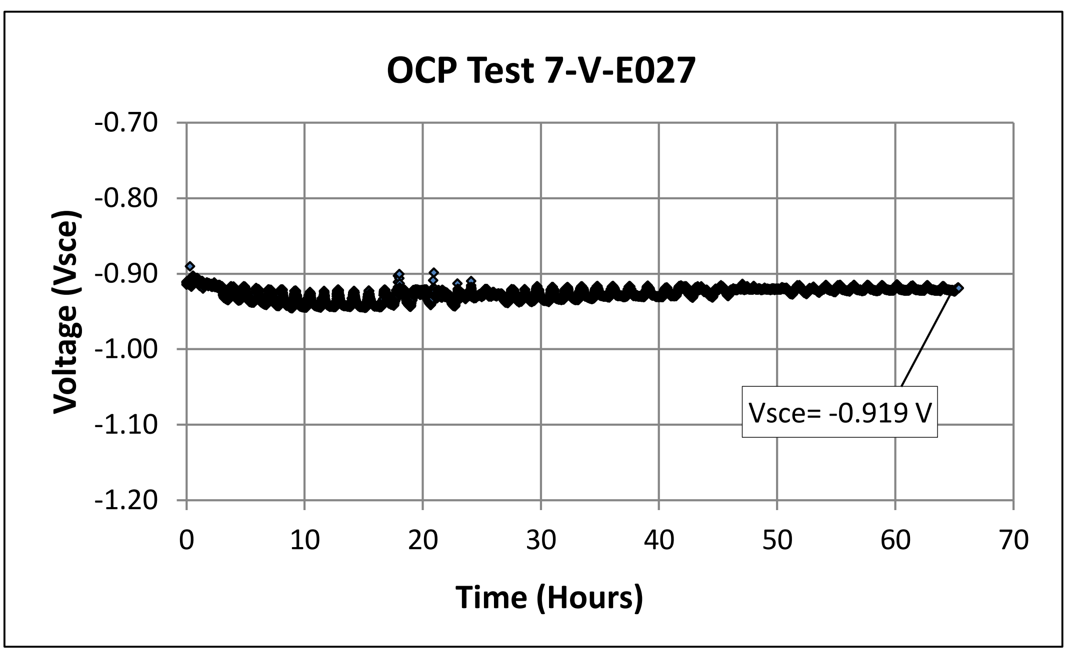


Figure O.2-1: Open Circuit Potential for Rod 7-V-E027

O.3 Hardness

The hardness data and profile for sample 7-V-E027 are shown in **Table O.3-1** and **Figure O.3-1**.

Table O.3-1: Hardness Data of Rod 7-V-E027 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	29.0	29.0
MR 1, FFS	32.5	31.9
MR 3, EHE	31.5	
MR 5, EHE	32.5	
MR 6, EHE	31.0	
OD 1, FFS	36.0	36.3
OD 3, EHE	36.0	
OD 4, EHE	36.5	
OD 5, EHE	36.5	
Thd 1, FFS	36.5	
Thd 3, EHE	36.5	
Thd 6, EHE	36.5	
Thd 7, EHE	36.0	

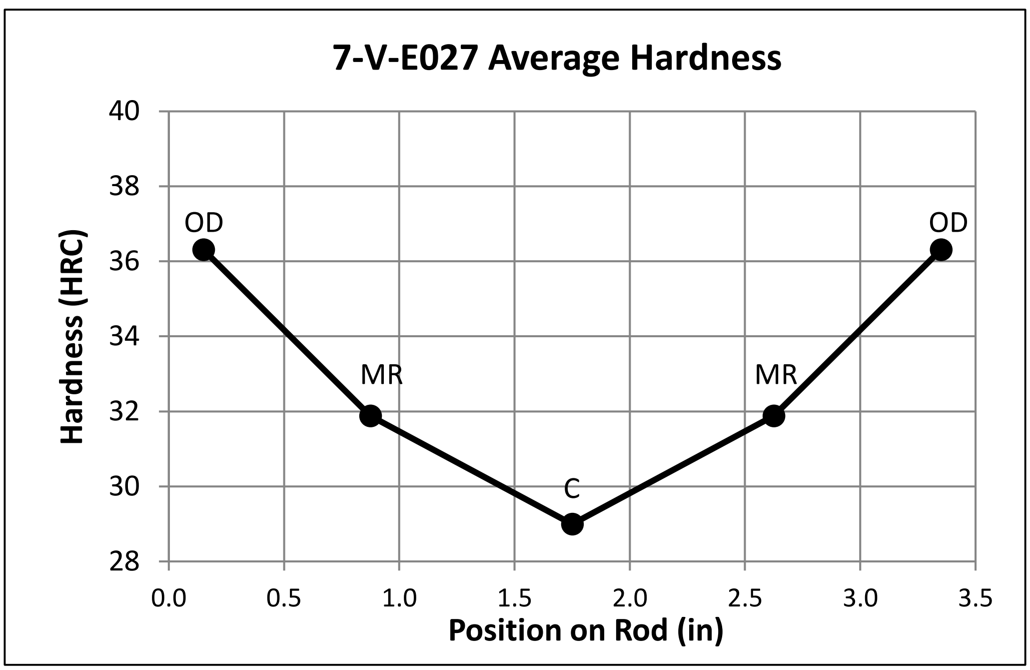


Figure O.3-1: Hardness Profile of Rod 7-V-E027

O.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

O.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E027						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)				
Rod#:	**7-V-E027**					
Product Form:	**1e**	**Comments**: 2010 Rolled Threads, Heat OTD				
Rod OD:	**3.5"**	Same Heat of Rod as Test Rigs #9 and #10 in Test IV				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**36.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	87.0 0.54 0.96 8200		
	OD 3, EHE	**36.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			72.7 0.45 0.81 2.2
	OD 4, EHE	**36.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			24.0 0.15 0.27 1.4
	OD 5, EHE	**36.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			26.1 0.16 0.29 0.89
	MR 1, FFS	**32.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	79.5 0.54 0.88 8200		

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E027						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable) **Comments**: 2010 Rolled Threads, Heat OTD Same Heat of Rod as Test Rigs #9 and #10 in Test IV				
Rod#:	**7-V-E027**					
Product Form:	**1e**					
Rod OD:	**3.5"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 3, EHE**	**31.5**	$K_{threshold}$			34.9
			DTI_{th}			0.24
			Fu			0.39
			Strain Rate ($x10^{-8}$ in/in/sec)			2.1
	MR 5, EHE	**32.5**	$K_{threshold}$			35.6
			DTI_{th}			0.24
			Fu			0.39
			Strain Rate ($x10^{-8}$ in/in/sec)			1.5
	MR 6, EHE	**31.0**	$K_{threshold}$			34.4
			DTI_{th}			0.24
			Fu			0.38
			Strain Rate ($x10^{-8}$ in/in/sec)			1.1
	Center 1, FFS	**29.0**	K_{max}	76.1		
			DTI_{th}	0.57		
			Fu	0.84		
			Strain Rate ($x10^{-8}$ in/in/sec)	8300		

O.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E027						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable) **Comments**: 2010 Rolled Threads, Heat OTD Same Heat of Rod as Test Rigs #9 and #10 in Test IV				
Rod#:	**7-V-E027**					
Product Form:	**1e**					
Rod OD:	**3.5"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**36.5**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	349.5 1.13 1.5 3000		
	Thd 3, EHE	**36.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			304.2 0.98 1.3 2.4
	Thd 6, EHE	**36.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			223.3 0.72 1.0 1.5
	Thd 7, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			235.6 0.76 1.0 0.7

O.4.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-E027
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**7-V-E027**
Product Form:	**1e**
Rod OD:	**3.5"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	P_{max}, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	36.0	162	98.1	98.1	98.1	100.0%	87.0	0.54	295.0	1.8	8200	0.2083	143.9	50 lbs/min		0.96	
	OD 3, EHE	3.5% NaCl @ -1.106V	36.0	162	63.0	88.2	81.5	83.6%	72.7	0.45	247.1	1.5	2.2	0.2082		10/5/2,4		0.81	Bifurcation occurred at Crack Root
	OD 4, EHE	3.5% NaCl @ -1.106V	36.5	164	40.0	34.0	26.0	27.6%	24.0	0.15	82.5	0.5	1.4	0.2139		10/5/2,4		0.27	
	OD 5, EHE	3.5% NaCl @ -1.106V	36.5	164	26.0	32.3	29.8	30.0%	26.1	0.16	88.5	0.5	0.89	0.2079		10/5/2,4		0.29	
	MR 1, FFS	Air	32.5	147	89.1	89.1	89.1	100.0%	79.5	0.54	269.8	1.8	8200	0.2102	149.2	50 lbs/min		0.88	
	MR 3, EHE	3.5% NaCl @ -1.106V	31.5	143	59.0	53.1	38.2	43.9%	34.9	0.24	119.3	0.8	2.1	0.214		10/5/2,4		0.39	
	MR 5, EHE	3.5% NaCl @ -1.106V	32.5	147	40.0	48.0	37.9	44.8%	35.6	0.24	122.8	0.8	1.5	0.2184		10/5/2,4		0.39	
	MR 6, EHE	3.5% NaCl @ -1.106V	31.0	141	30.0	45.9	36.8	43.3%	34.4	0.24	118.0	0.8	1.1	0.2163		10/5/2,4		0.38	
	Center 1, FFS	Air	29.0	134	84.9	84.9	84.9	100.0%	76.1	0.57	258.8	1.9	8300	0.2105	142.3	50 lbs/min		0.84	
Threaded	Thd 1, FFS	Air	36.5	164	386.0	386.0	386.0	100.0%	101.9	0.62	247.3	1.5	3000	N/A		0.4 in/min	349.5	1.13	
	Thd 3, EHE	3.5% NaCl @ -1.106V	36.5	164	307.0	328.9	316.3	87.0%	88.7	0.54	218.9	1.3	2.4	N/A		10/5/2,4	304.2	0.98	Did not crack initially in Holiday
	Thd 6, EHE	3.5% NaCl @ -1.106V	36.5	164	200.0	290.3	238.4	63.9%	65.1	0.40	158.8	1.0	1.5	N/A		10/5/2,4	223.3	0.72	Did not crack in Holiday
	Thd 7, EHE	3.5% NaCl @ -1.106V	36.0	162	200.0	270.1	258.5	67.4%	68.7	0.42	166.5	1.0	0.7	N/A		10/5/1,8	235.6	0.76	Did not crack in Holiday

O.5 Fatigue Pre-cracked Specimen Test Results

O.5.1 OD 1, FFS:

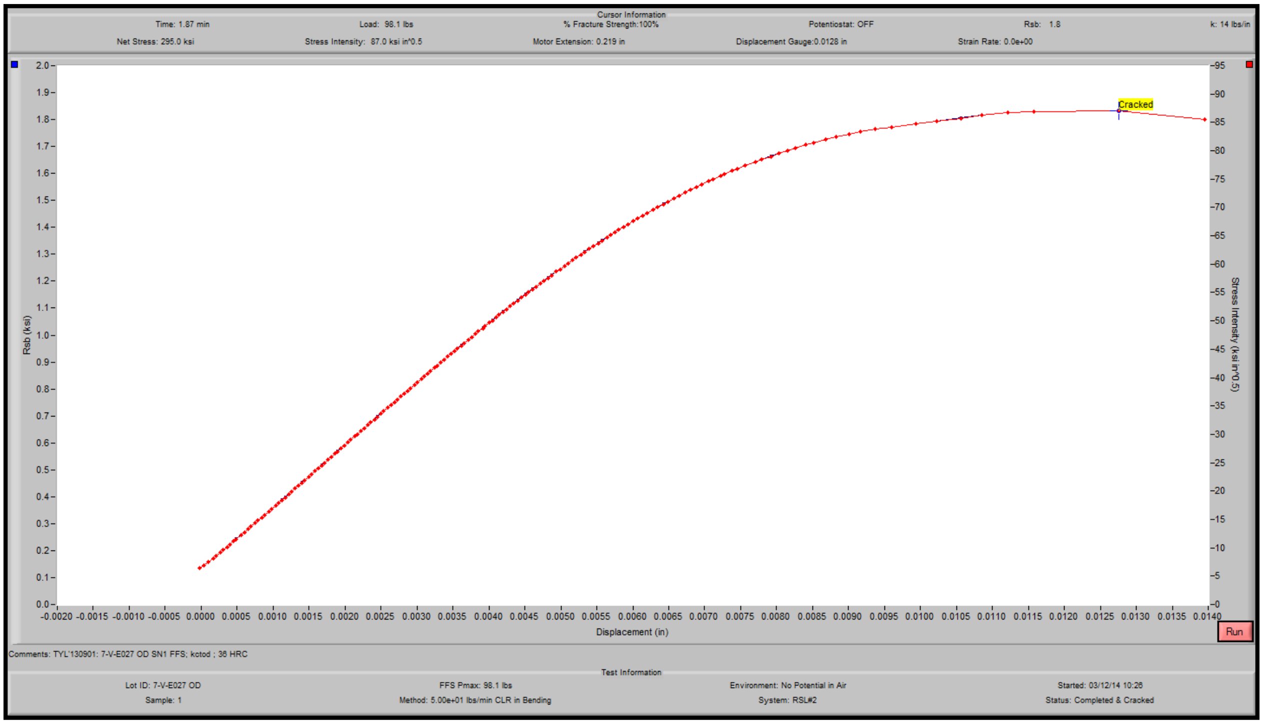


Figure O.5-1: Rod 7-V-E027 OD 1, Graphical FFS Results

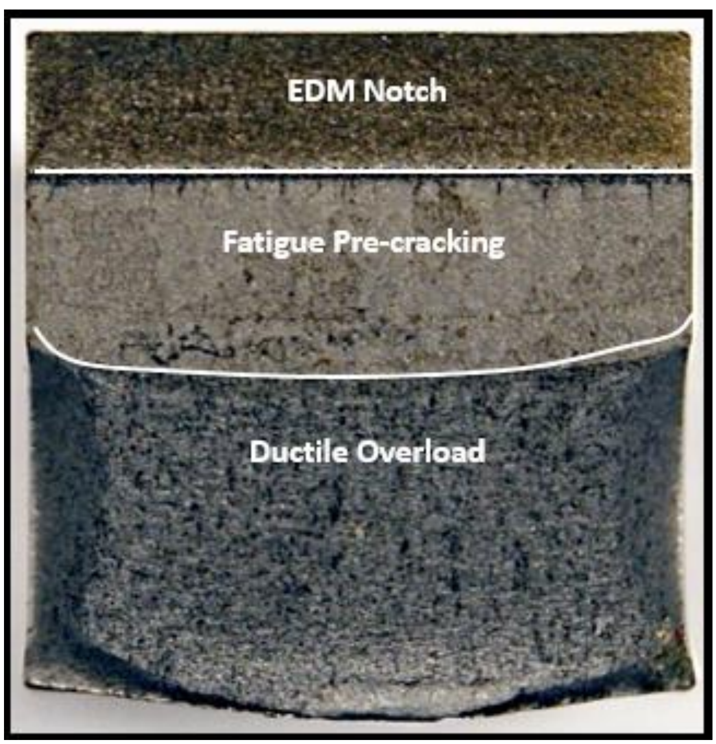


Figure O.5-2: Fracture Face of Rod 7-V-E027 OD 1, FFS

O.5.2 OD 3, EHE:

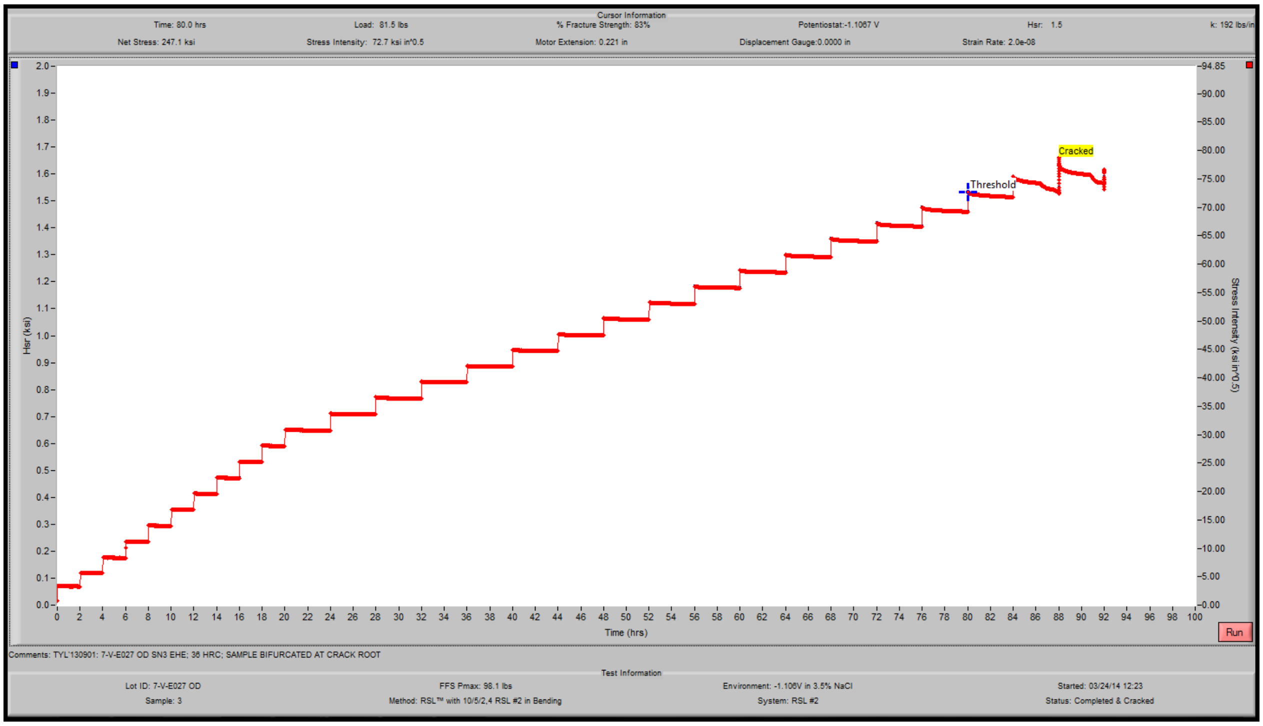


Figure O.5-3: Rod 7-V-E027 OD 3, Graphical EHE Results

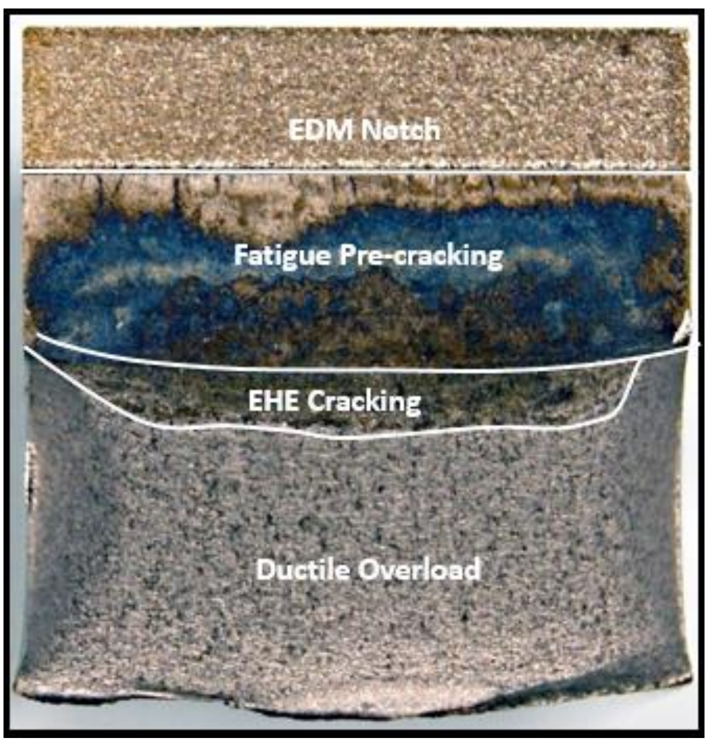


Figure O.5-4: Fracture Face of Rod 7-V-E027 OD 3, EHE

O.5.3 OD 4, EHE:

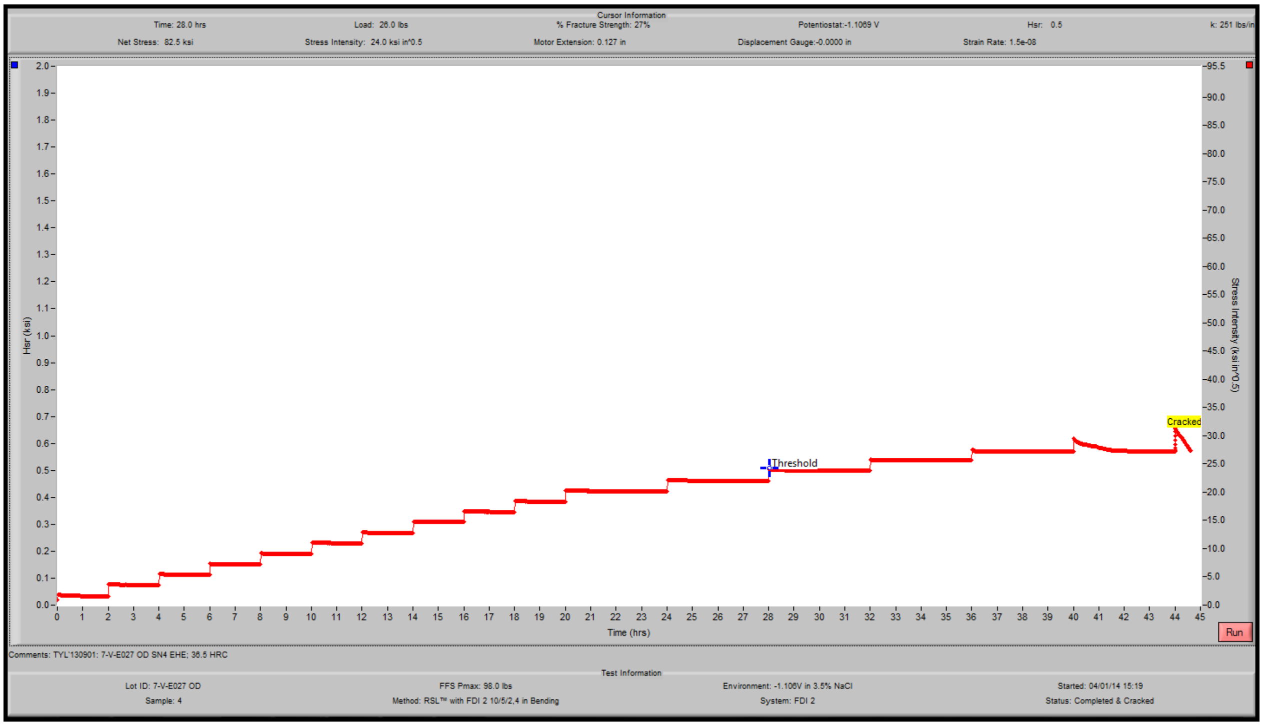


Figure O.5-5: Rod 7-V-E027 OD 4, Graphical EHE Results

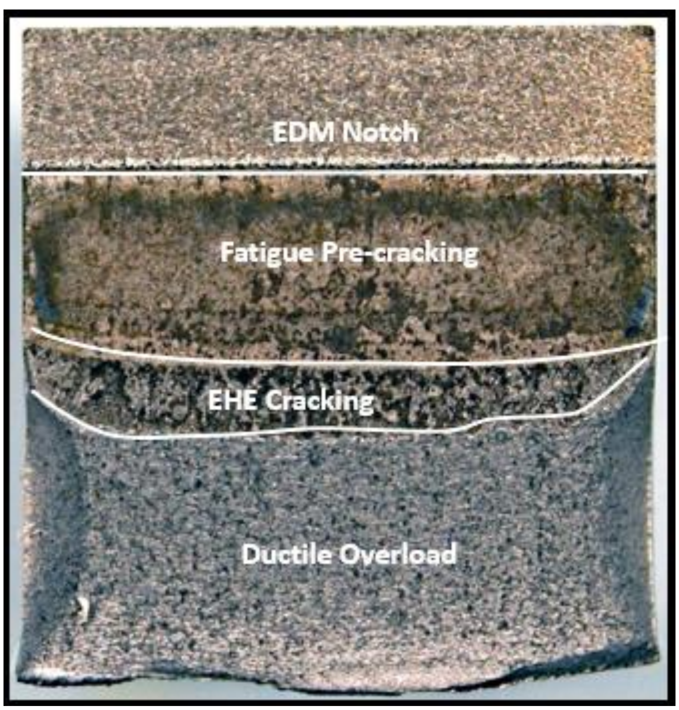


Figure O.5-6: Fracture Face of Rod 7-V-E027 OD 4, EHE

O.5.4 OD 5, EHE:

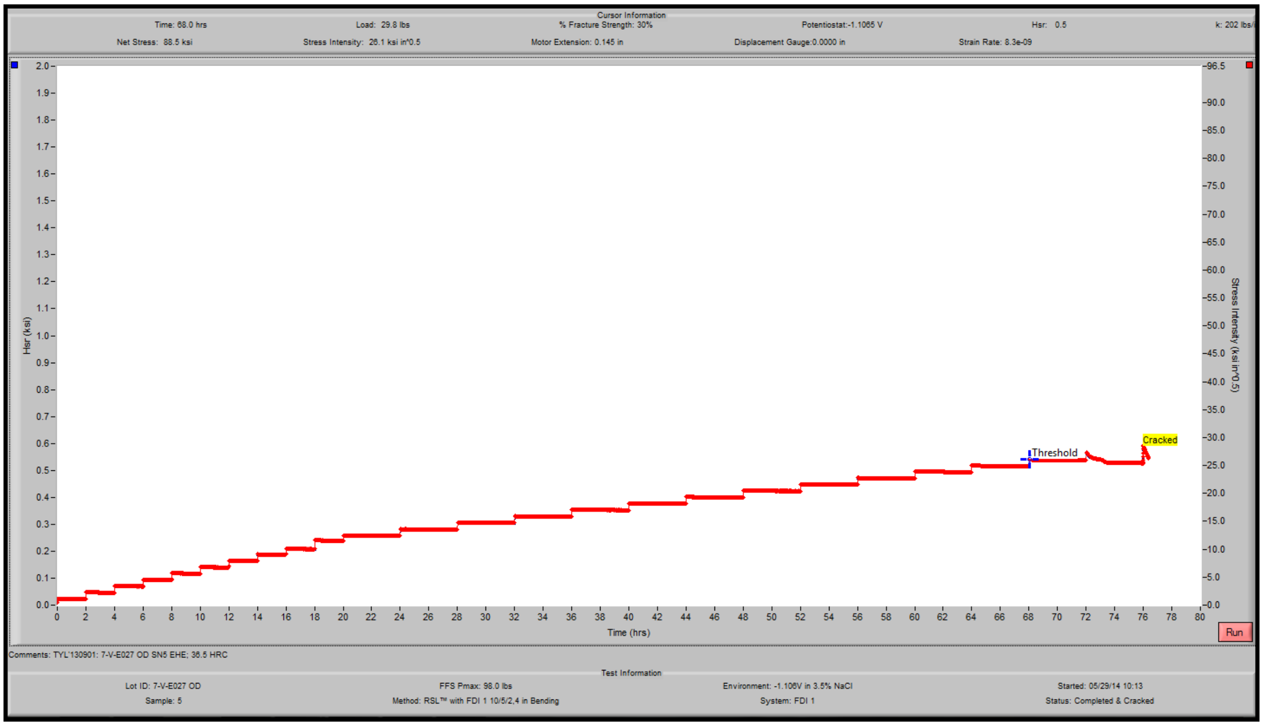


Figure O.5-7: Rod 7-V-E027 OD 5, Graphical EHE Results

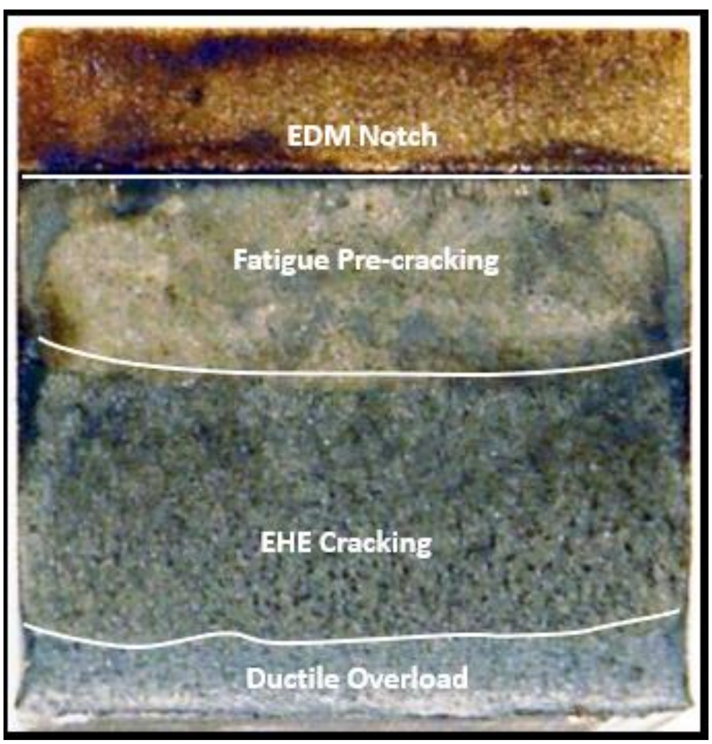


Figure O.5-8: Fracture Face of Rod 7-V-E027 OD 5, EHE

O.5.5 MR 1, FFS:

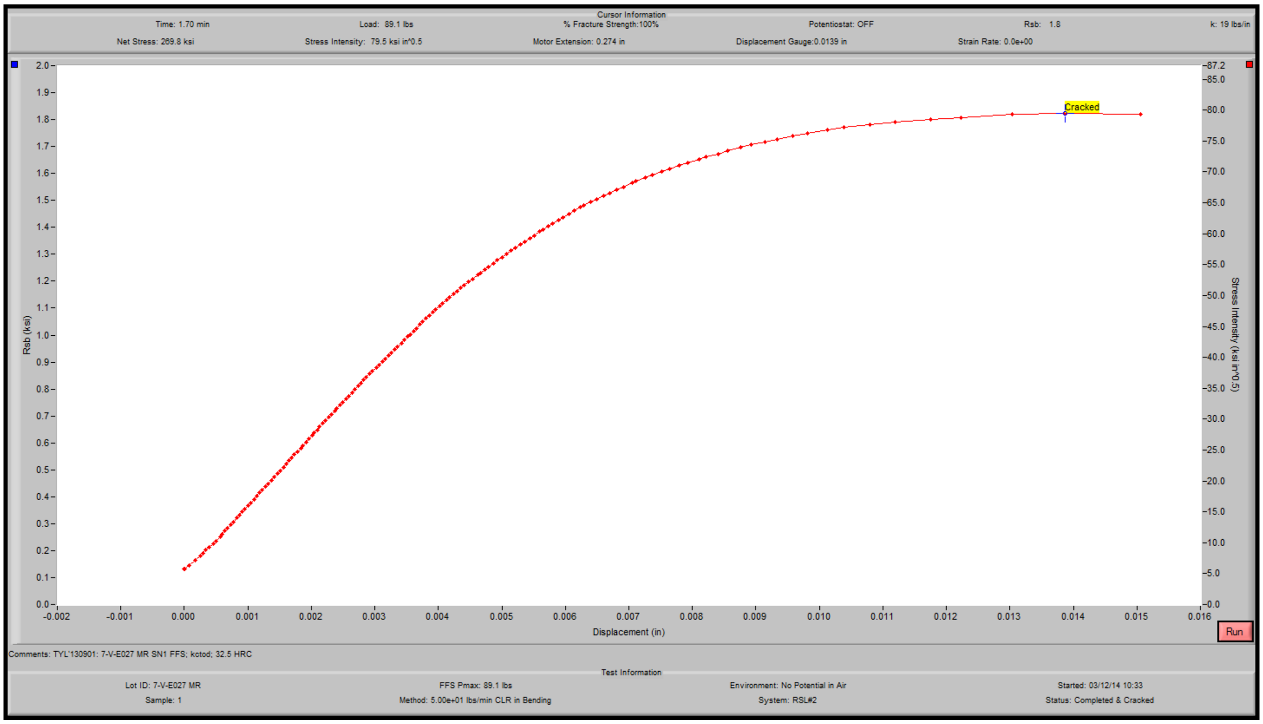


Figure O.5-9: Rod 7-V-E027 MR 1, Graphical FFS Results

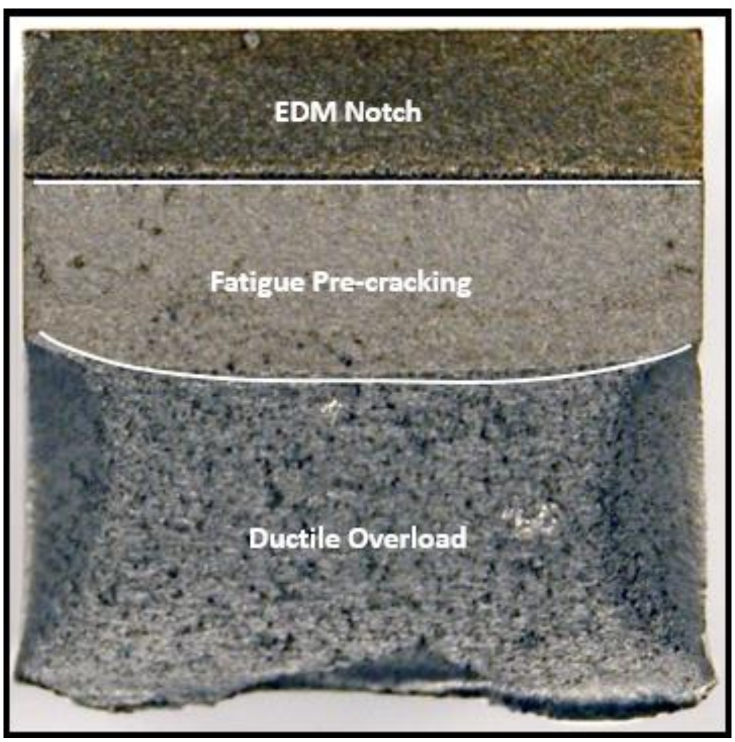


Figure O.5-10: Fracture Face of Rod 7-V-E027 MR 1, FFS

O.5.6 MR 3, EHE:

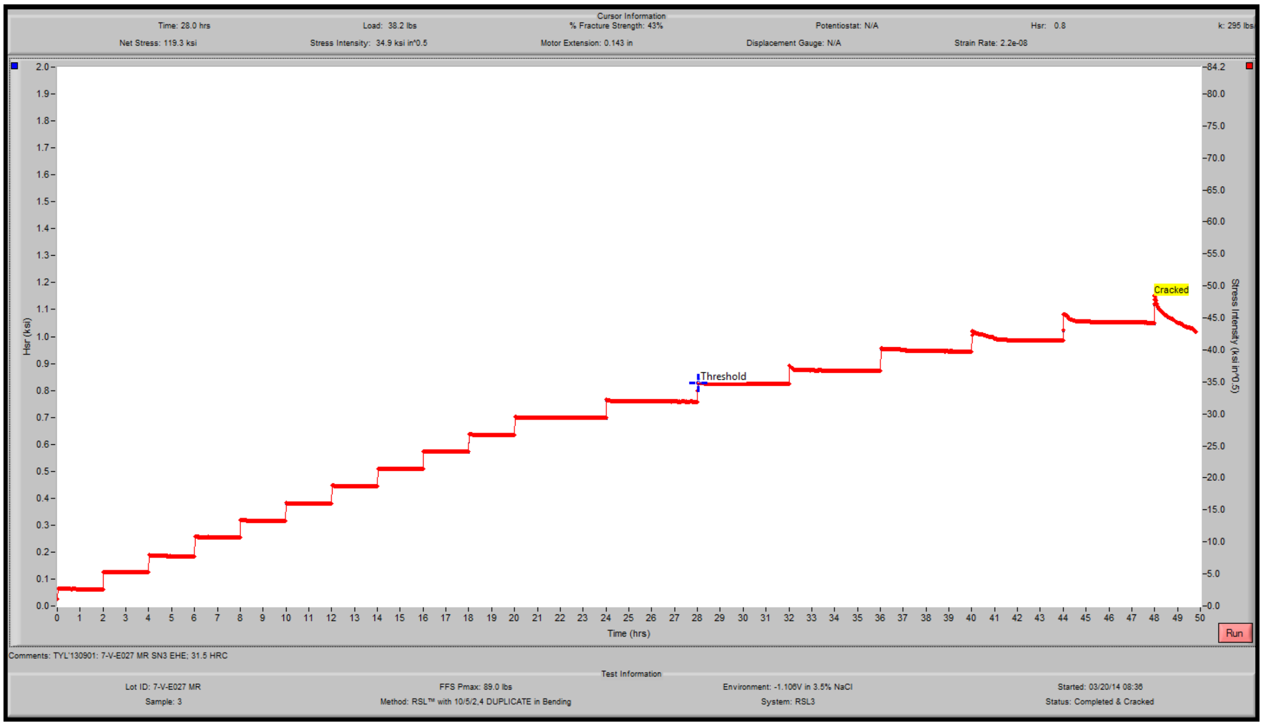


Figure O.5-11: Rod 7-V-E027 MR 3, Graphical EHE Results

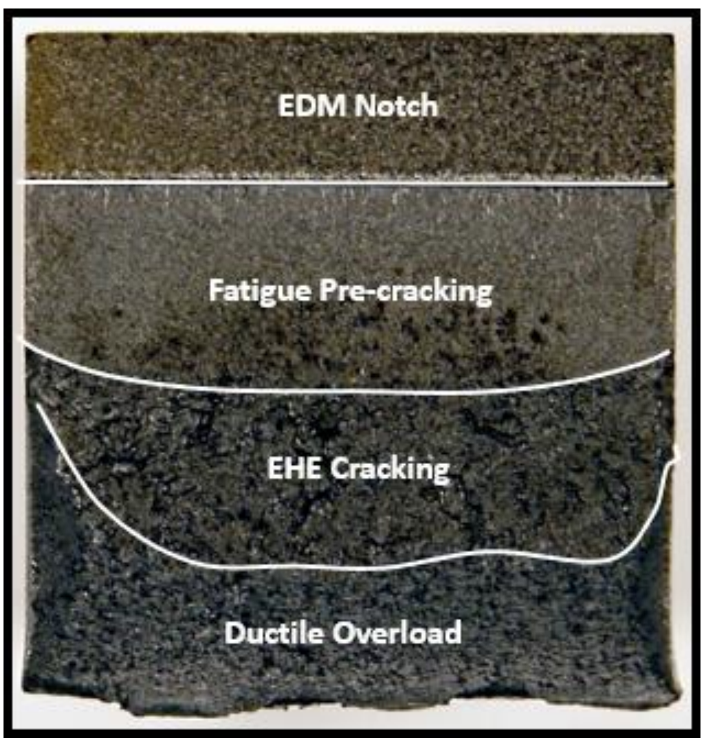


Figure O.5-12: Fracture Face of Rod 7-V-E027 MR 3, EHE

O.5.7 MR 5, EHE:

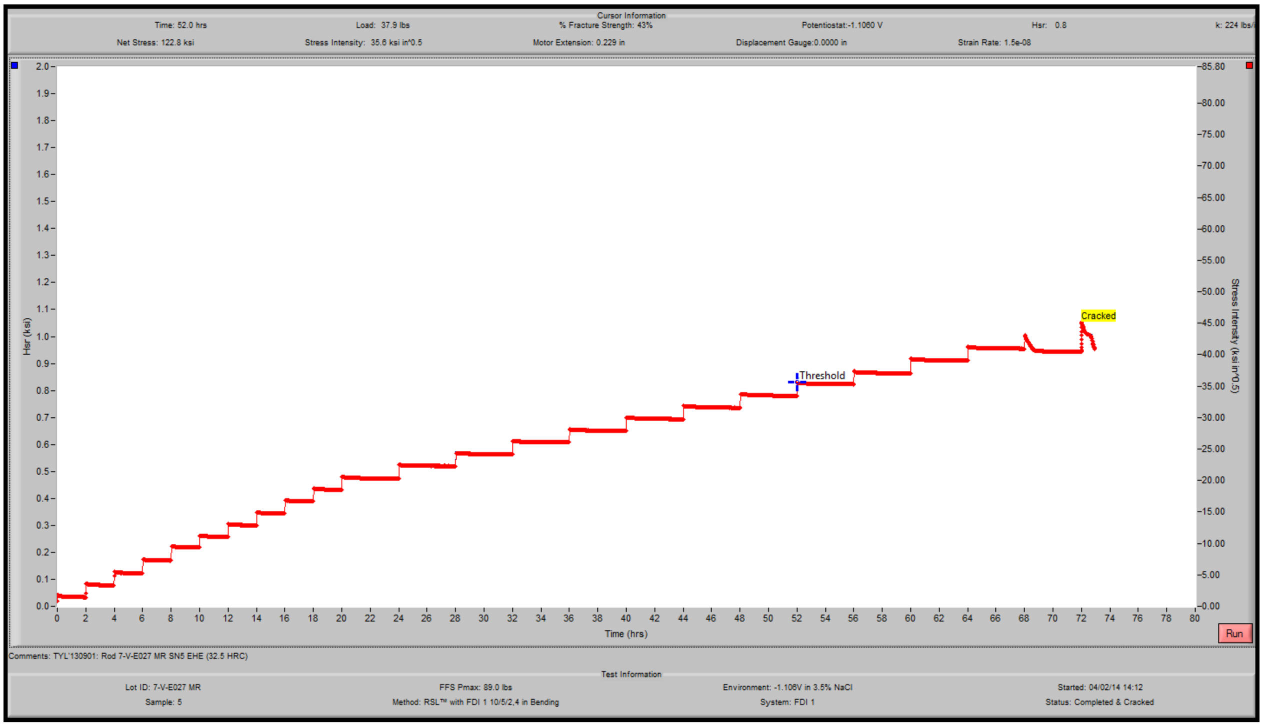


Figure O.5-13: Rod 7-V-E027 MR 5, Graphical EHE Results

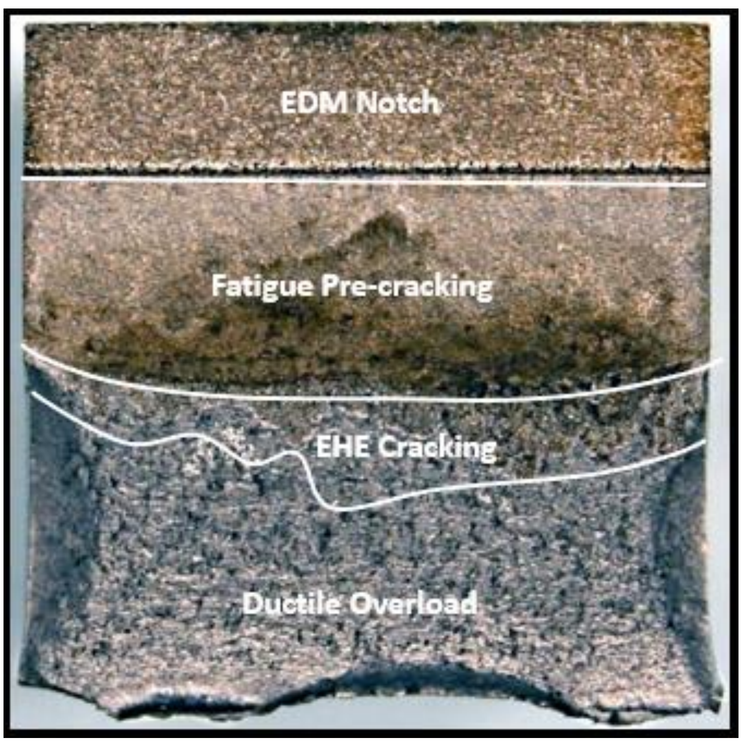


Figure O.5-14: Fracture Face of Rod 7-V-E027 MR 5, EHE

O.5.8 MR 6, EHE:

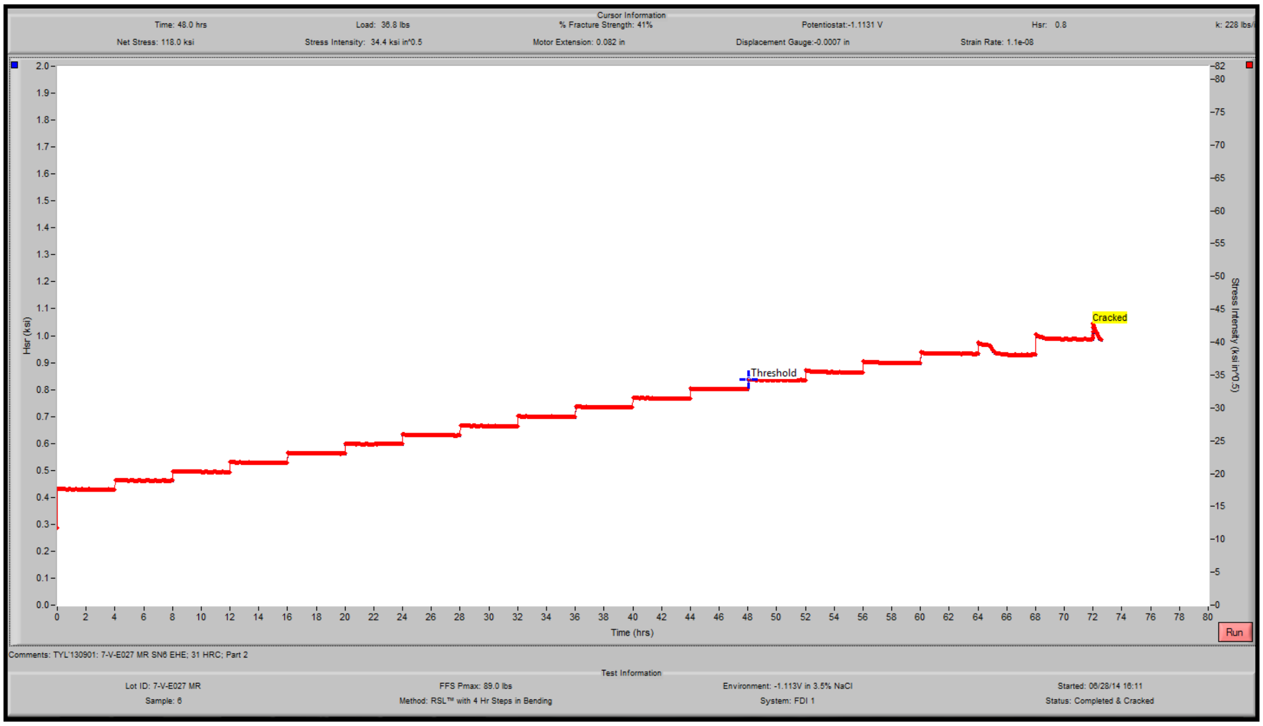


Figure O.5-15: Rod 7-V-E027 MR 6, Graphical EHE Results

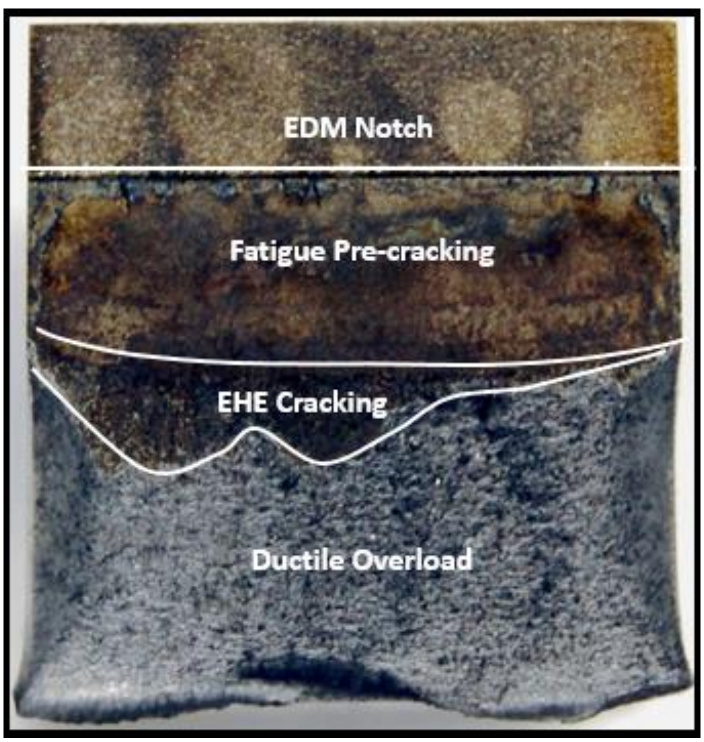


Figure O.5-16: Fracture Face of Rod 7-V-E027 MR 6, EHE

O.5.9 Center 1, FFS:

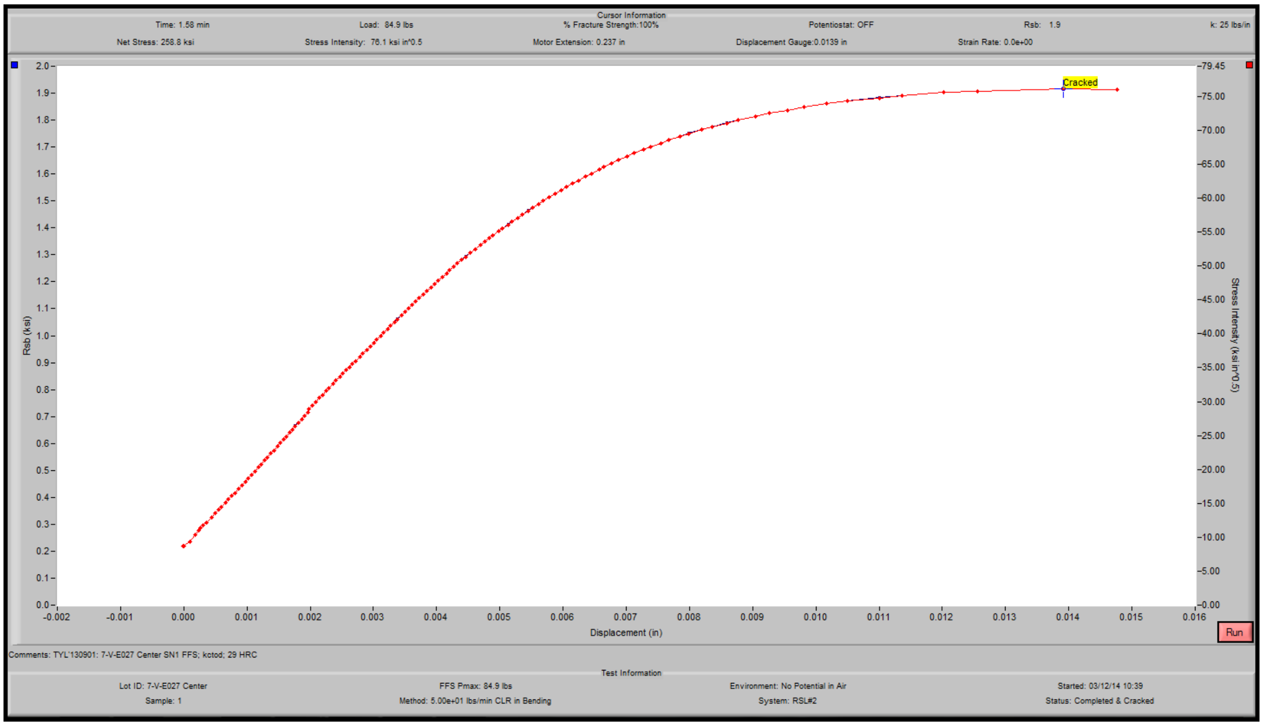


Figure O.5-17: Rod 7-V-E027 Center 1, Graphical FFS Results

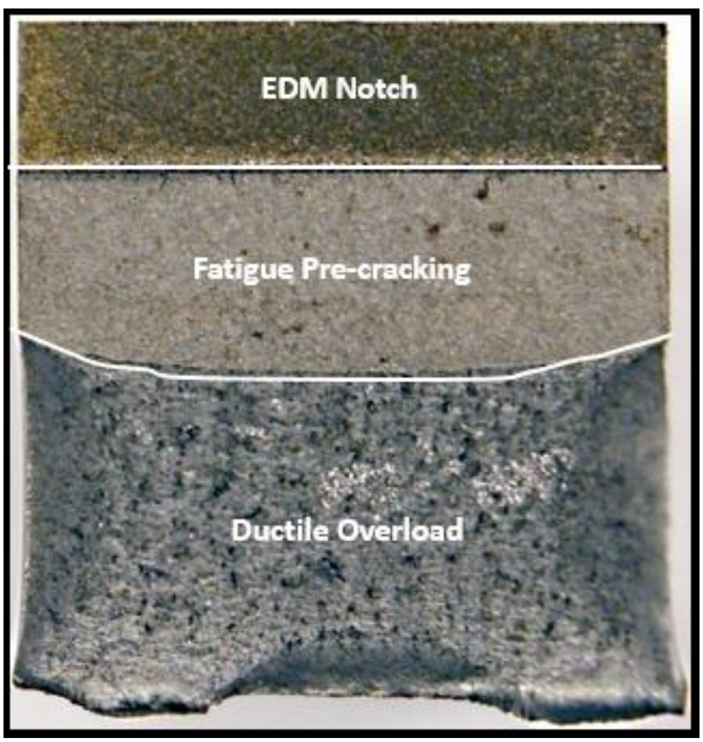


Figure O.5-18: Fracture Face of Rod 7-V-E027 Center 1, FFS

O.6 Threaded Specimen Test Results

O.6.1 Thd 1, FFS:

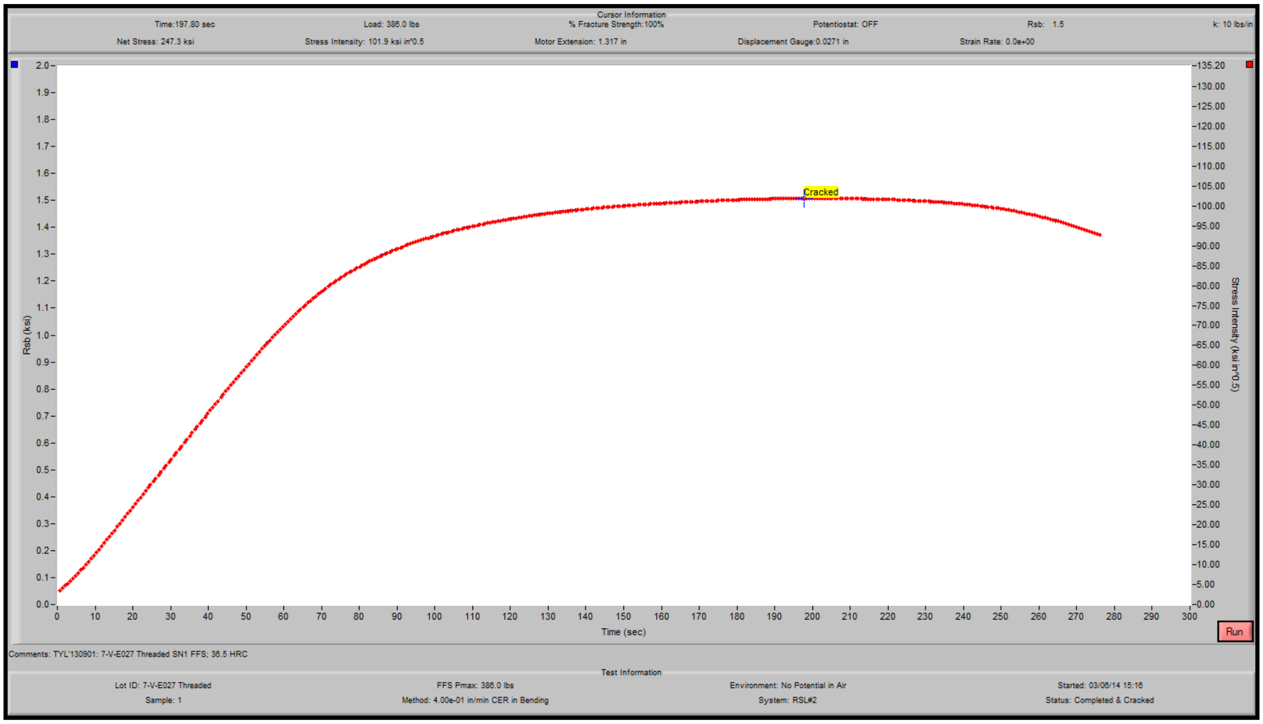


Figure O.6-1: Rod 7-V-E027 Thd 1, Graphical FFS Results

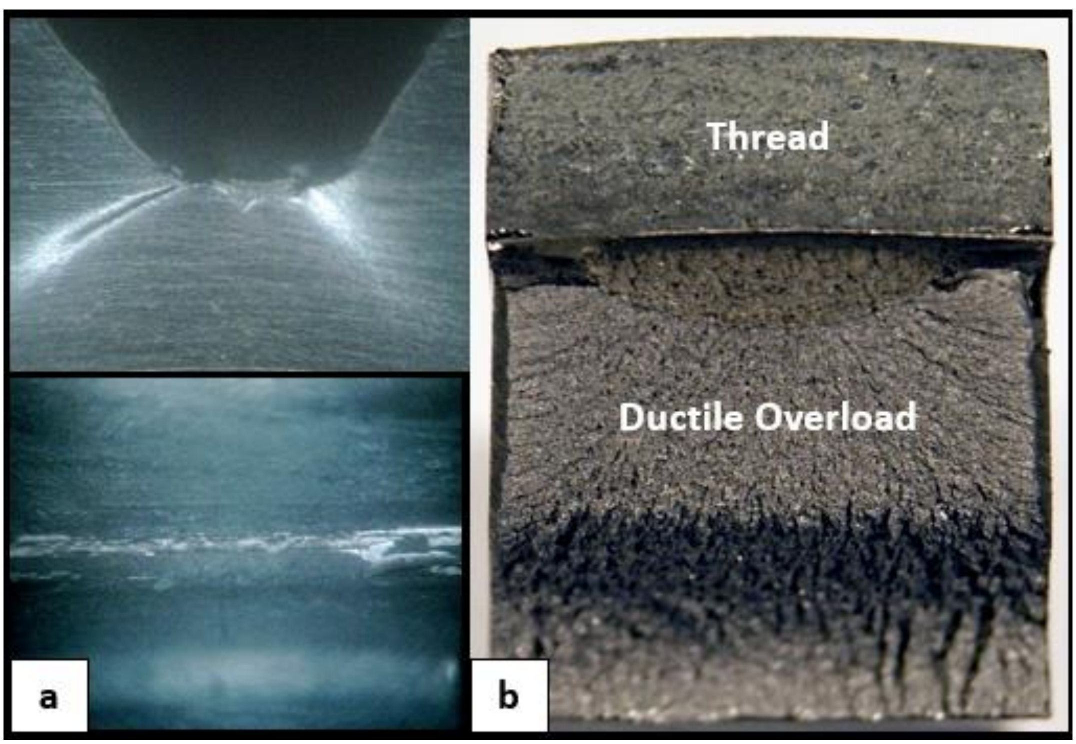


Figure O.6-2: Rod 7-V-E027 Thd 1 a) Thread Root Post FFS Test V and Pre-Charpy Impact and b) FFS Fracture Face

O.6.2 Thd 3, EHE:

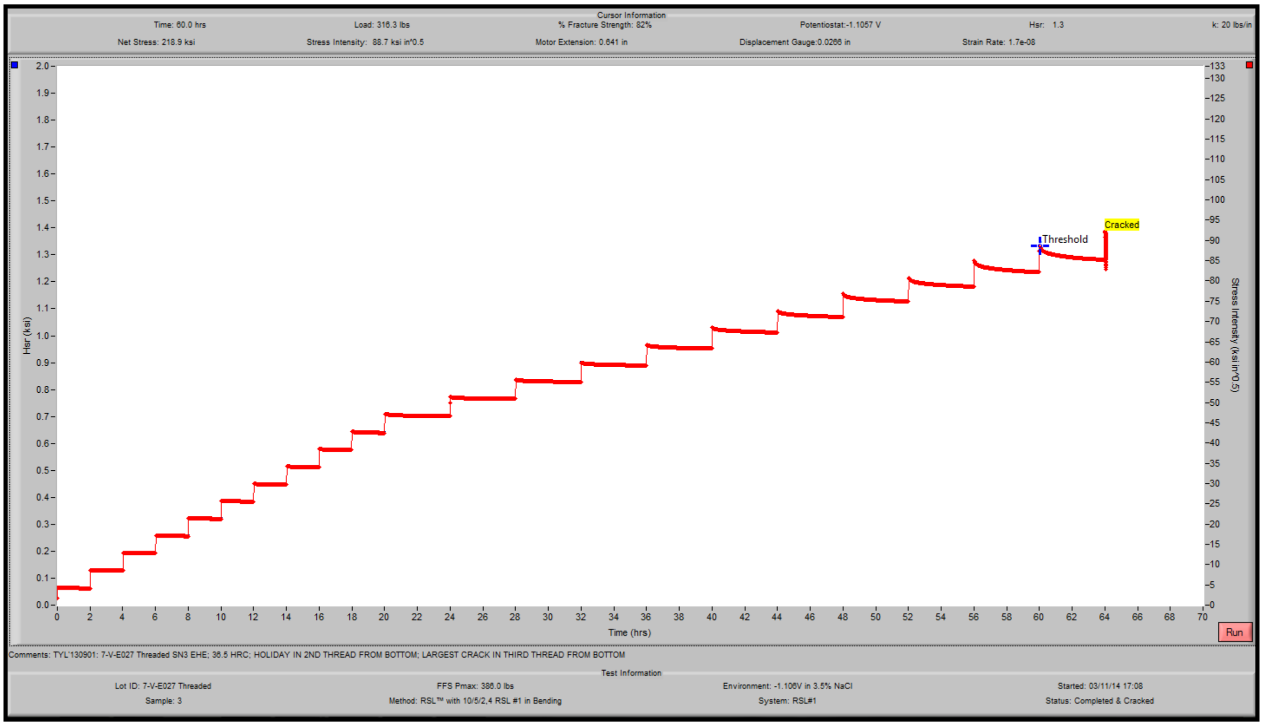


Figure O.6-3: Rod 7-V-E027 Thd 3, Graphical EHE Results

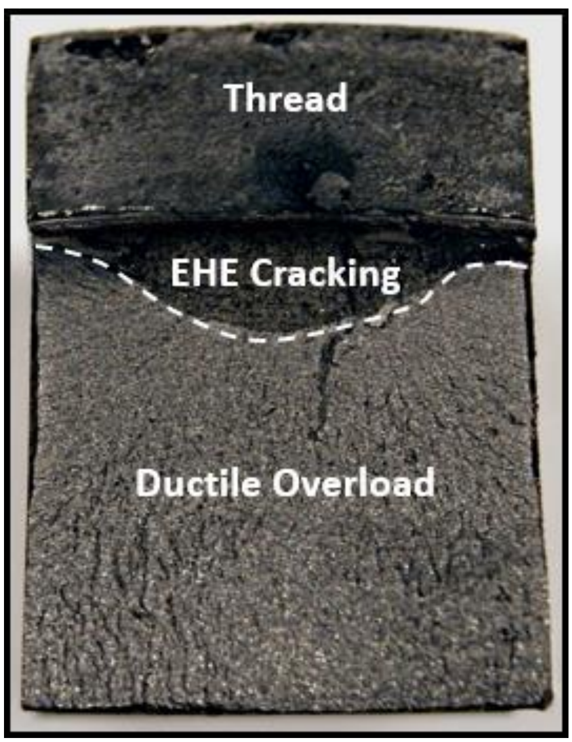
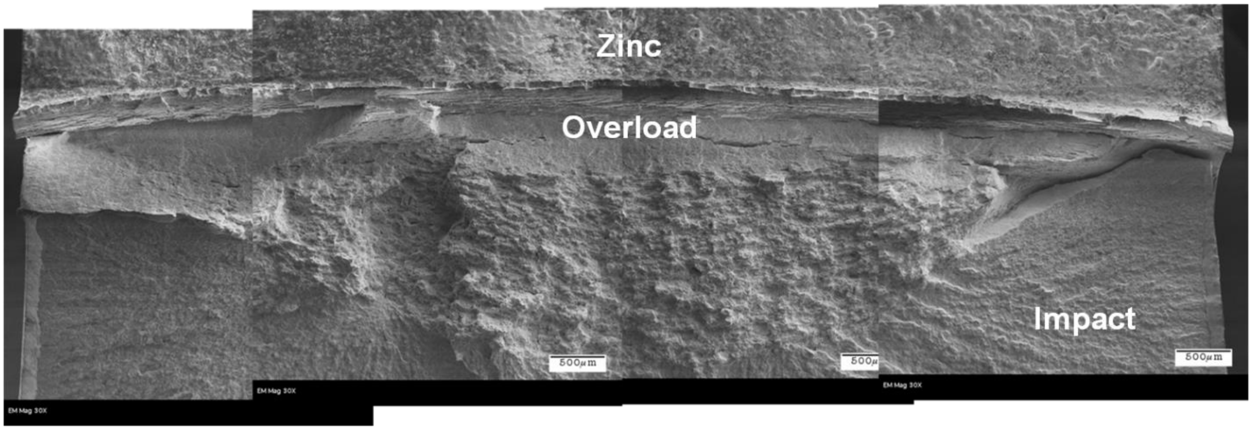
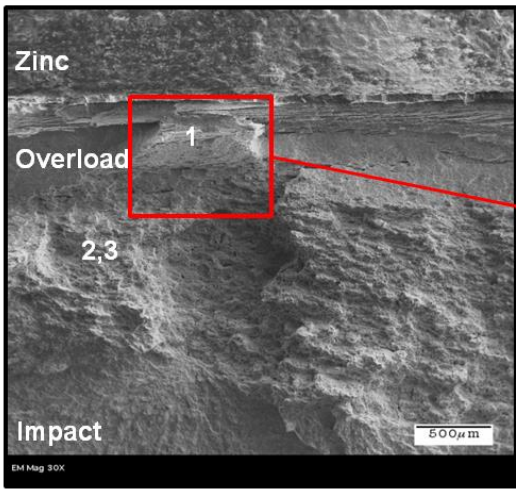


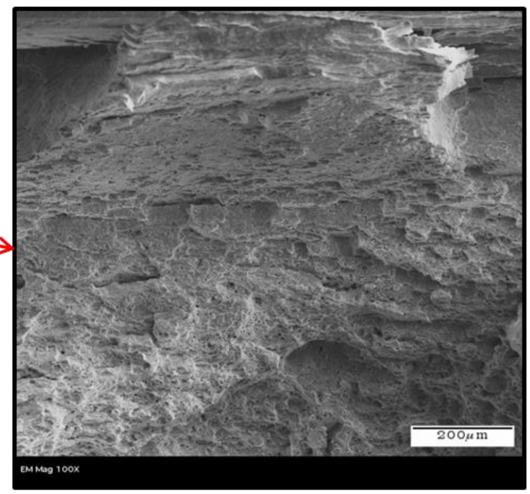
Figure O.6-4: Rod 7-V-E027 Thd 3 EHE Fracture Face

Figure O.6-5: SEM of Rod 7-V-E027 Thd 3, EHE

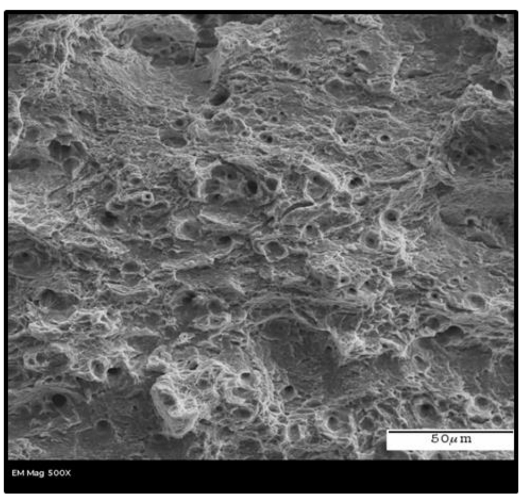




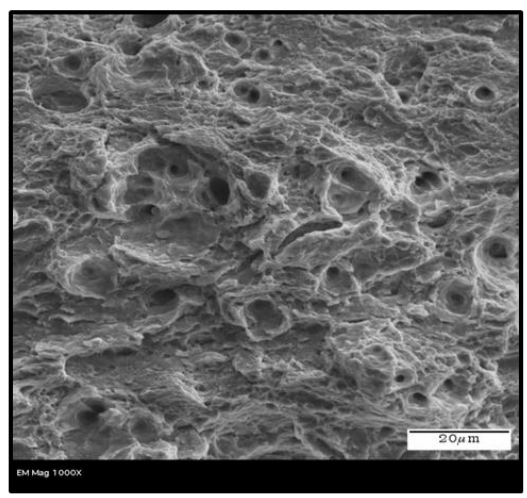
Thread Root 30X



1) Ductile Overload 100X



2) Ductile Overload 500X



3) Ductile Overload 1000X

O.6.3 Thd 6, EHE:

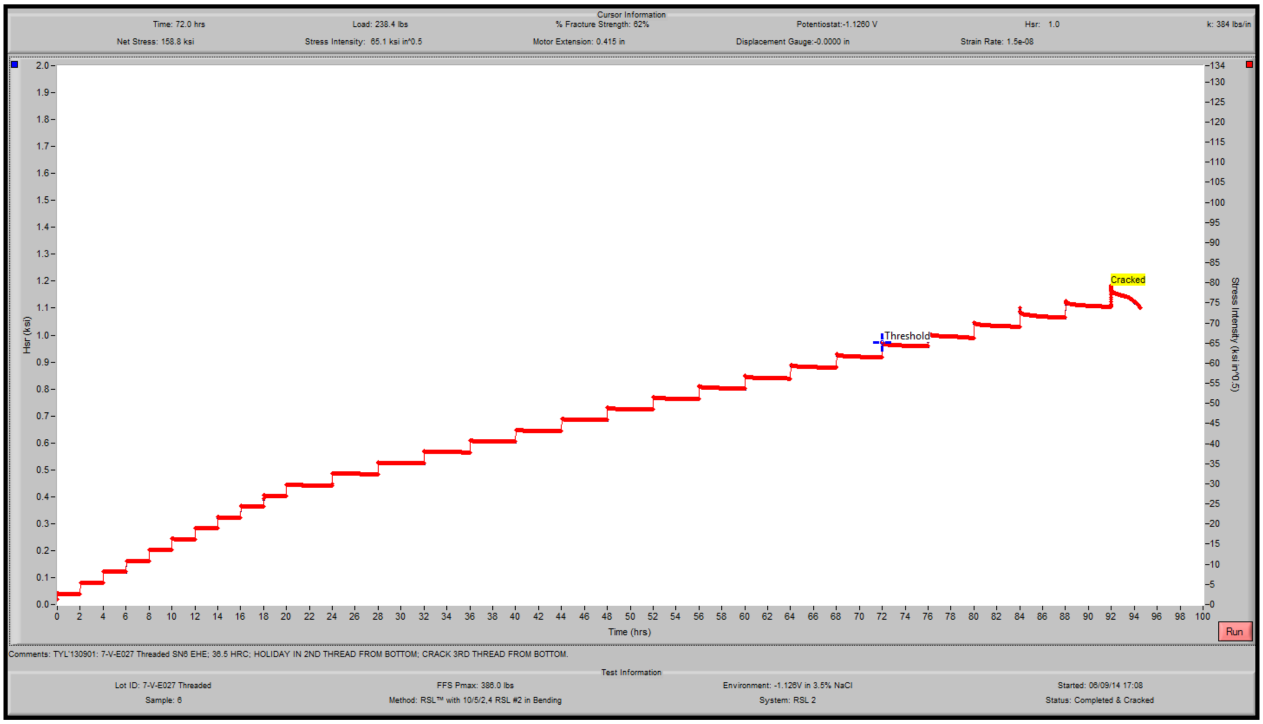


Figure O.6-6: Rod 7-V-E027 Thd 6, Graphical EHE Results

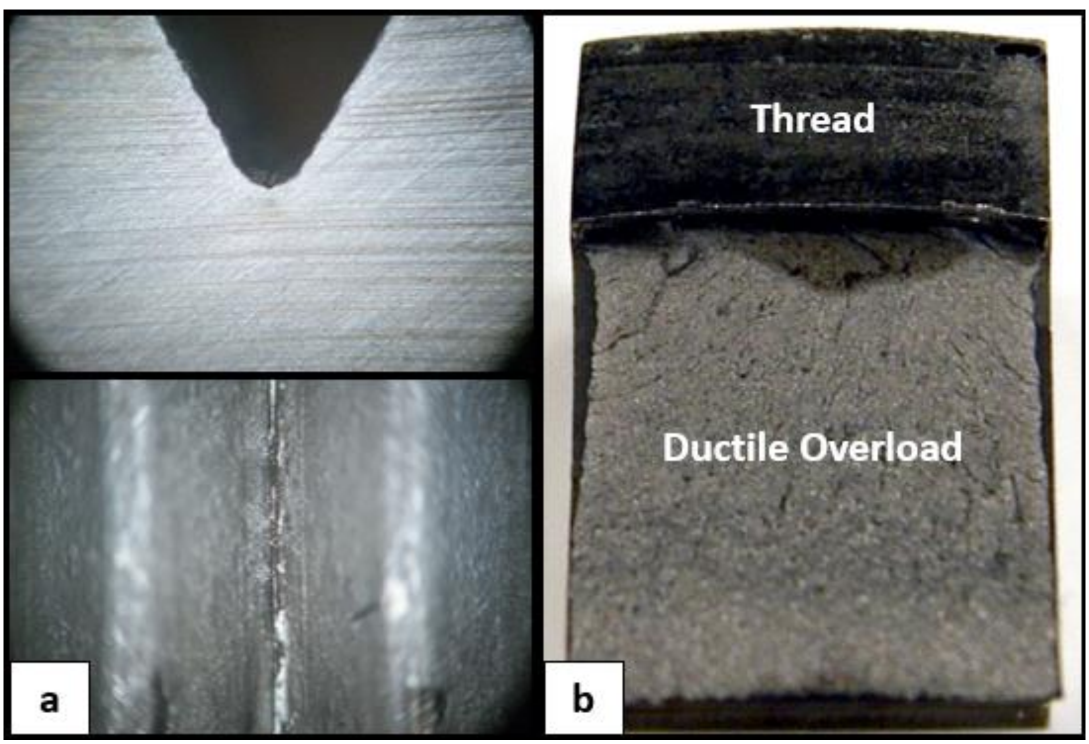
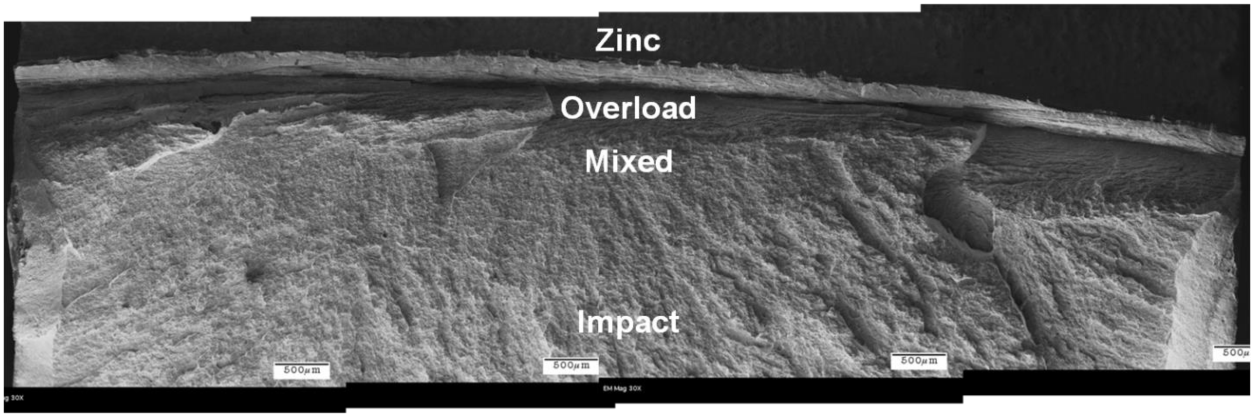
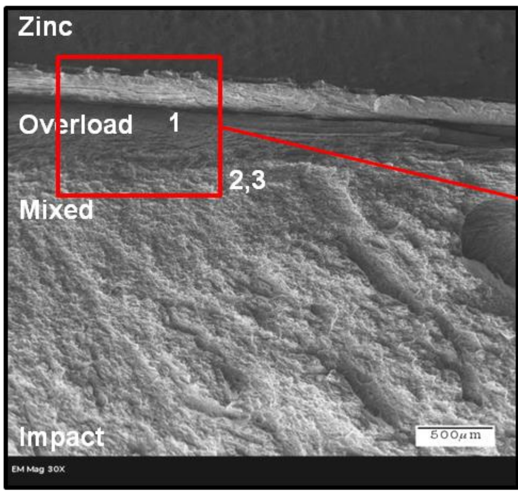


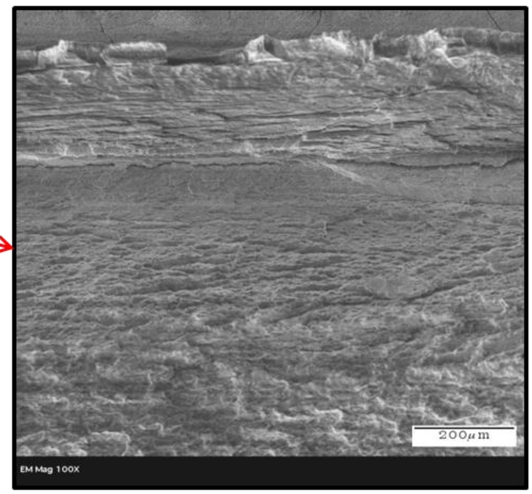
Figure O.6-7: Rod 7-V-E027 Thd 6 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure O.6-8: SEM of Rod 7-V-E027 Thd 6, EHE

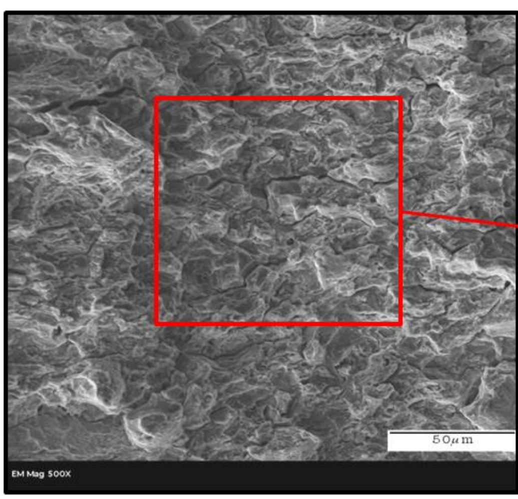




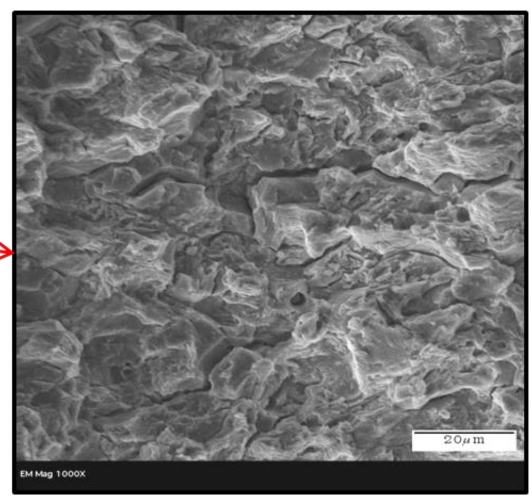
Thread Root 30X



1) Ductile Overload 100X



2) Mixed: Ductile Overload, Intergranular 500X



3) Mixed: Ductile Overload, Intergranular 1000X

O.6.4 Thd 7, EHE:

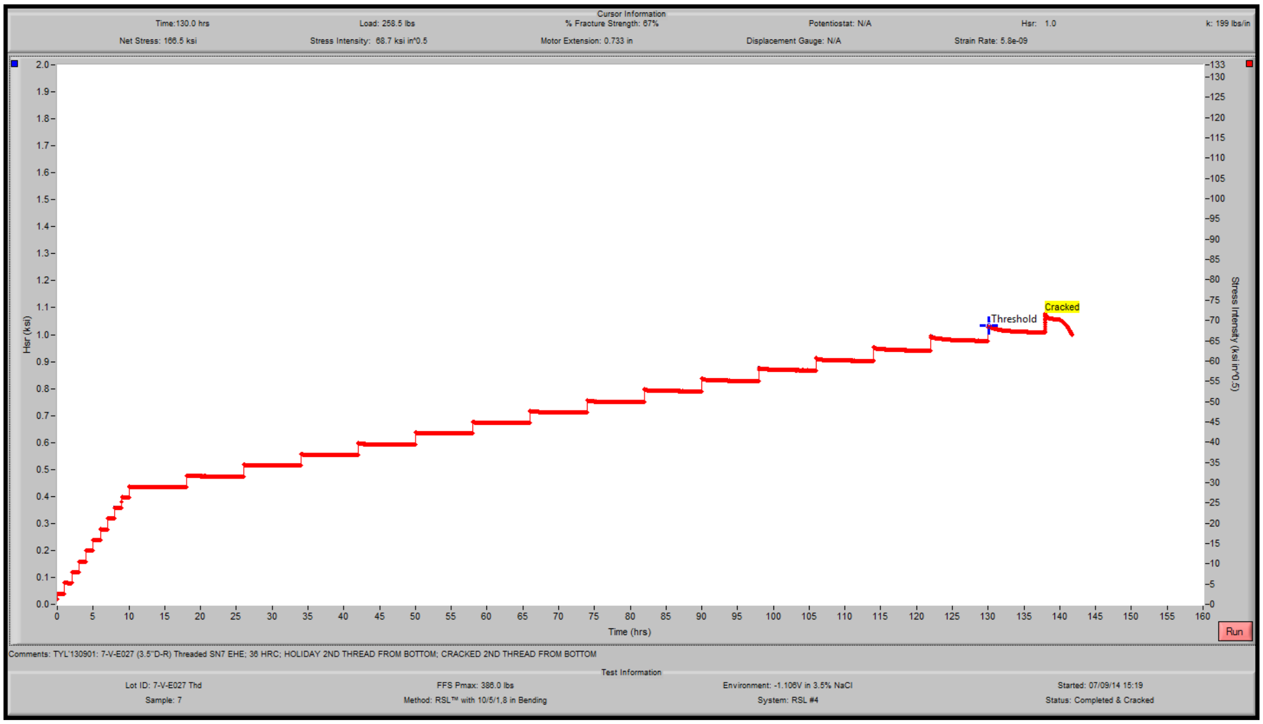


Figure O.6-9: Rod 7-V-E027 Thd 7, Graphical EHE Results

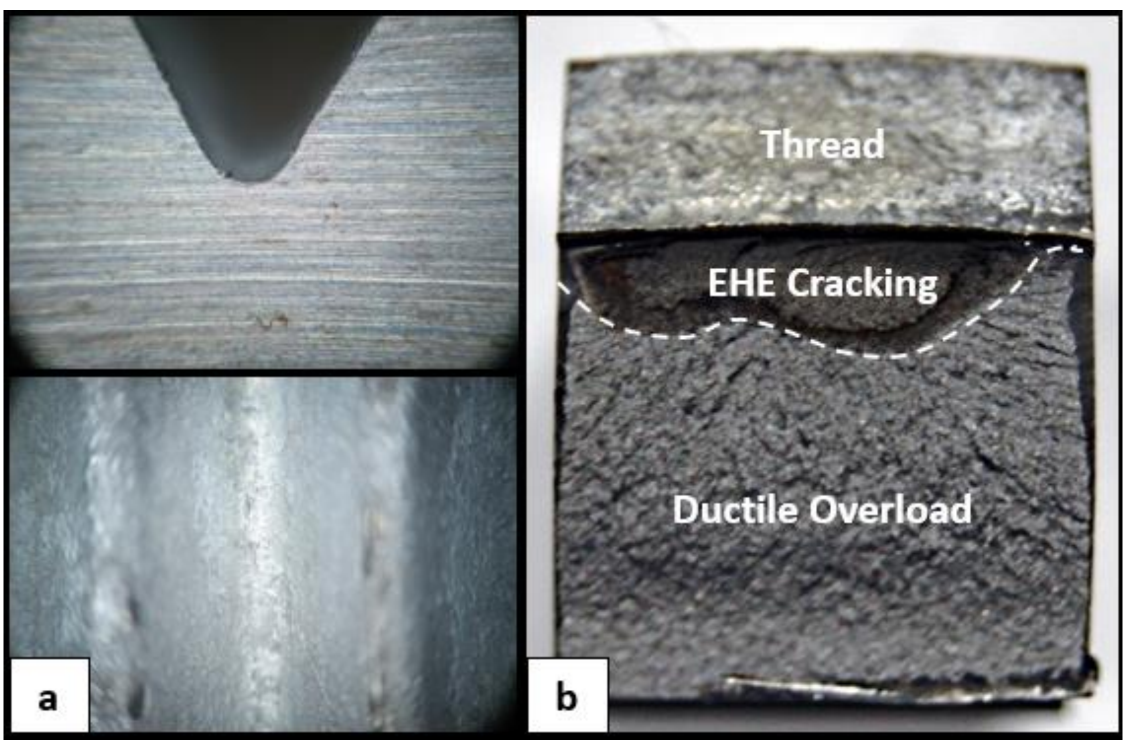


Figure O.6-10: Rod 7-V-E027 Thd 7 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix P: Rod 7-V-E093

P.1 Description of Sample

Rod 7-V-E093 was a PWS Strand Anchor Rod located at the anchorage location above Pier E2 from the same heat as the rod in Test Rig #11 tested in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. The bolts are 3.5 inches in diameter with machined threads. The segment from one of the rod pieces provided to LRA is shown in **Figure P.1-1**.

Figure P.1-1: Pier E2 Anchorage PWS Strand Anchor, Rod 7-V-E093

P.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 7-V-E093 and can be seen versus time in **Figure P**.2-1. The final OCP recorded for Rod 7-V-E093 was Vsce=-1.071 V.

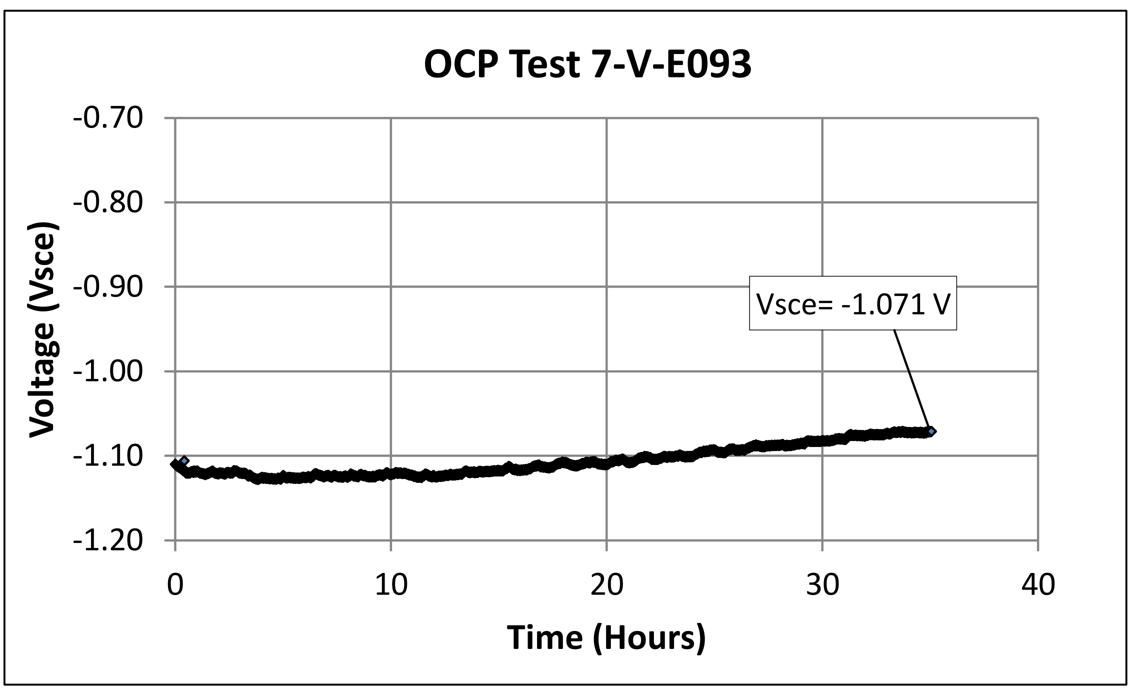


Figure P.2-1: Open Circuit Potential for Rod 7-V-E093

P.3 Hardness

The hardness data and profile for sample 7-V-E093 are shown in **Table P.3-1** and **Figure P.3-1**.

Table P.3-1: Hardness Data of Rod 7-V-E093 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	29.0	29.0
MR 1, FFS	34.0	33.0
MR 3, EHE	32.5	
MR 4, EHE	32.5	
OD 1, FFS	37.5	37.6
OD 3, EHE	37.0	
OD 4, EHE	38.0	
OD 5, EHE	37.5	
Thd 1, FFS	38.0	
Thd 3, EHE	37.5	
Thd 5, EHE	37.5	
Thd 6, EHE	38.0	
Thd 7, EHE	37.5	

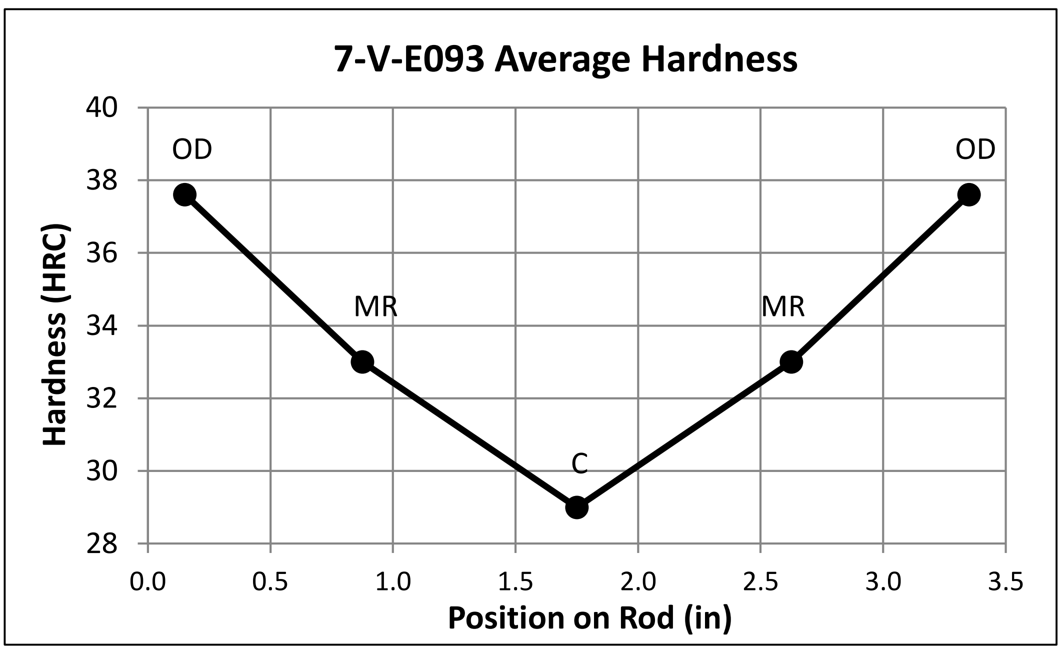


Figure P.3-1: Hardness Profile of Rod 7-V-E093

P.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

P.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E093						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable) **Comments**: 2010 Machined Threads, Heat OOF Same Heat as Rod in Test Rig #11 in Test IV				
Rod#:	**7-V-E093**					
Product Form:	**1e**					
Rod OD:	**3.5"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**37.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	88.6 0.52 0.98 8200		
	OD 3, EHE	**37.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			27.0 0.16 0.30 4.1
	OD 4, EHE	**38.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			23.0 0.13 0.25 1.1
	OD 5, EHE	**37.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			22.2 0.13 0.25 0.98

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E093						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)				
Rod#:	**7-V-E093**					
Product Form:	**1e**	**Comments**: 2010 Machined Threads, Heat OOF				
Rod OD:	**3.5"**	Same Heat as Rod in Test Rig #11 in Test IV				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 1, FFS**	**34.0**	K_{max}	79.2		
			DTI_{th}	0.52		
			Fu	0.88		
			Strain Rate ($x10^{-8}$ in/in/sec)	8300		
	MR 3, EHE	**32.5**	$K_{threshold}$			43.5
			DTI_{th}			0.30
			Fu			0.48
			Strain Rate ($x10^{-8}$ in/in/sec)			2
	MR 4, EHE	**32.5**	$K_{threshold}$			41.4
			DTI_{th}			0.28
			Fu			0.46
			Strain Rate ($x10^{-8}$ in/in/sec)			1.80
	Center 1, FFS	**29.0**	K_{max}	75.9		
			DTI_{th}	0.57		
			Fu	0.84		
			Strain Rate ($x10^{-8}$ in/in/sec)	8500		

P.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E093						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable) **Comments**: 2010 Machined Threads, Heat OOF Same Heat as Rod in Test Rig #11 in Test IV				
Rod#:	**7-V-E093**					
Product Form:	**1e**					
Rod OD:	**3.5"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**38.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	365.9 1.18 1.5 3900		
	Thd 3, EHE	**37.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			211.6 0.68 0.9 2.2
	Thd 5, EHE	**37.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			195.1 0.63 0.8 2.0
	Thd 6, EHE	**38.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			186.9 0.60 0.8 1.9
	Thd 7, EHE	**37.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			192.4 0.62 0.8 1.6

P.4.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-E093
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**7-V-E093**
Product Form:	**1e**
Rod OD:	**3.5"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, Pth (lbs)	%FS (Pth/Pmax)	Kmax, KIscc, KIp_{-EHE} (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	37.5	169	99.2	99.2	99.2	100.0%	88.6	0.52	300.3	1.8	8200	0.2147	139.0	50 lbs/min		0.98	
	OD 3, EHE	3.5% NaCl @ -1.106 V	37.0	167	67.0	36.9	30.0	30.5%	27.0	0.16	91.7	0.6	4.1	0.2155		10/5/2,4		0.30	Cracked Before 4 Hour Steps
	OD 4, EHE	3.5% NaCl @ -1.106 V	38.0	172	33.0	31.4	26.3	26.0%	23.0	0.13	77.5	0.5	1.1	0.212		10/5/2,4		0.25	
	OD 5, EHE	3.5% NaCl @ -1.106 V	37.5	169	28.0	29.5	25.1	25.1%	22.2	0.13	74.9	0.4	0.98	0.2127		10/5/2,4		0.25	
	MR 1, FFS	Air	34.0	153	89.0	89.0	89.0	100.0%	79.2	0.52	268.7	1.8	8300	0.2117	143.7	50 lbs/min		0.88	
	MR 3, EHE	3.5% NaCl @ -1.106 V	32.5	147	60.0	60.1	47.8	54.9%	43.5	0.30	148.6	1.0	2.0	0.2133		10/5/2,4		0.48	
	MR 4, EHE	3.5% NaCl @ -1.106 V	32.5	147	50.0	52.6	44.9	52.3%	41.4	0.28	141.7	1.0	1.8	0.2157		10/5/2,4		0.46	
	Center 1, FFS	Air	29.0	134	82.5	82.5	82.5	100.0%	75.9	0.57	259.6	1.9	8500	0.2127	149.7	50 lbs/min		0.84	
Threaded	Thd 1, FFS	Air	38.0	172	380.2	380.2	380.2	100.0%	106.7	0.62	263.7	1.5	3900	N/A		0.4 in/min	365.9	1.18	
	Thd 3, EHE	3.5% NaCl @ -1.106 V	37.5	169	295.0	309.9	235.1	57.8%	61.7	0.37	151.4	0.9	2.2	N/A		10/5/2,4	211.6	0.68	Did Not Crack In Holiday
	Thd 5, EHE	3.5% NaCl @ -1.106 V	37.5	169	250.0	262.4	199.3	53.3%	56.9	0.34	141.0	0.8	2.0	N/A		10/5/2,4	195.1	0.63	Did Not Crack In Holiday
	Thd 6, EHE	3.5% NaCl @ -1.106 V	38.0	172	225.0	191.3	179.4	51.1%	54.5	0.32	136.8	0.8	1.9	N/A		10/5/2,4	186.9	0.60	Cracked in Holiday
	Thd 7, EHE	3.5% NaCl @ -1.106 V	37.5	169	200.0	210.1	199.1	52.6%	56.1	0.33	138.4	0.8	1.6	N/A		10/5/2,4	192.4	0.62	Cracked in Holiday

P.5 Fatigue Pre-cracked Specimen Test Results

P.5.1 OD 1, FFS:

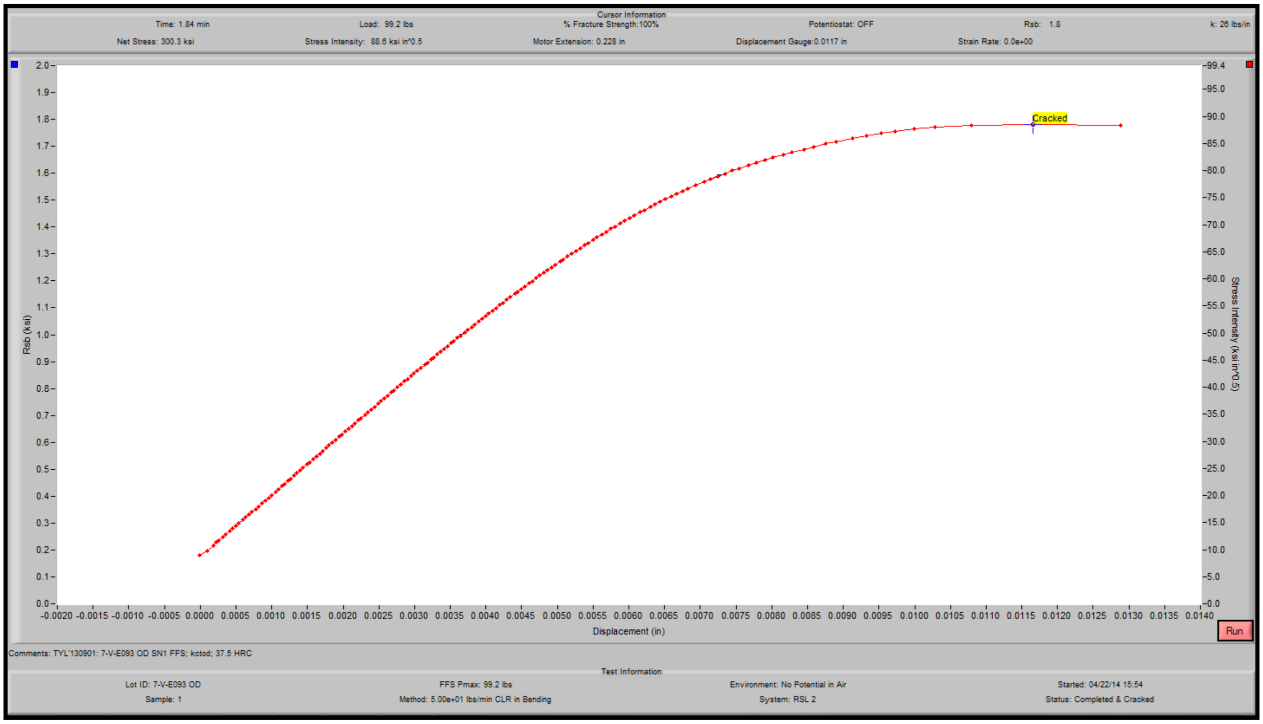


Figure P.5-1: Rod 7-V-E093 OD 1, Graphical FFS Results

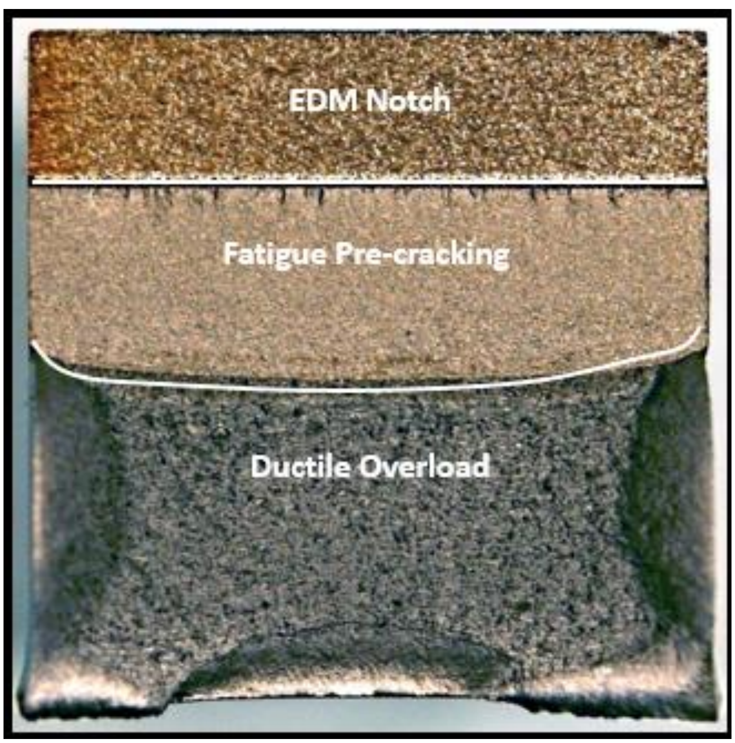


Figure P.5-2: Fracture Face of Rod 7-V-E093 OD 1, FFS

P.5.2 OD 3, EHE:

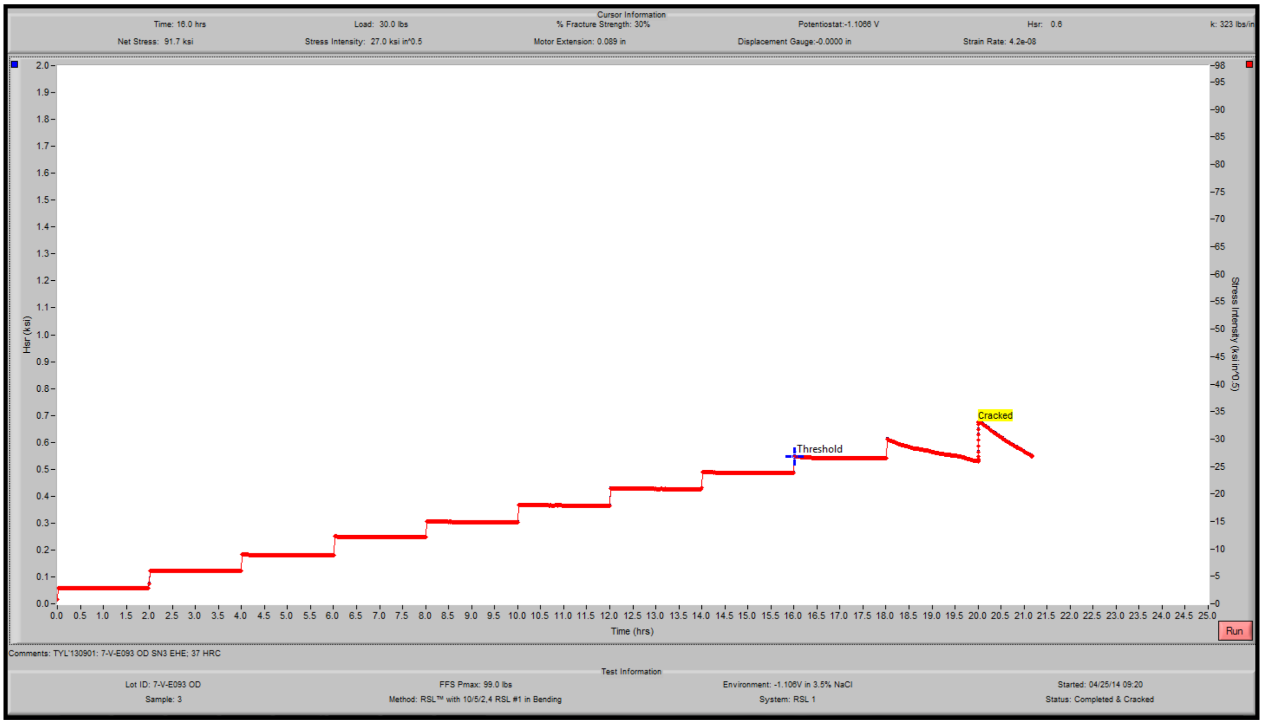


Figure P.5-3: Rod 7-V-E093 OD 3, Graphical EHE Results

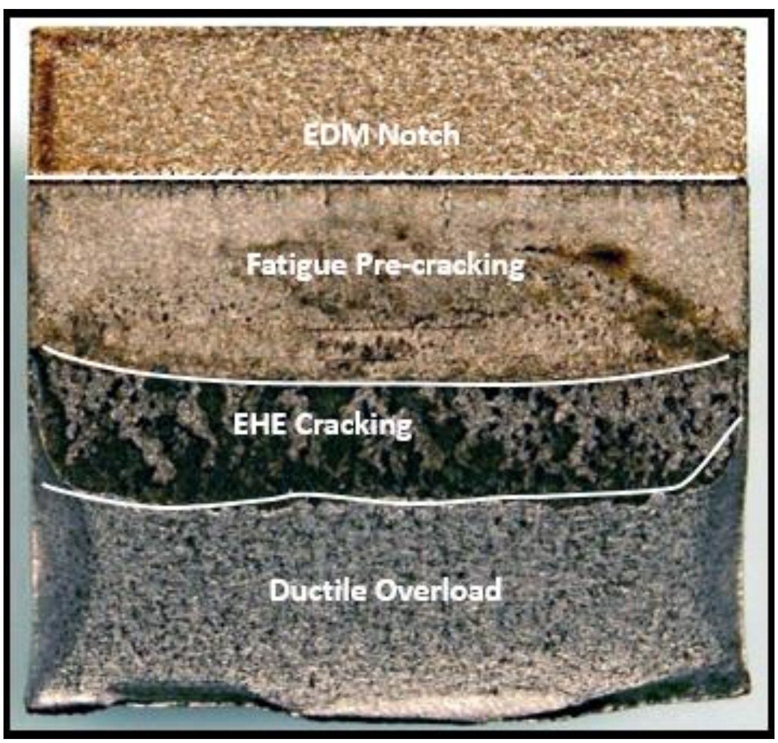


Figure P.5-4: Fracture Face of Rod 7-V-E093 OD 3, EHE

P.5.3 OD 4, EHE:

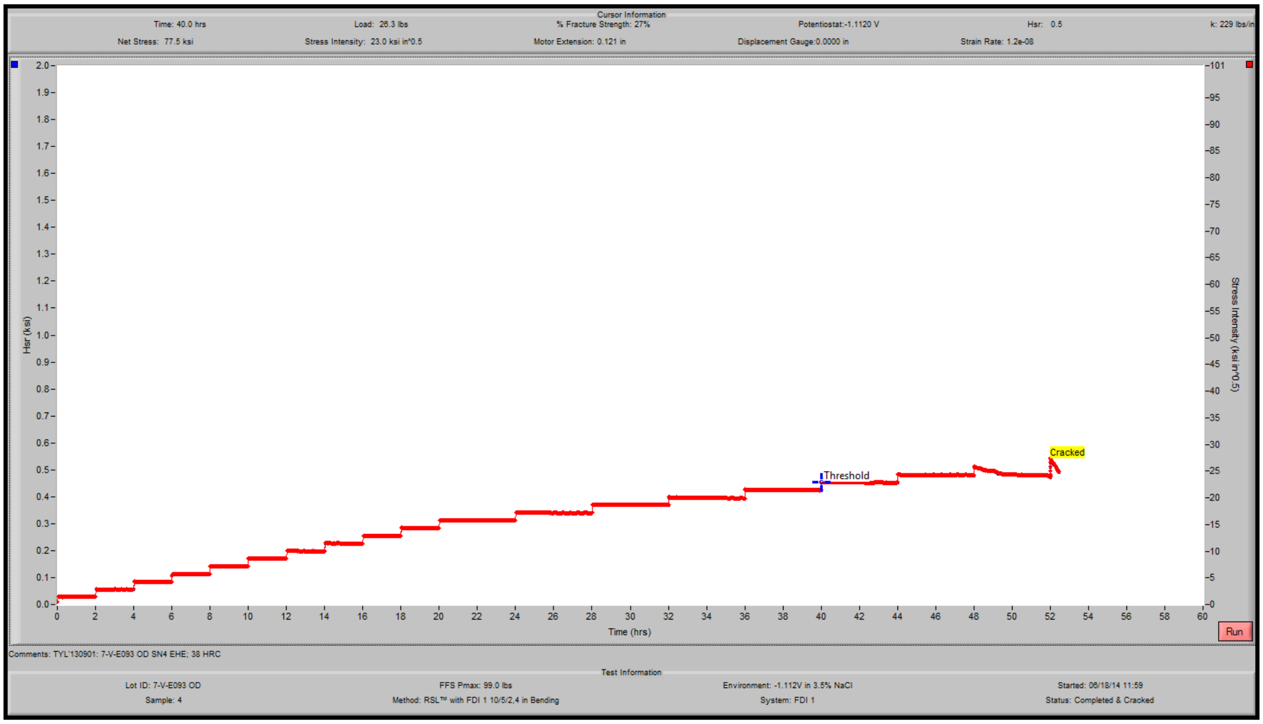


Figure P.5-5: Rod 7-V-E093 OD 4, Graphical EHE Results

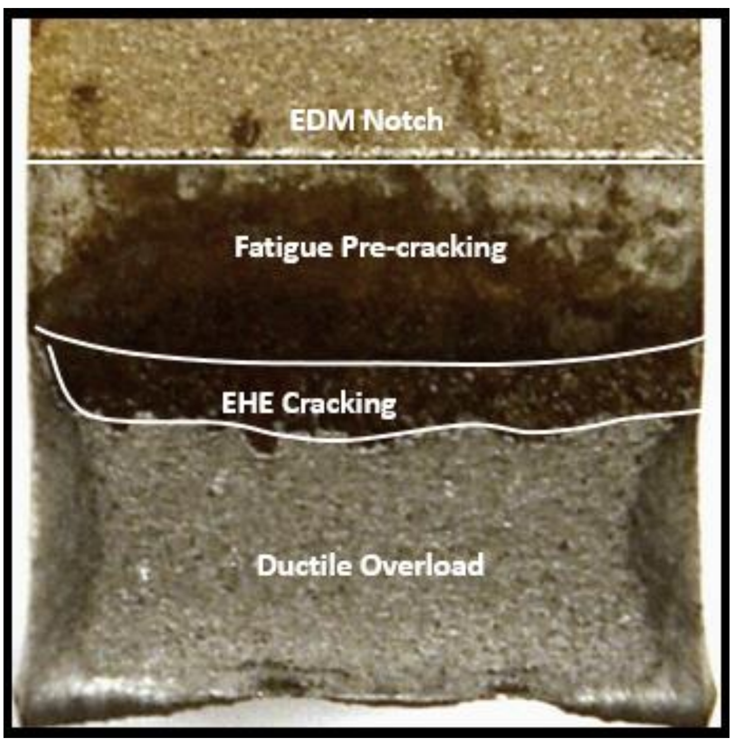


Figure P.5-6: Fracture Face of Rod 7-V-E093 OD 4, EHE

P.5.4 OD 5, EHE:

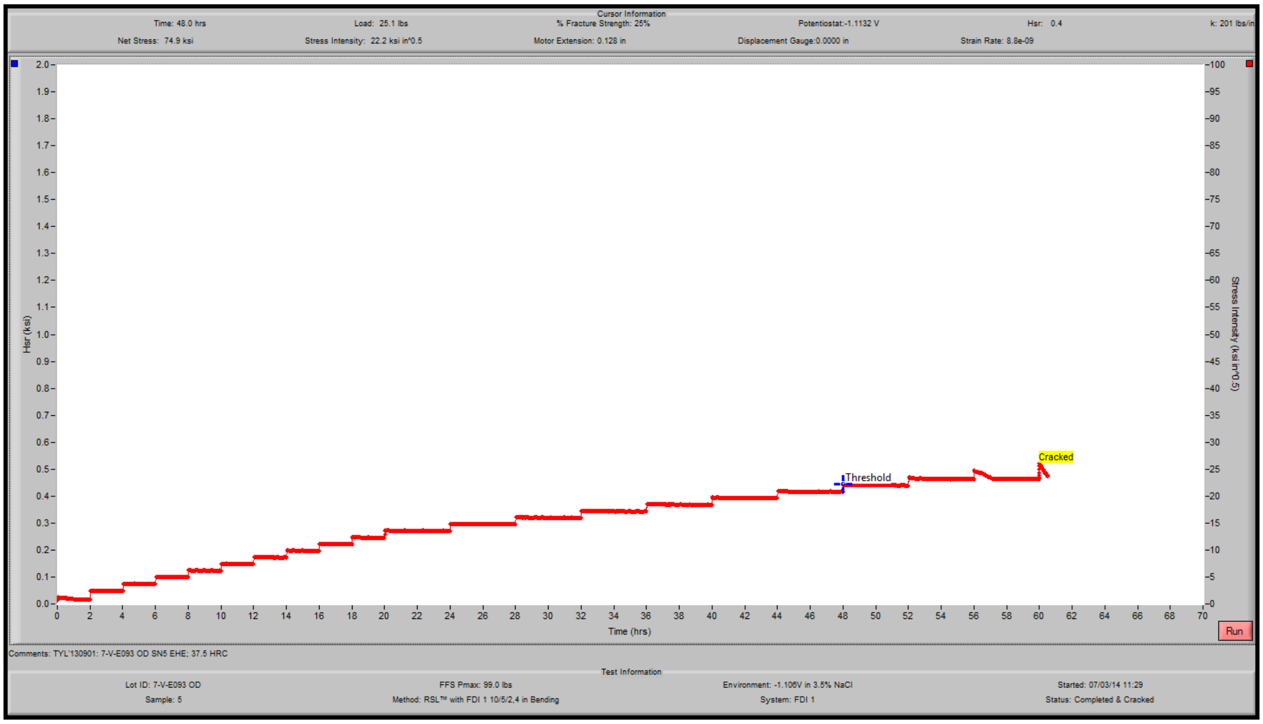


Figure P.5-7: Rod 7-V-E093 OD 5, Graphical EHE Results

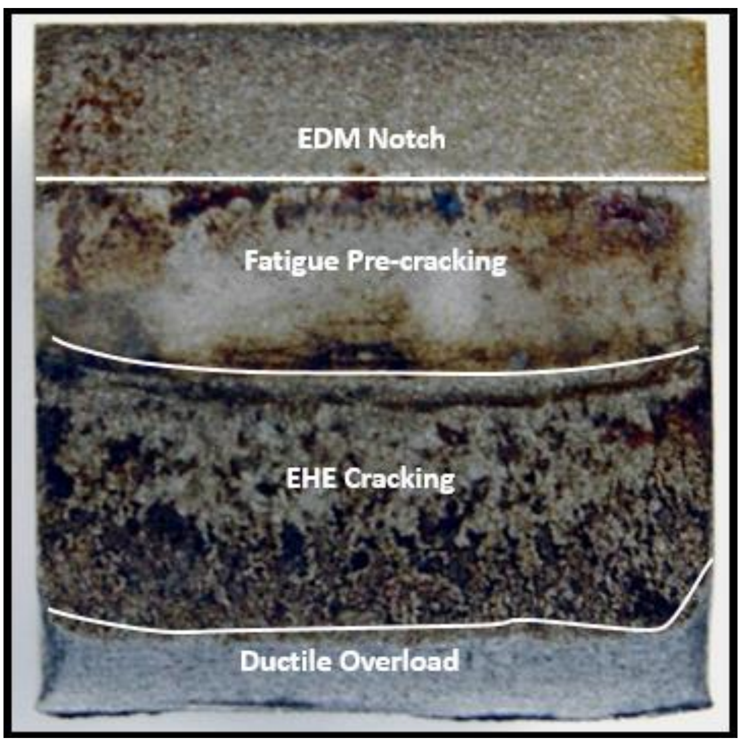


Figure P.5-8: Fracture Face of Rod 7-V-E093 OD 5, EHE

P.5.5 MR 1, FFS:

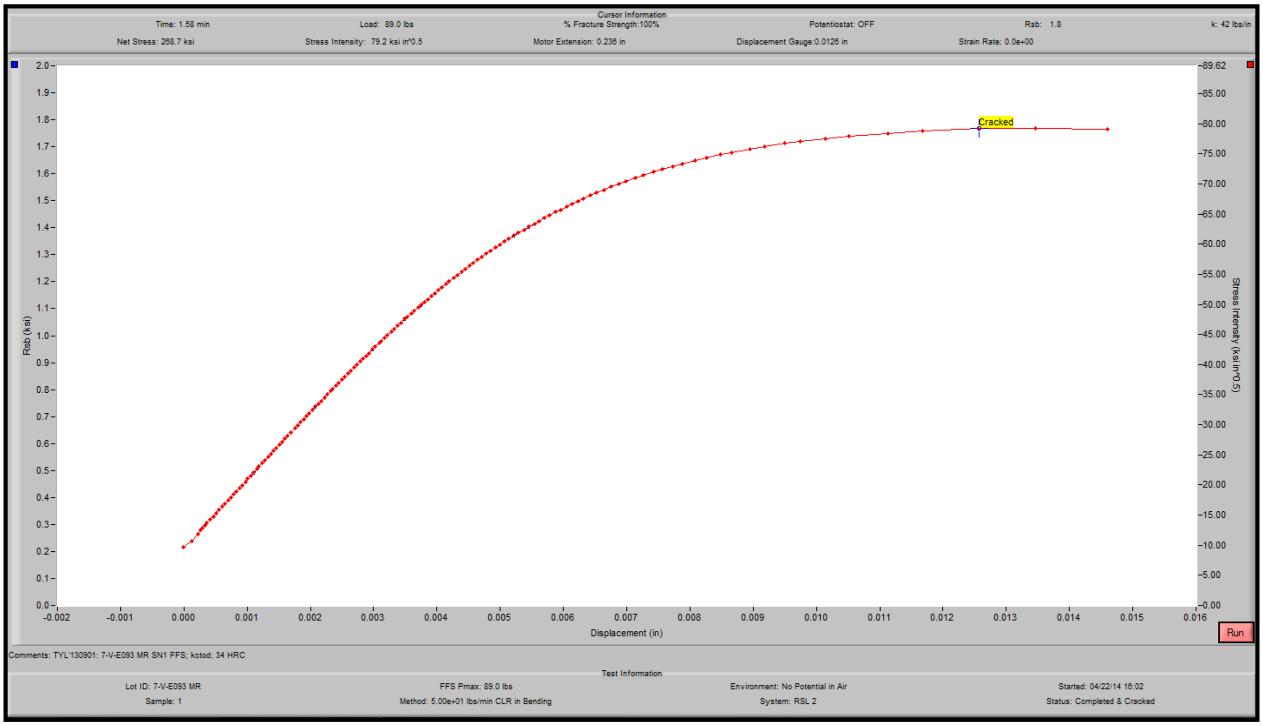


Figure P.5-9: Rod 7-V-E093 MR 1, Graphical FFS Results

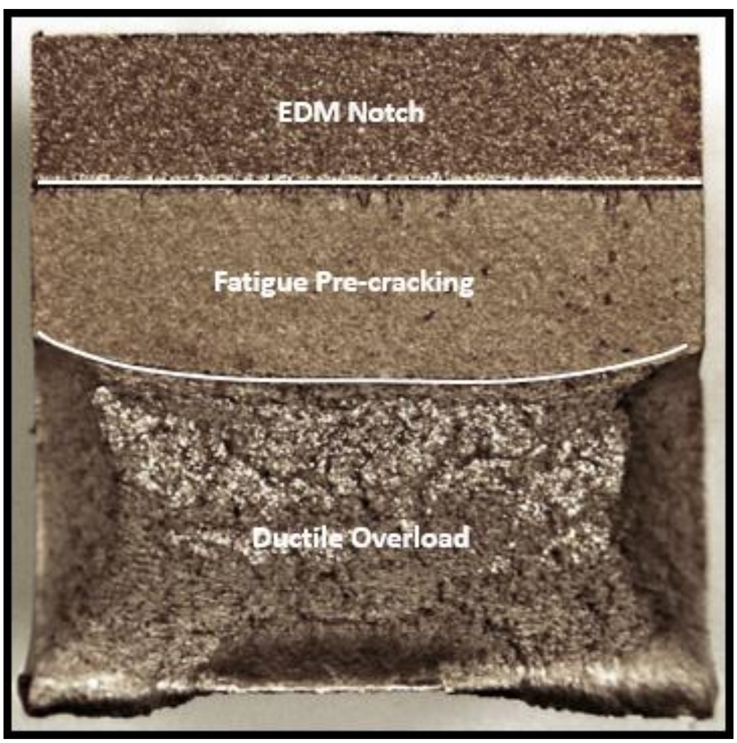


Figure P.5-10: Fracture Face of Rod 7-V-E093 MR 1, FFS

P.5.6 MR 3, EHE:

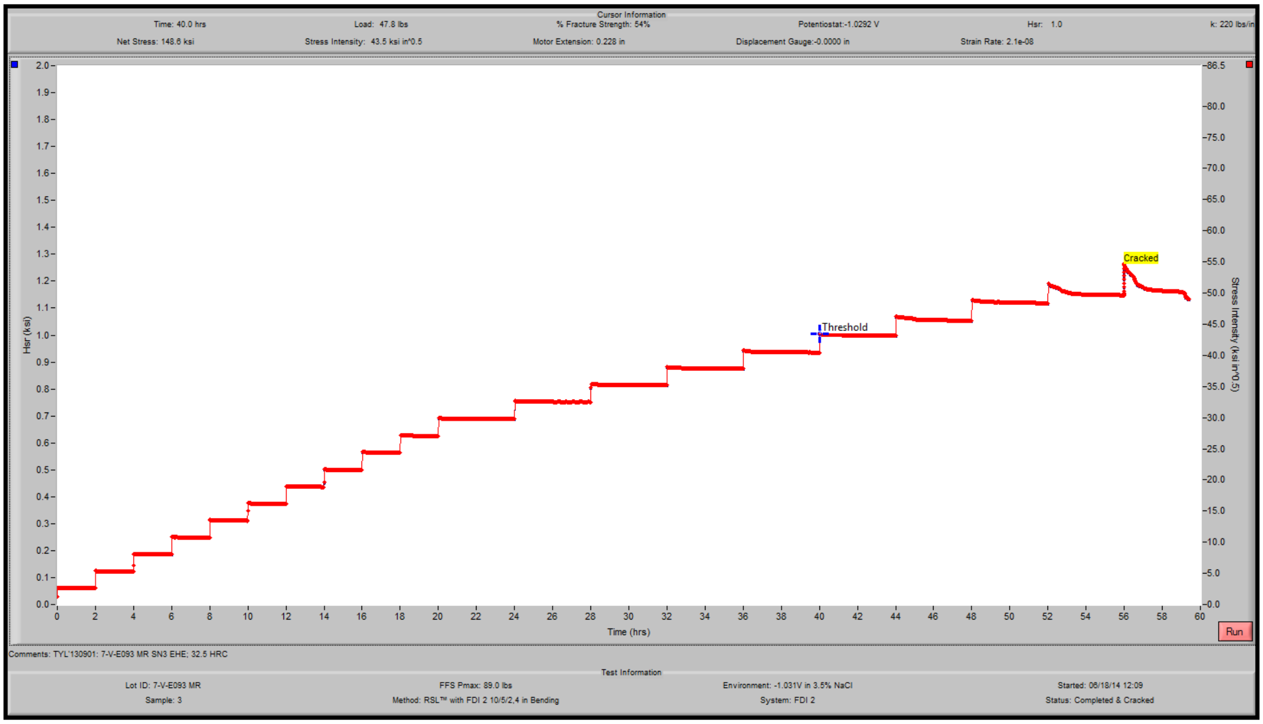


Figure P.5-11: Rod 7-V-E093 MR 3, Graphical EHE Results

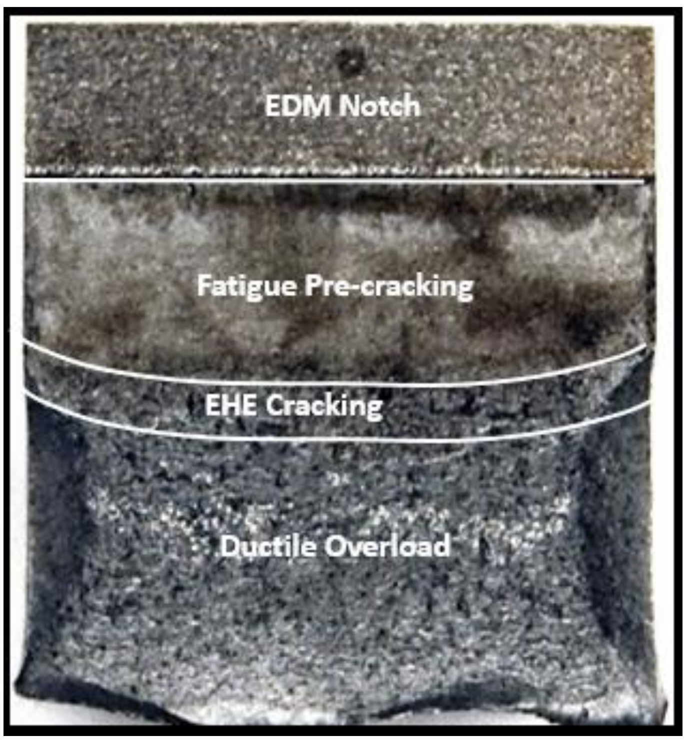


Figure P.5-12: Fracture Face of Rod 7-V-E093 MR 3, EHE

P.5.7 MR 4, EHE:

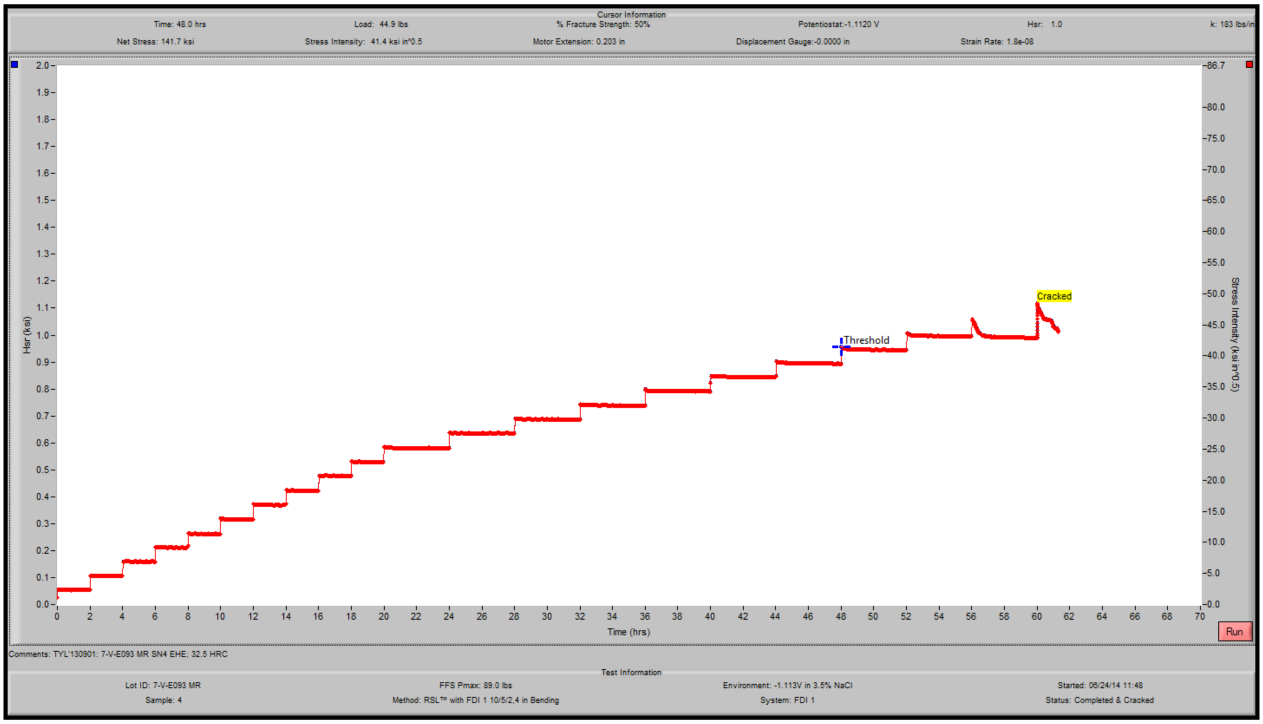


Figure P.5-13: Rod 7-V-E093 MR 4, Graphical EHE Results

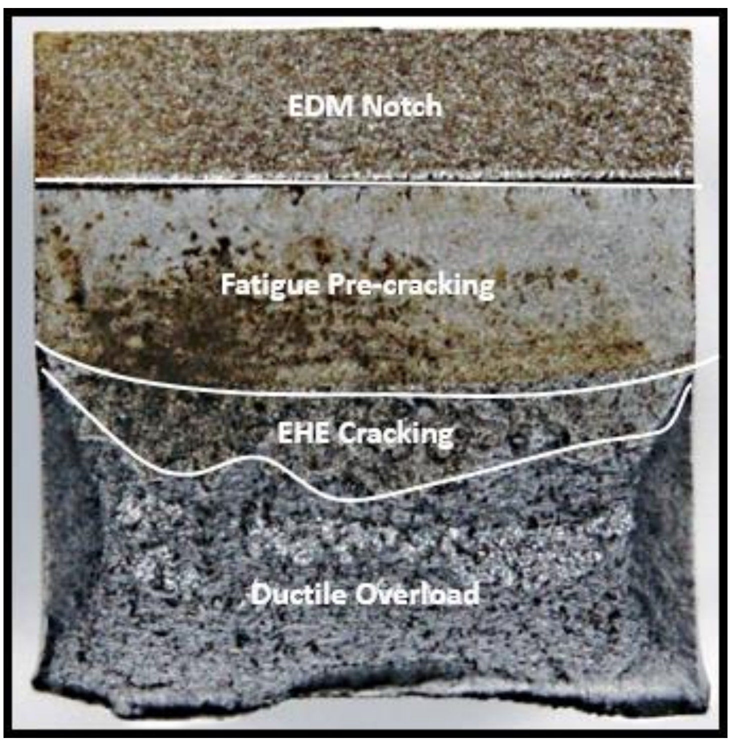


Figure P.5-14: Fracture Face of Rod 7-V-E093 MR 4, EHE

P.5.8 Center 1, FFS:

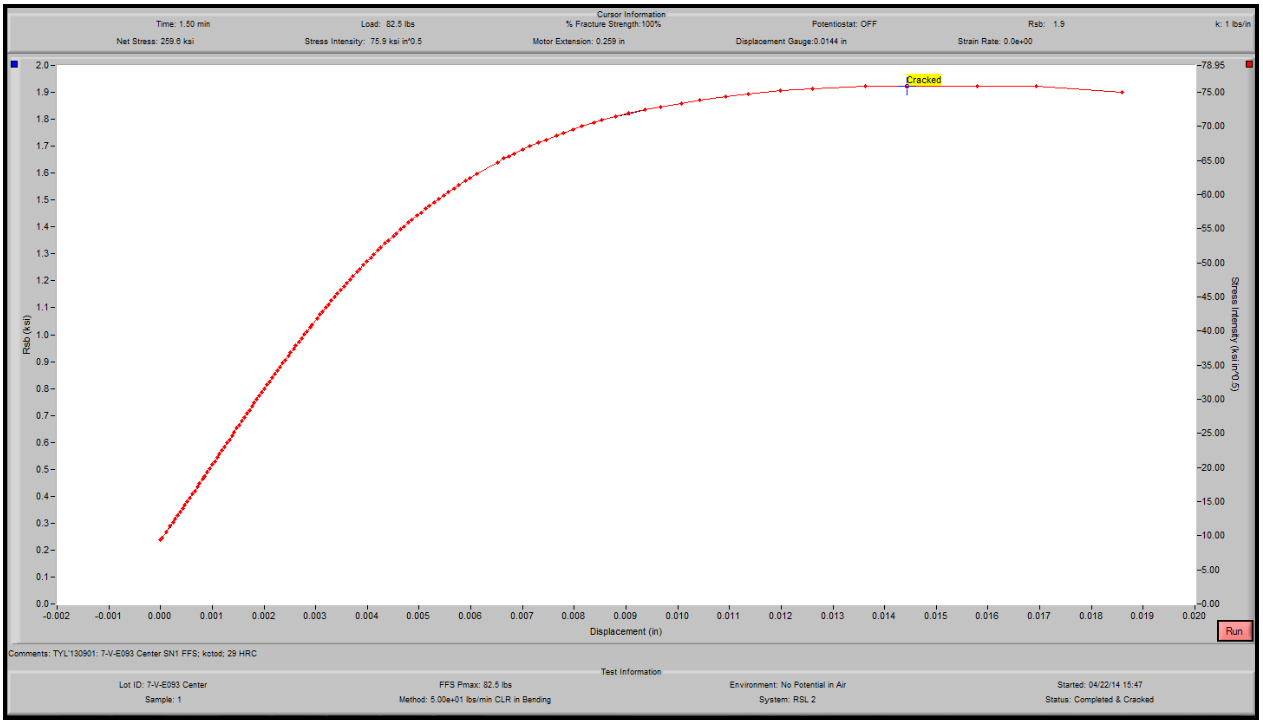


Figure P.5-15: Rod 7-V-E093 Center 1, Graphical FFS Results

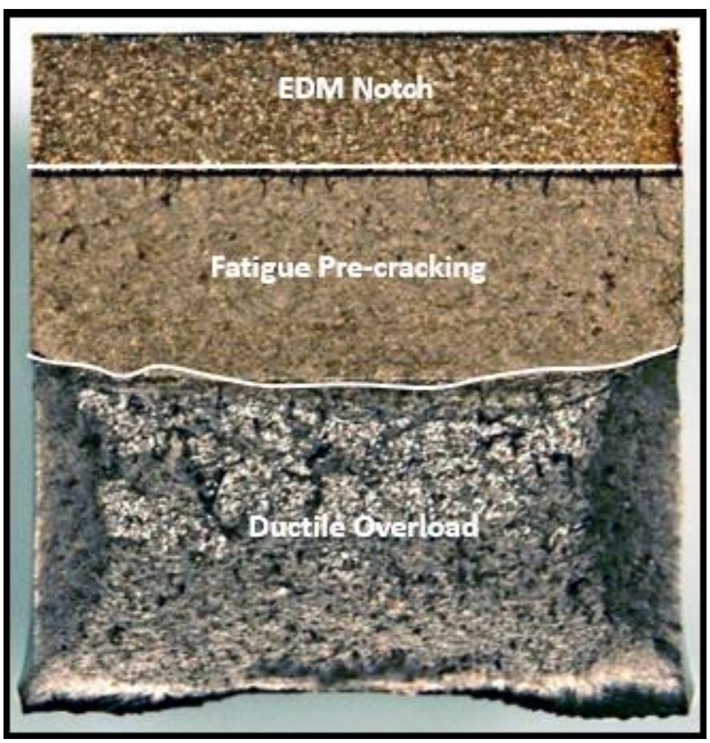


Figure P.5-16: Fracture Face of Rod 7-V-E093 Center 1, FFS

P.6 Threaded Specimen Test Results

P.6.1 Thd 1, FFS:

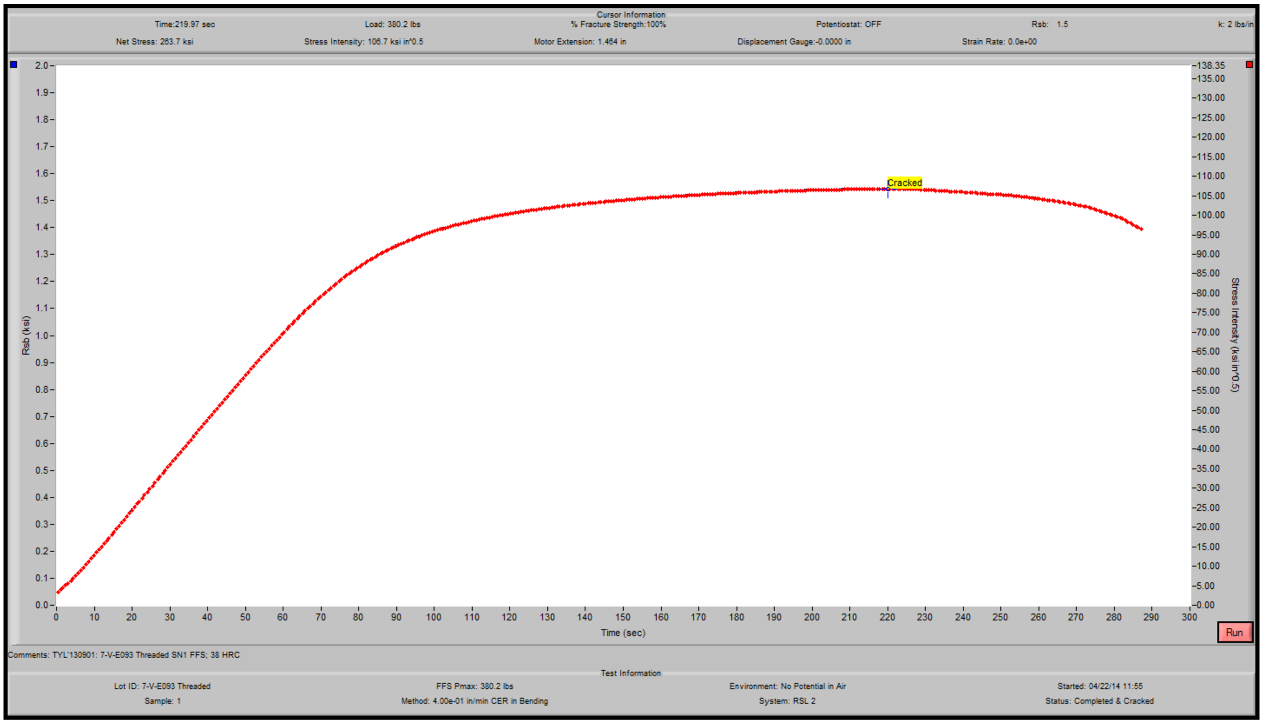


Figure P.6-1: Rod 7-V-E093 Thd 1, Graphical FFS Results

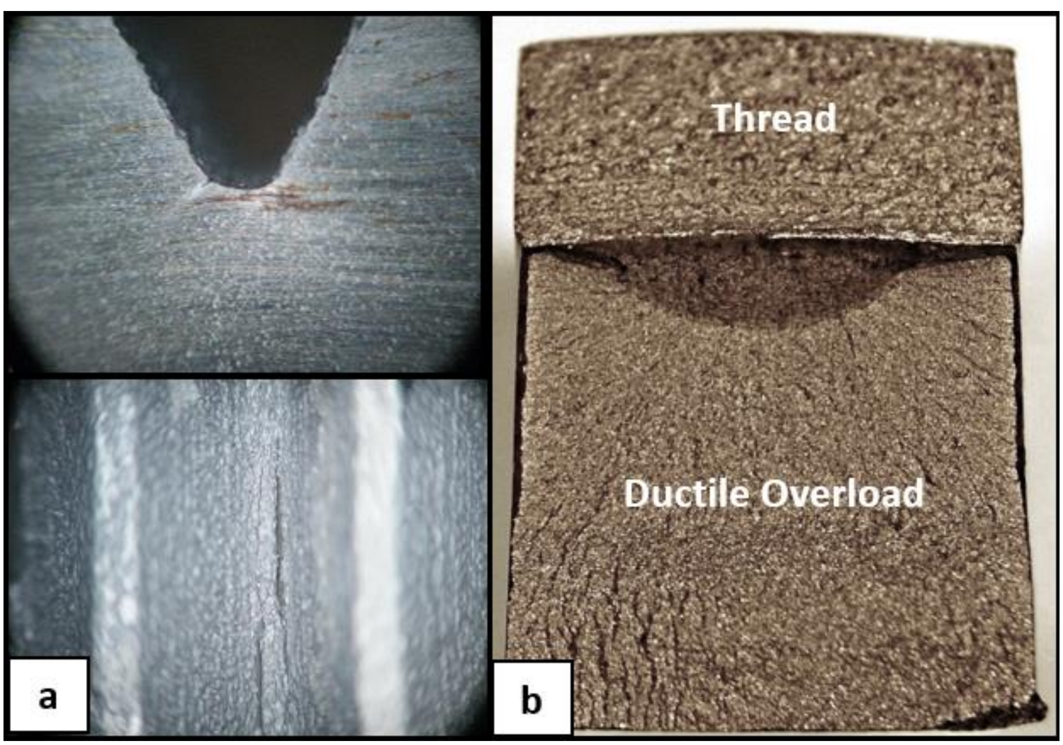


Figure P.6-2: Rod 7-V-E093 Thd 1 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

P.6.2 Thd 3, EHE:

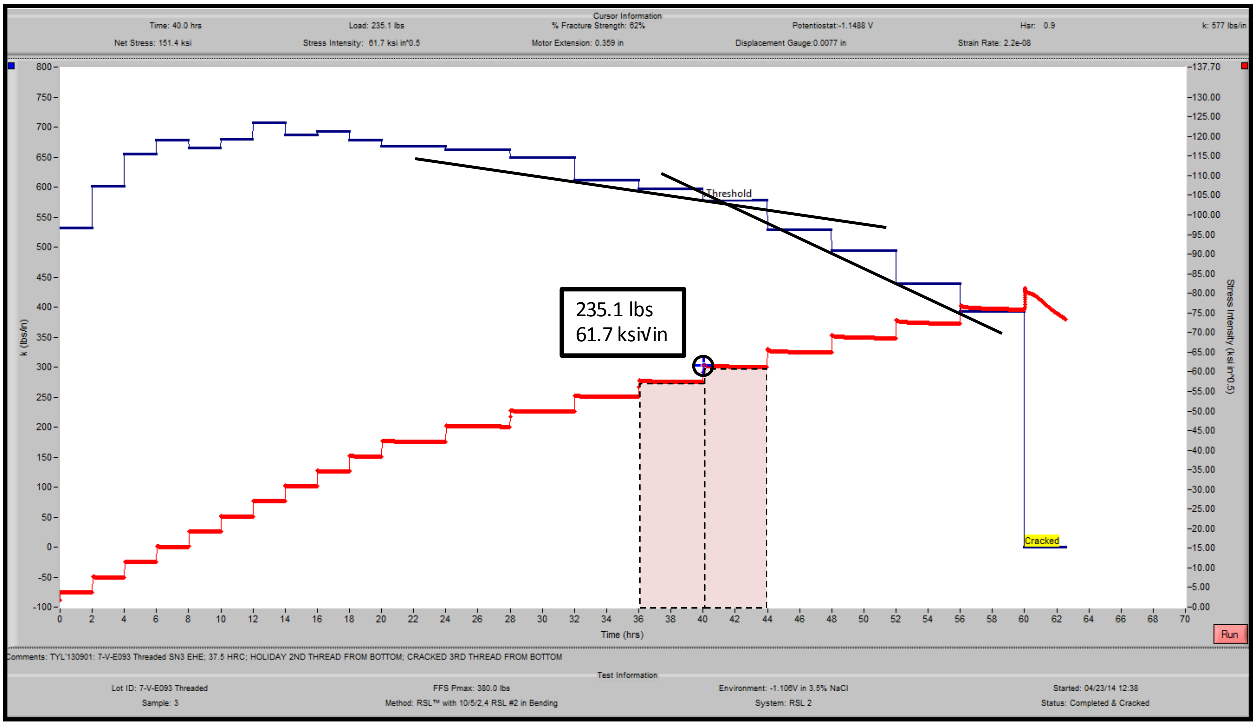


Figure P.6-3: Rod 7-V-E093 Thd 3, Graphical EHE Results

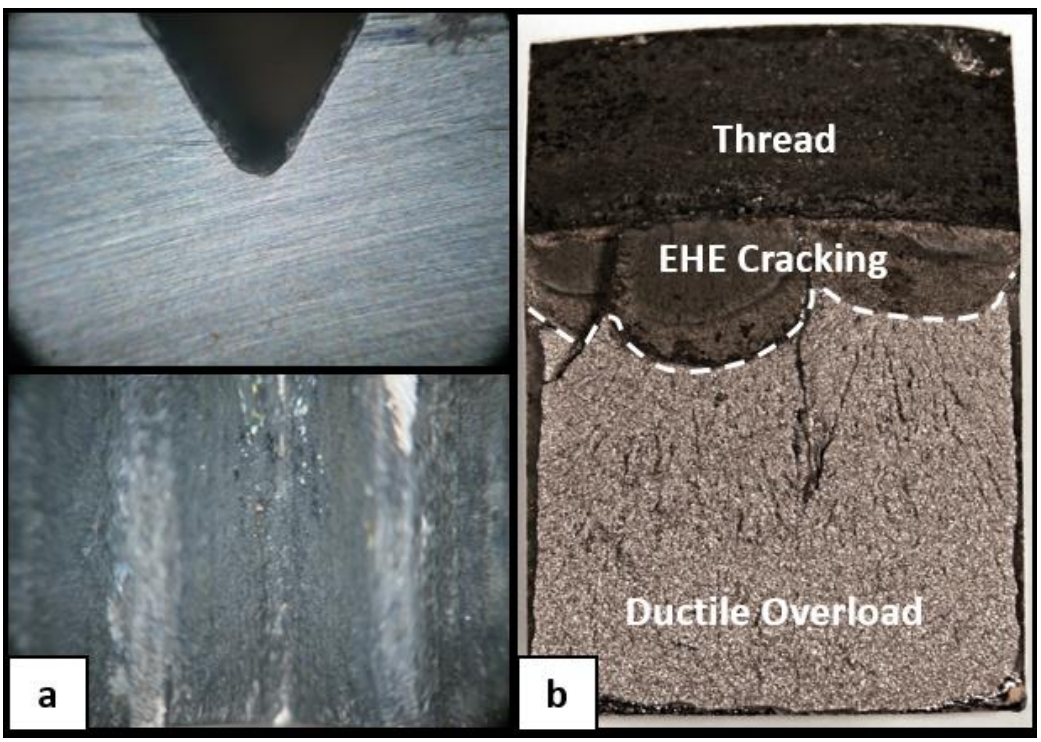
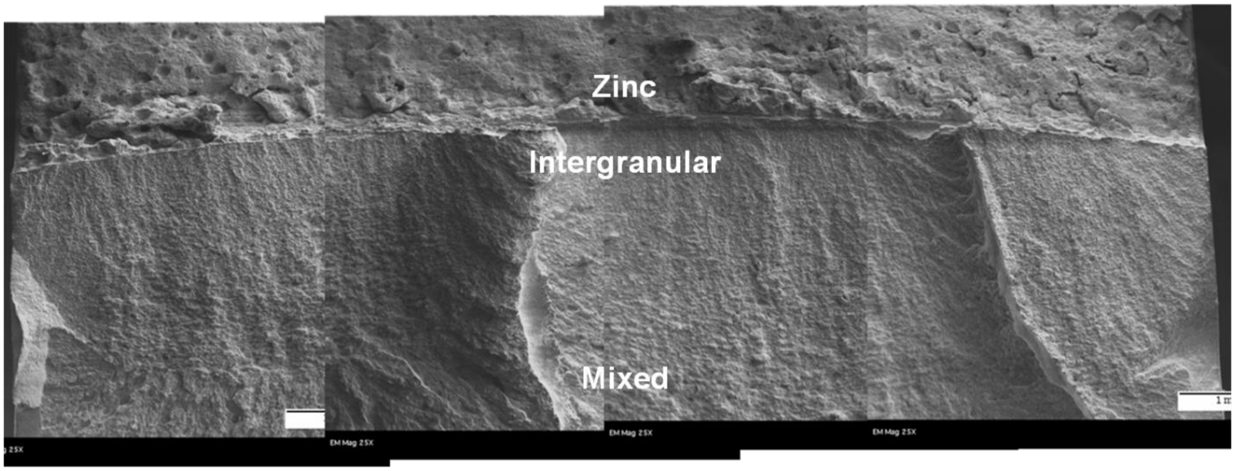
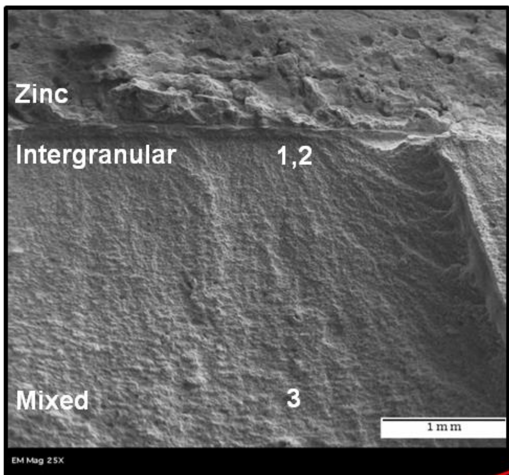


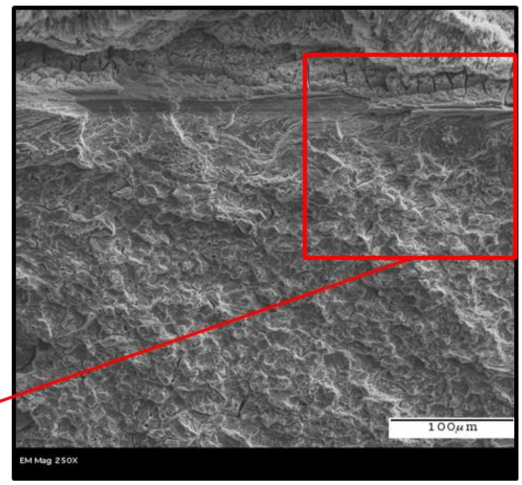
Figure P.6-4: Rod 7-V-E093 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure P.6-5: SEM of Rod 7V-E093 Thd 3, EHE

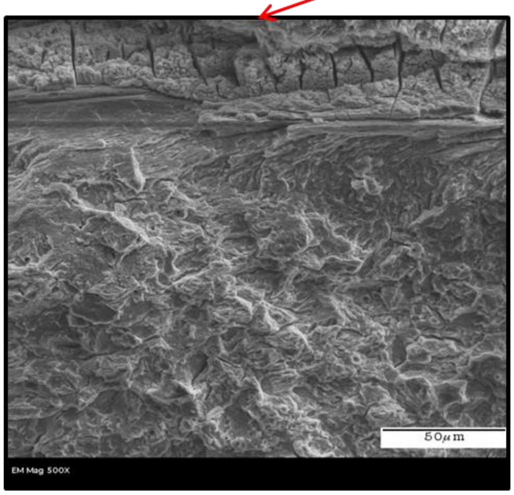




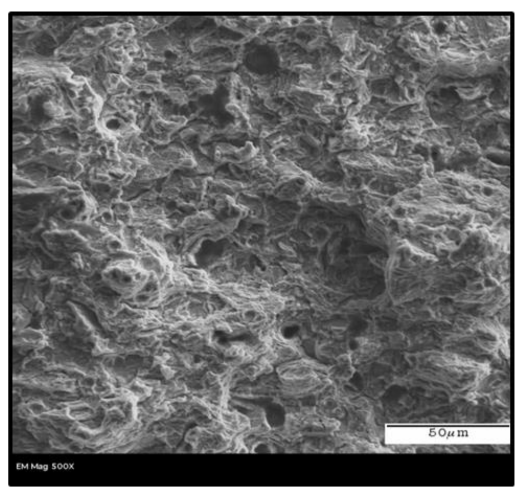
Thread Root 25X



1) Thread Root 250X



2) Mixed: Ductile Overload, Intergranular 500X



3) Mixed: Ductile Overload, Intergranular 500X

P.6.3 Thd 5, EHE:

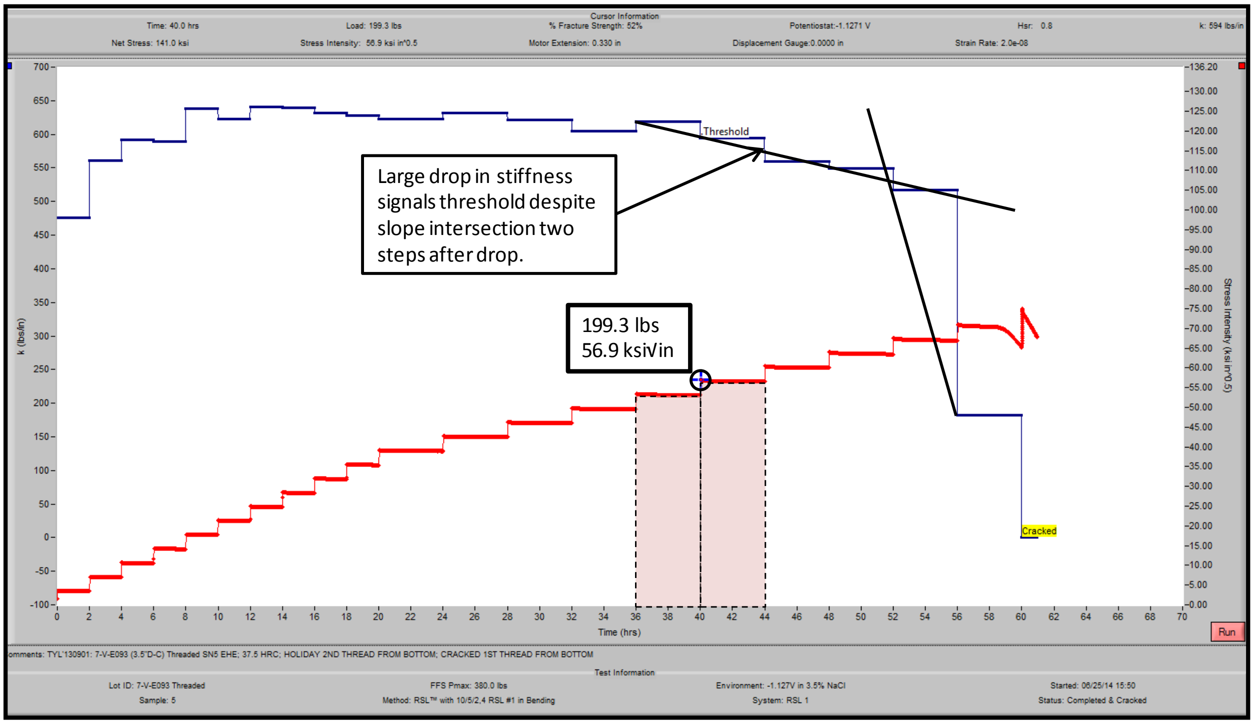


Figure P.6-6: Rod 7-V-E093 Thd 5, Graphical EHE Results

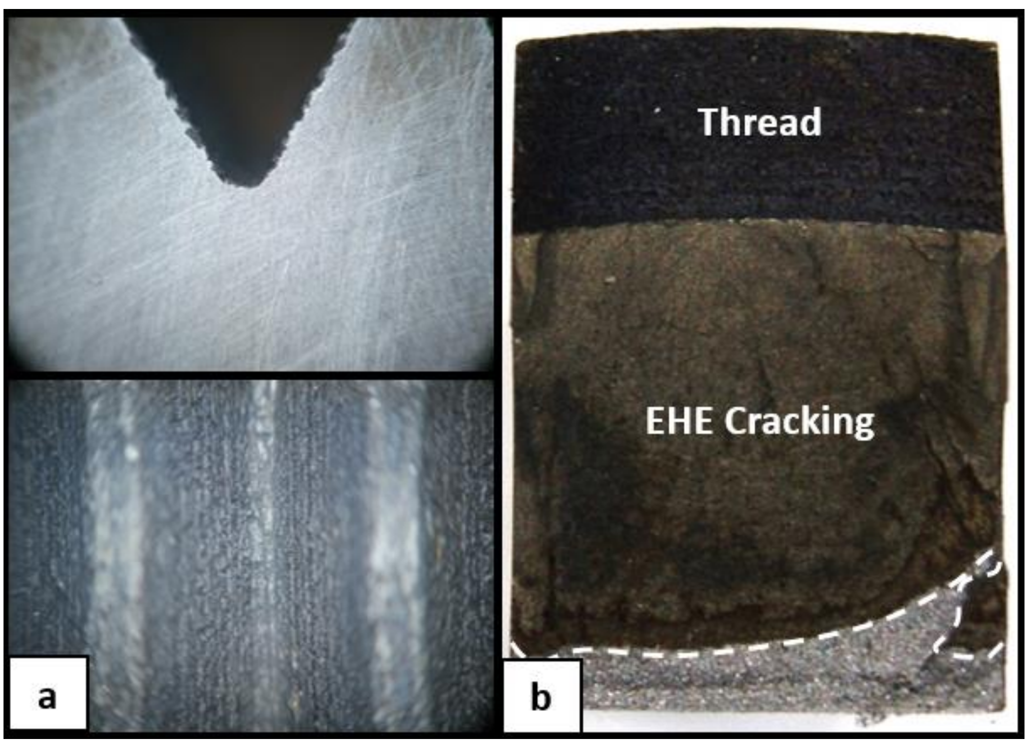


Figure P.6-7: Rod 7-V-E093 Thd 5 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

P.6.4 Thd 6, EHE:

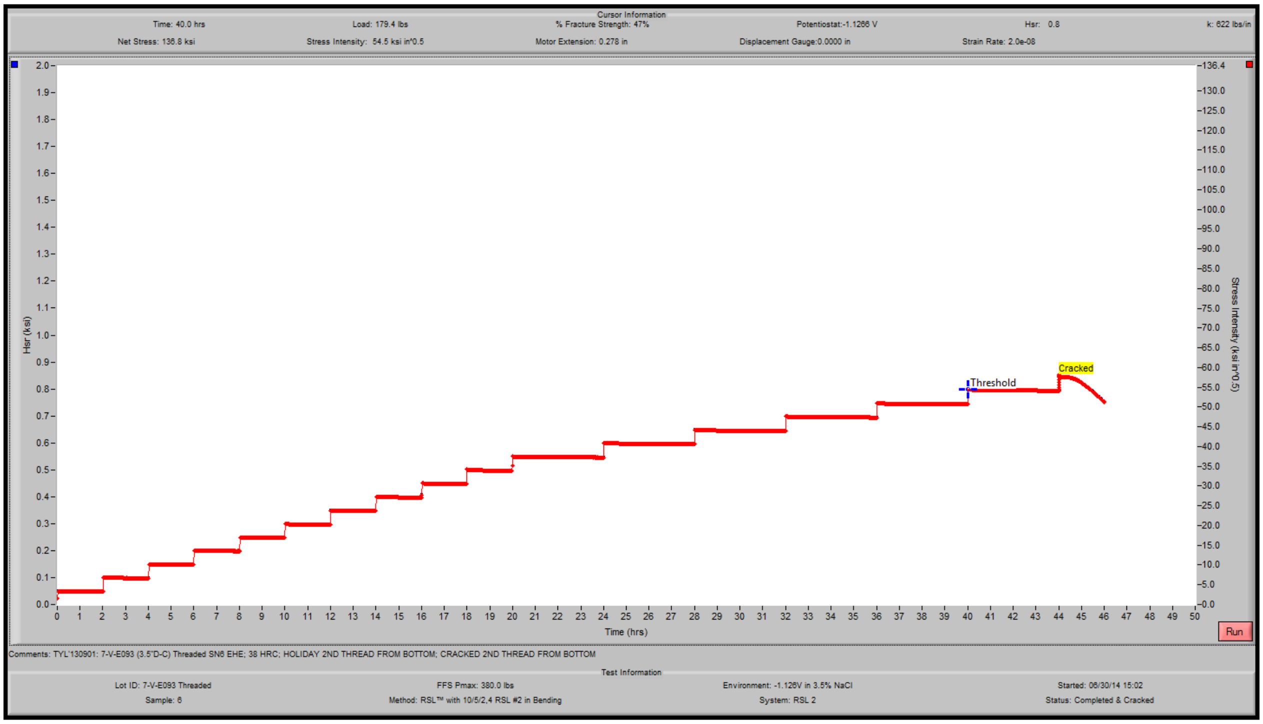


Figure P.6-8: Rod 7-V-E093 Thd 6, Graphical EHE Results

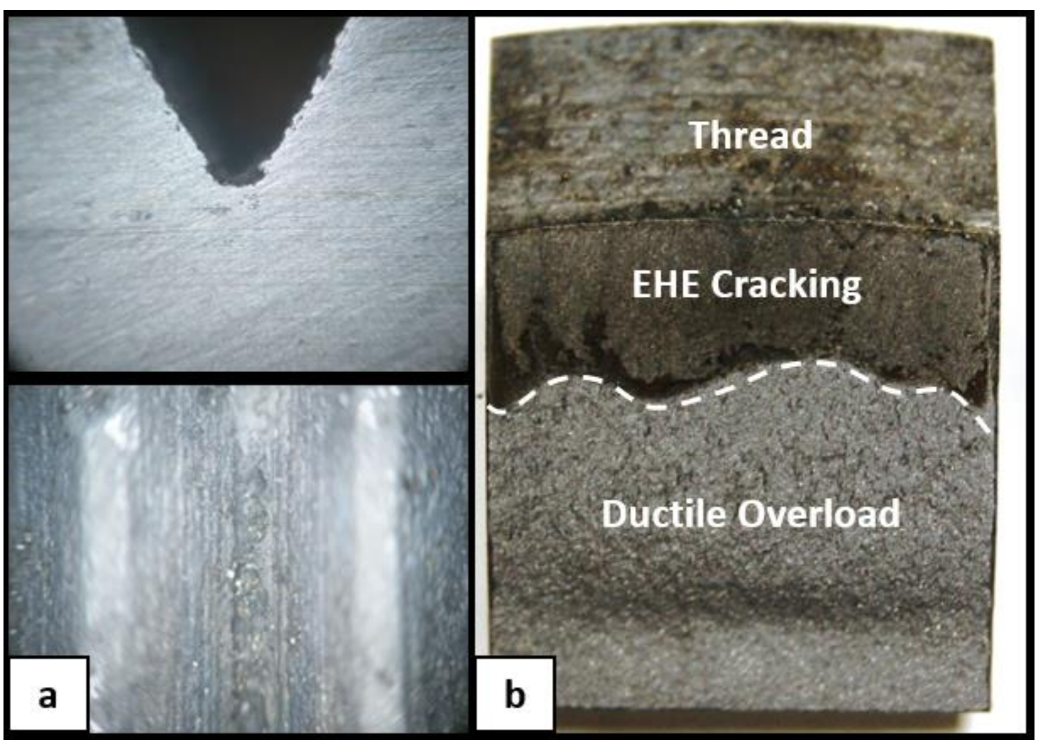


Figure P.6-9: Rod 7-V-E093 Thd 6 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

P.6.5 Thd 7, EHE:

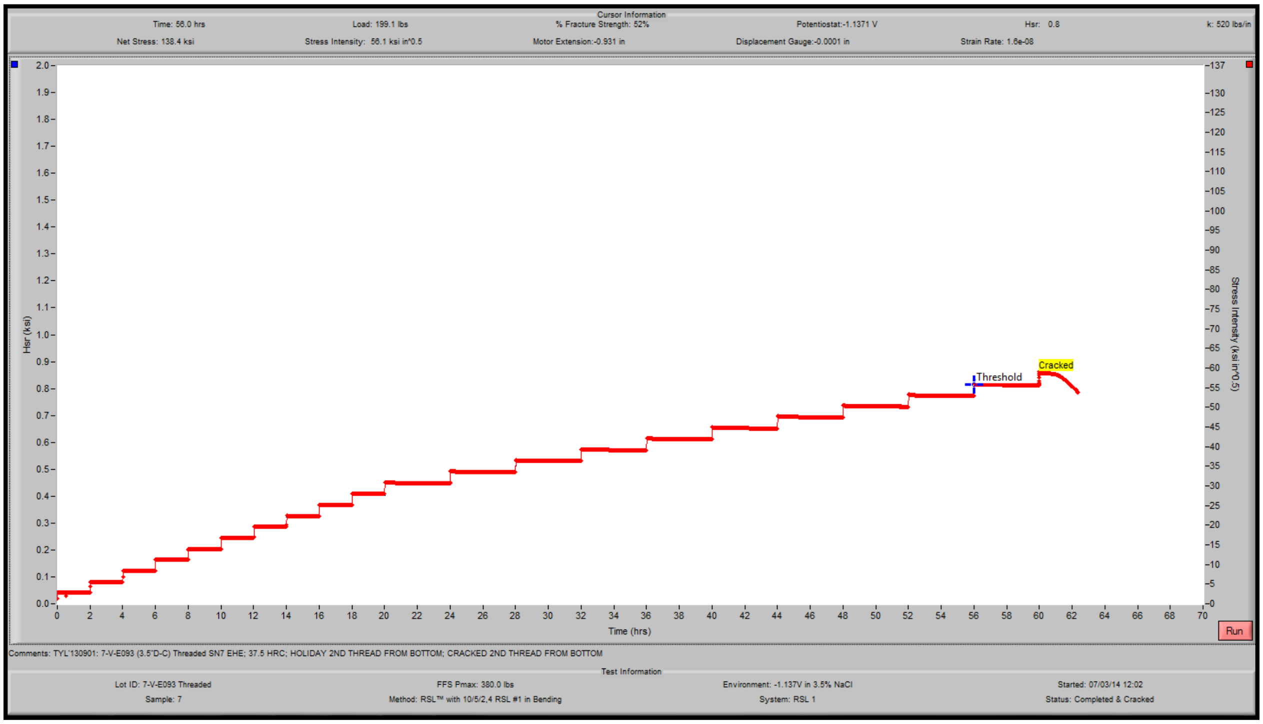


Figure P.6-10: Rod 7-V-E093 Thd 7, Graphical EHE Results

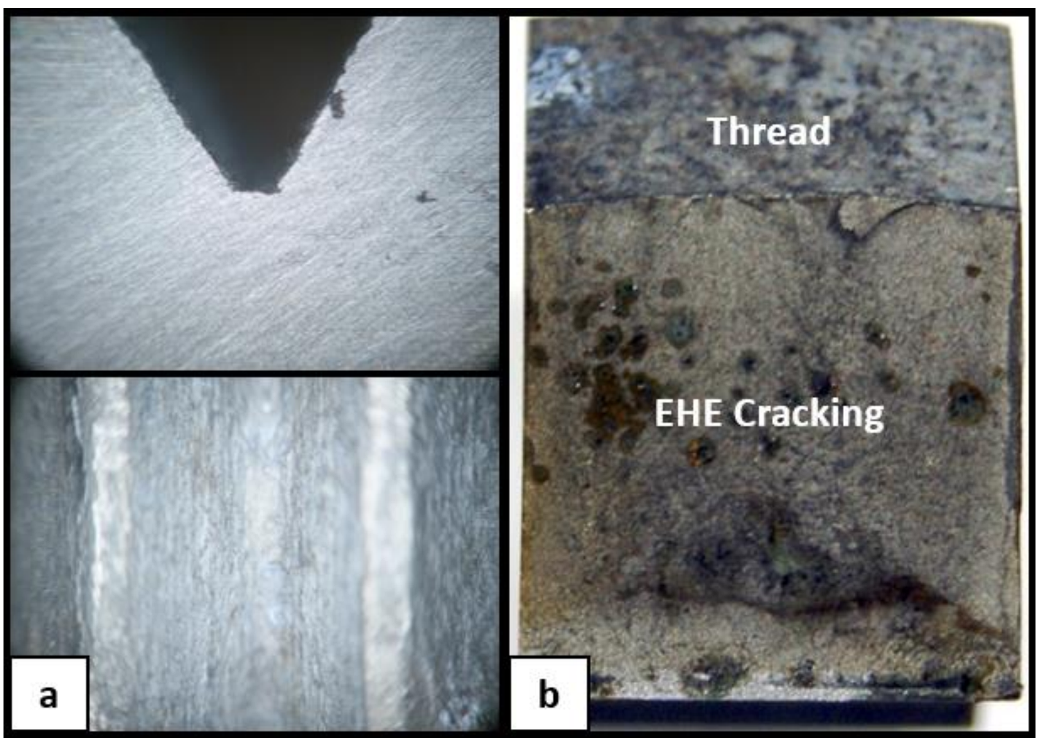


Figure P.6-11: Rod 7-V-E093 Thd 7 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix Q: Rod 7-V-E096

Q.1 Description of Sample

Rod 7-V-E096 was a PWS Strand Anchor Rod located at the anchorage location above Pier E2 from the same heat as the rod in Test Rig #8 tested in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. The bolts are 3.5 inches in diameter with rolled threads. The segment from one of the rod pieces provided to LRA is shown in **Figure Q.1-1**.

Figure Q.1-1: Pier E2 Anchorage PWS Strand Anchor, Rod 7-V-E096

Q.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 7-V-E096 and can be seen versus time in **Figure Q**.2-1. The final OCP recorded for Rod 7-V-E096 was Vsce=-0.966 V.

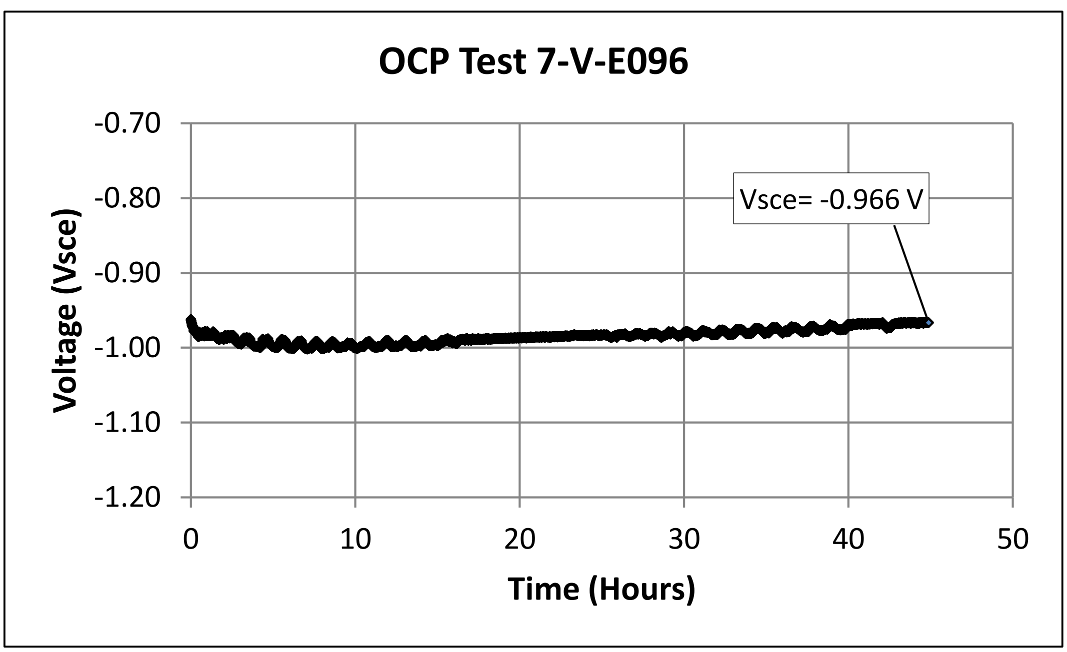


Figure Q.2-1: Open Circuit Potential for Rod 7-V-E096

Q.3 Hardness

The hardness data and profile for sample 7-V-E096 are shown in **Table Q.3-1** and **Figure Q.3-1**.

Table Q.3-1: Hardness Data of Rod 7-V-E096 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	28.5	28.5
MR 1, FFS	30.0	32.3
MR 3, EHE	33.5	
MR 4, EHE	33.5	
MR 5, EHE	32.0	
OD 1, FFS	35.5	35.2
OD 4, EHE	35.5	
OD 5, EHE	34.5	
OD 6, EHE	35.0	
Th 1, FFS	35.0	
Th 3, EHE	35.0	
Th 4, EHE	36.0	

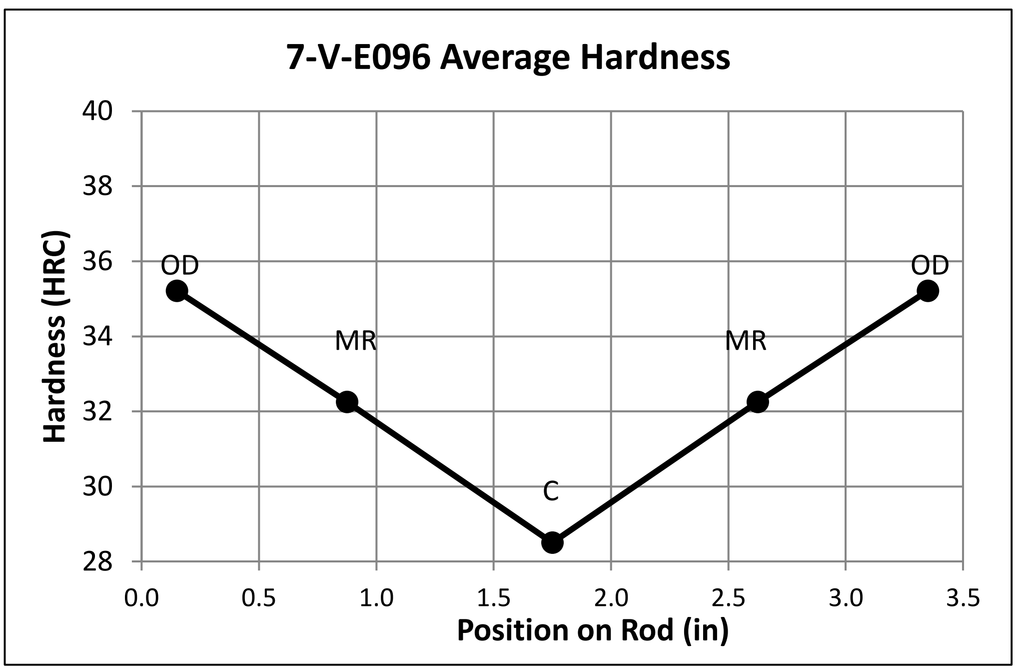


Figure Q.3-1: Hardness Profile of Rod 7-V-E096

Q.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

Q.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E096						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)				
Rod#:	**7-V-E096**					
Product Form:	**1e**	**Comments**: 2010 Rolled Threads, Heat OYI				
Rod OD:	**3.5"**	Same Heat as Rod in Test Rig #8 in Test IV				
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**35.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	84.0 0.53 0.93 7100		
	OD 4, EHE	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			51.8 0.32 0.57 1.1
	OD 5, EHE	**34.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			27.0 0.17 0.30 0.8
	OD 6, EHE	**35.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			26.5 0.17 0.29 0.77
	MR 1, FFS	**30.0**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	80.2 0.58 0.89 8600		

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E096						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable) **Comments**: 2010 Rolled Threads, Heat OYI Same Heat as Rod in Test Rig #8 in Test IV				
Rod#:	**7-V-E096**					
Product Form:	**1e**					
Rod OD:	**3.5"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 3, EHE**	**33.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			42.7 0.28 0.47 1.9
	MR 4, EHE	**33.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			31.5 0.21 0.35 1.5
	MR 5, EHE	**32.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			32.8 0.23 0.36 1
	Center 1, FFS	**28.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	73.5 0.55 0.81 5800		

Q.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-E096						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable) **Comments**: 2010 Rolled Threads, Heat OYI Same Heat as Rod in Test Rig #8 in Test IV				
Rod#:	**7-V-E096**					
Product Form:	**1e**					
Rod OD:	**3.5"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	326.8 1.06 1.5 2300		
	Thd 3, EHE	**35.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			300.1 0.97 1.4 2.1
	Thd 4, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			305.6 0.99 1.4 1.9

Q.4.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-E096
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**7-V-E096**
Product Form:	**1e**
Rod OD:	**3.5"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, $KIp_{\text{-EHE}}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	35.5	159	94.6	94.6	94.6	100.0%	84.0	0.53	285.0	1.8	7100	0.2101	144.2	0.2 in/min		0.93	
	OD 4, EHE	3.5% NaCl @ -1.106V	35.5	159	30.0	60.0	54.0	61.7%	51.8	0.32	178.8	1.1	1.1	0.217		10/5/2,4		0.57	Potential Drift Early in Test
	OD 5, EHE	3.5% NaCl @ -1.106V	34.5	155	22.0	33.0	28.6	32.1%	27.0	0.17	93.0	0.6	0.8	0.2167		10/5/2,4		0.30	
	OD 6, EHE	3.5% NaCl @ -1.106V	35.0	157	20.0	30.0	27.9	31.5%	26.5	0.17	90.8	0.6	0.77	0.2129		10/5/2,4		0.29	
	MR 1, FFS	Air	30.0	138	87.1	87.1	87.1	100.0%	80.2	0.58	274.5	2.0	8600	0.2152	137.6	50 lbs/min		0.89	Data lag.
	MR 3, EHE	3.5% NaCl @ -1.106V	33.5	151	52.0	54.6	46.7	53.2%	42.7	0.28	146.0	1.0	1.9	0.2149		10/5/2,4		0.47	
	MR 4, EHE	3.5% NaCl @ -1.106V	33.5	151	45.0	42.8	35.9	39.3%	31.5	0.21	105.8	0.7	1.5	0.2067		10/5/2,4		0.35	
	MR 5, EHE	3.5% NaCl @ -1.106V	32.0	145	29.0	45.0	36.2	40.9%	32.8	0.23	111.9	0.8	1	0.2124		10/5/2,4		0.36	
	Center 1, FFS	Air	28.5	133	80.6	80.6	80.6	100.0%	73.5	0.55	250.8	1.9	5800	0.2145	143.9	0.2 in/min		0.81	
Threaded	Thd 1, FFS	Air	35.0	157	349.6	349.6	349.6	100.0%	95.3	0.61	232.8	1.5	2300	N/A		0.4 in/min	326.8	1.06	Ran out of Motor Extension.
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.0	157	283.0	333.1	318.6	91.8%	87.5	0.56	213.9	1.4	2.1	N/A		10/5/2,4	300.1	0.97	Did not crack in holiday.
	Thd 4, EHE	3.5% NaCl @ -1.106V	36.0	162	240.0	323.7	308.2	93.5%	89.1	0.55	221.3	1.4	1.9	N/A		10/5/2,4	305.6	0.99	Cracked in holiday.

Q.5 Fatigue Pre-cracked Specimen Test Results

Q.5.1 OD 1, FFS:

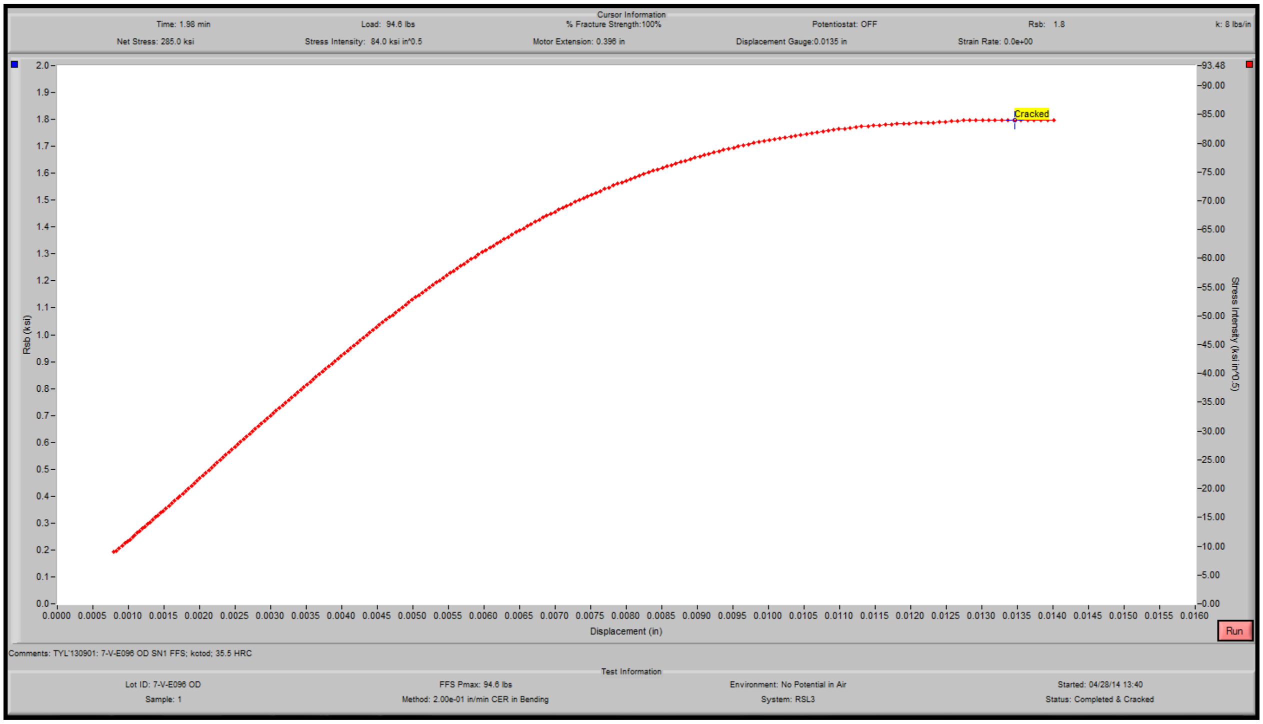


Figure Q.5-1: Rod 7-V-E096 OD 1, Graphical FFS Results

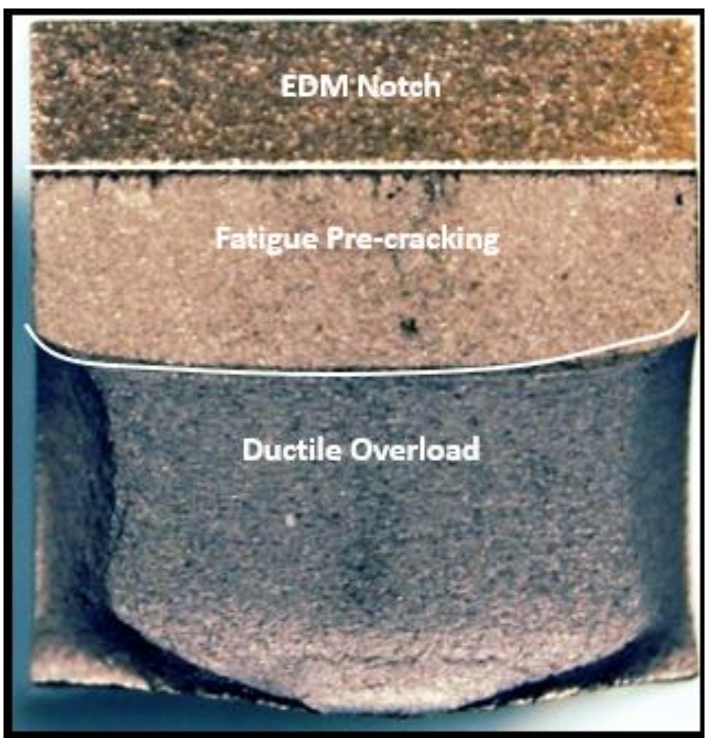


Figure Q.5-2: Fracture Face of Rod 7-V-E096 OD 1, FFS

Q.5.2 OD 4, EHE:

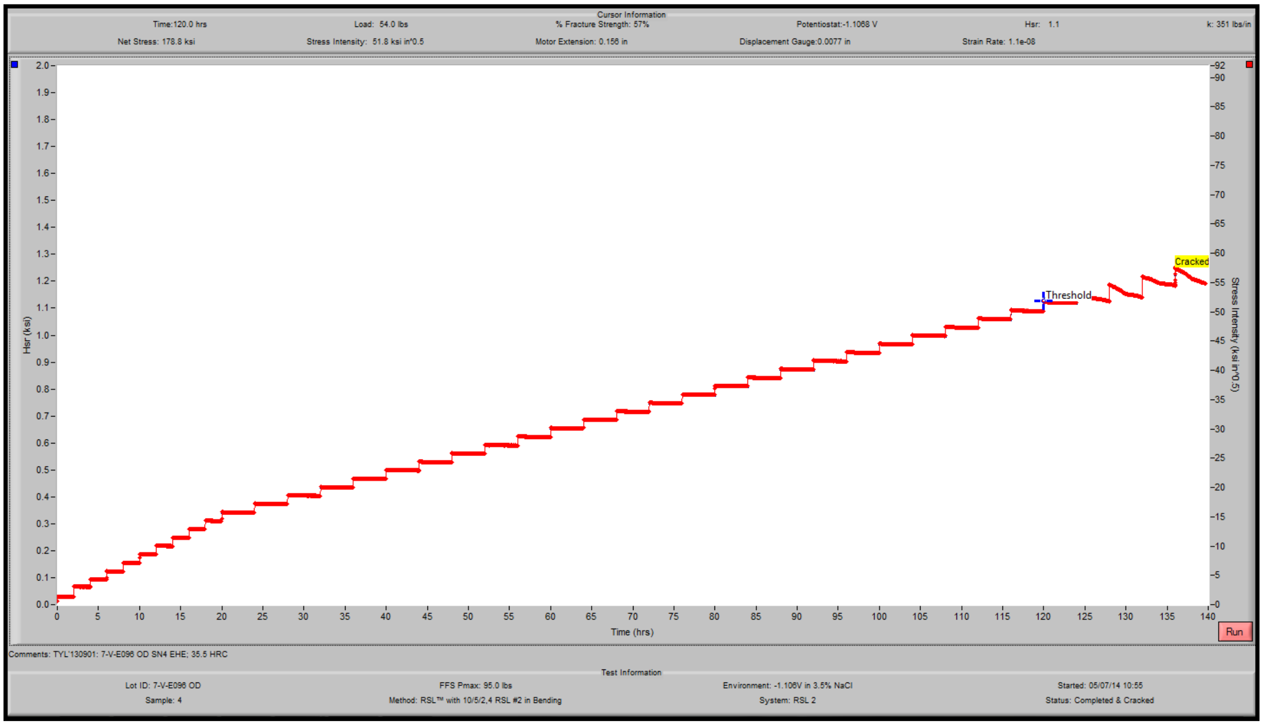


Figure Q.5-3: Rod 7-V-E096 OD 4, Graphical EHE Results

Figure Q.5-4: Fracture Face of Rod 7-V-E096 OD 4, EHE

Q.5.3 OD 5, EHE:

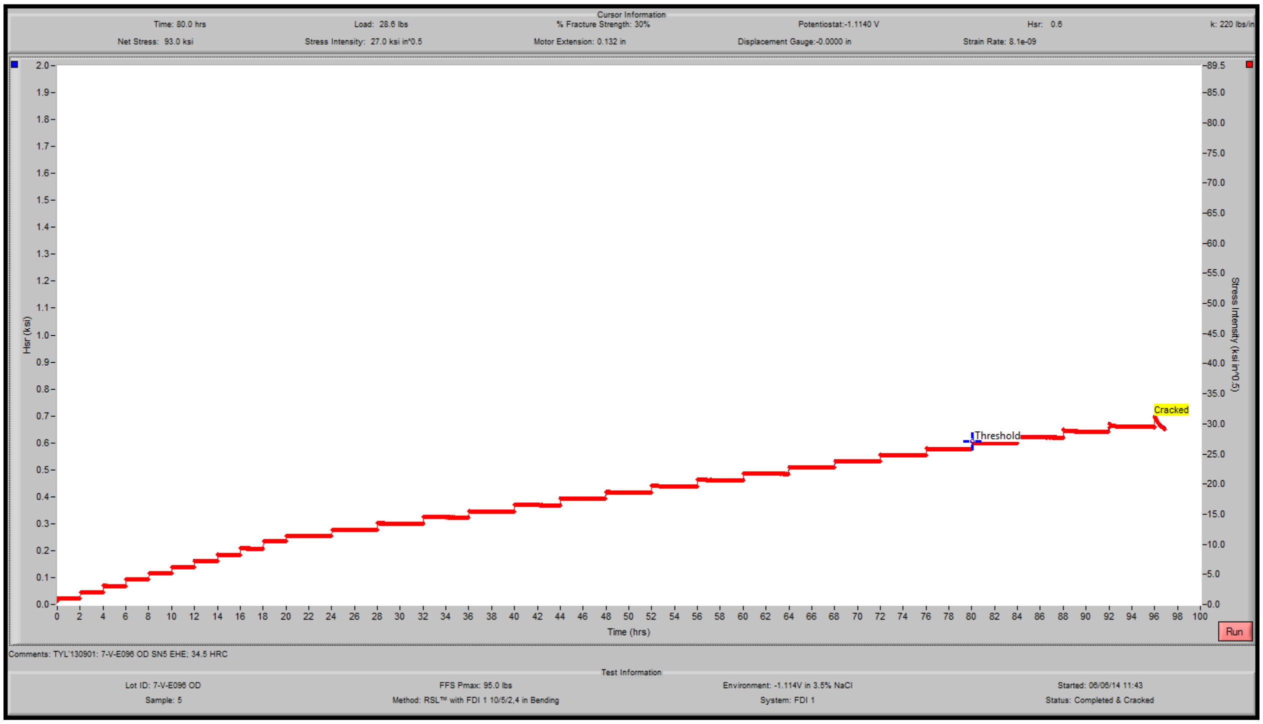


Figure Q.5-5: Rod 7-V-E096 OD 5, Graphical EHE Results

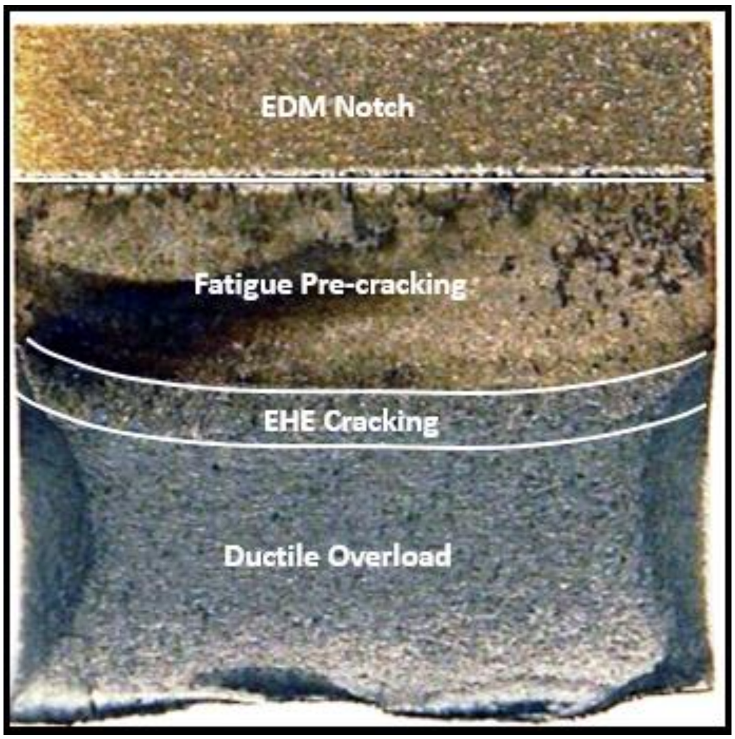


Figure Q.5-6: Fracture Face of Rod 7-V-E096 OD 5, EHE

Q.5.4 OD 6, EHE:

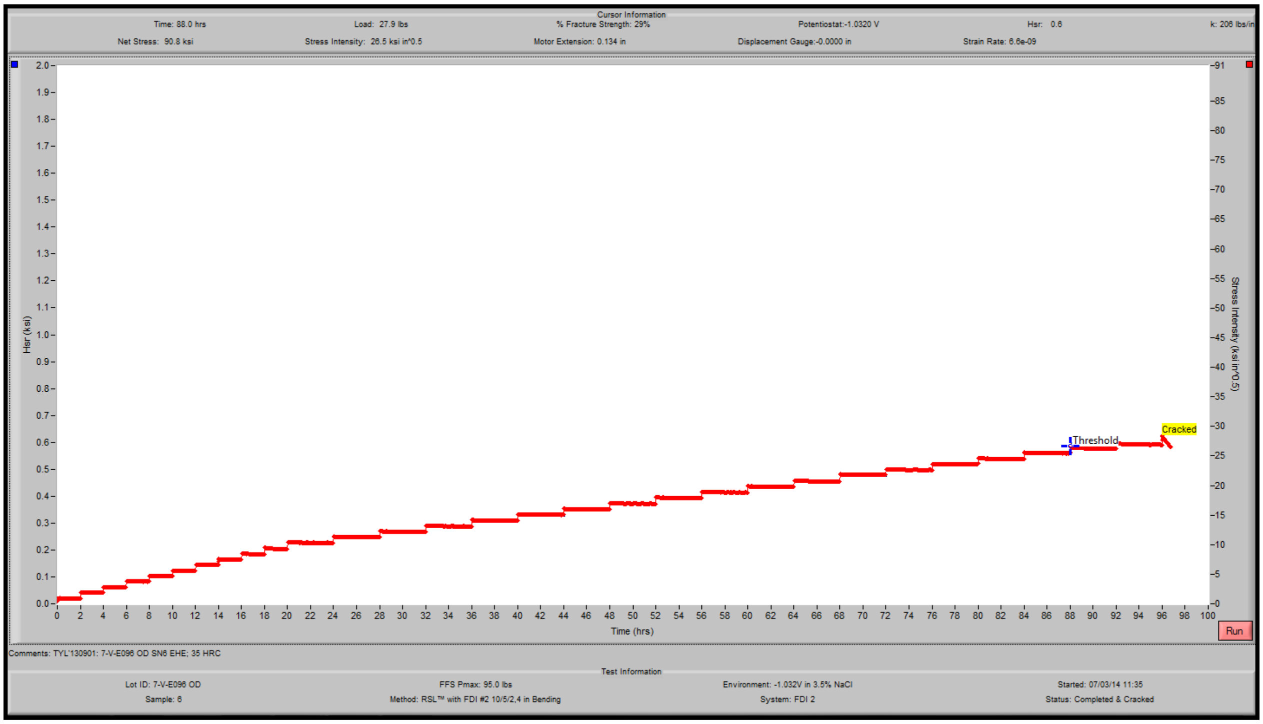


Figure Q.5-7: Rod 7-V-E096 OD 6, Graphical EHE Results

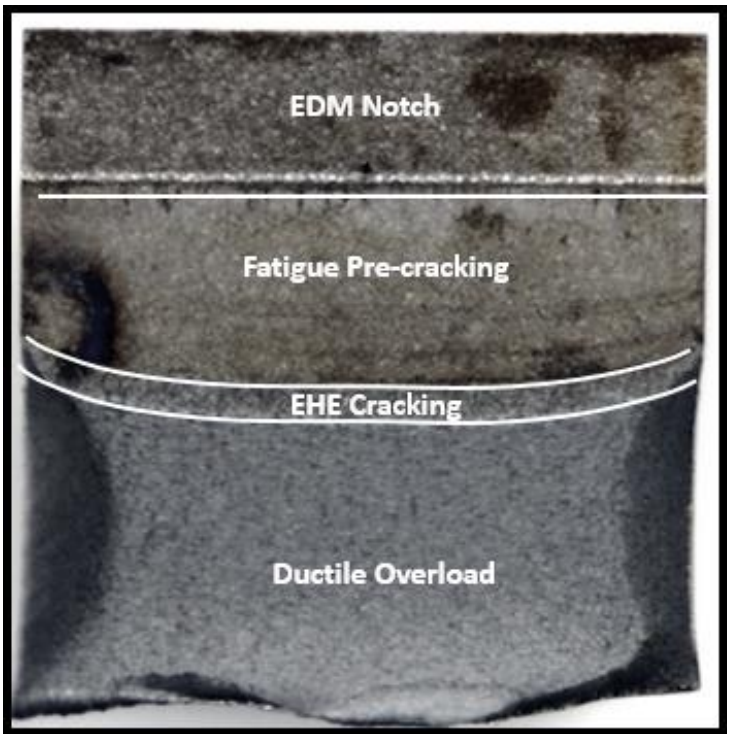


Figure Q.5-8: Fracture Face of Rod 7-V-E096 OD 6, EHE

Q.5.5 MR 1, FFS:

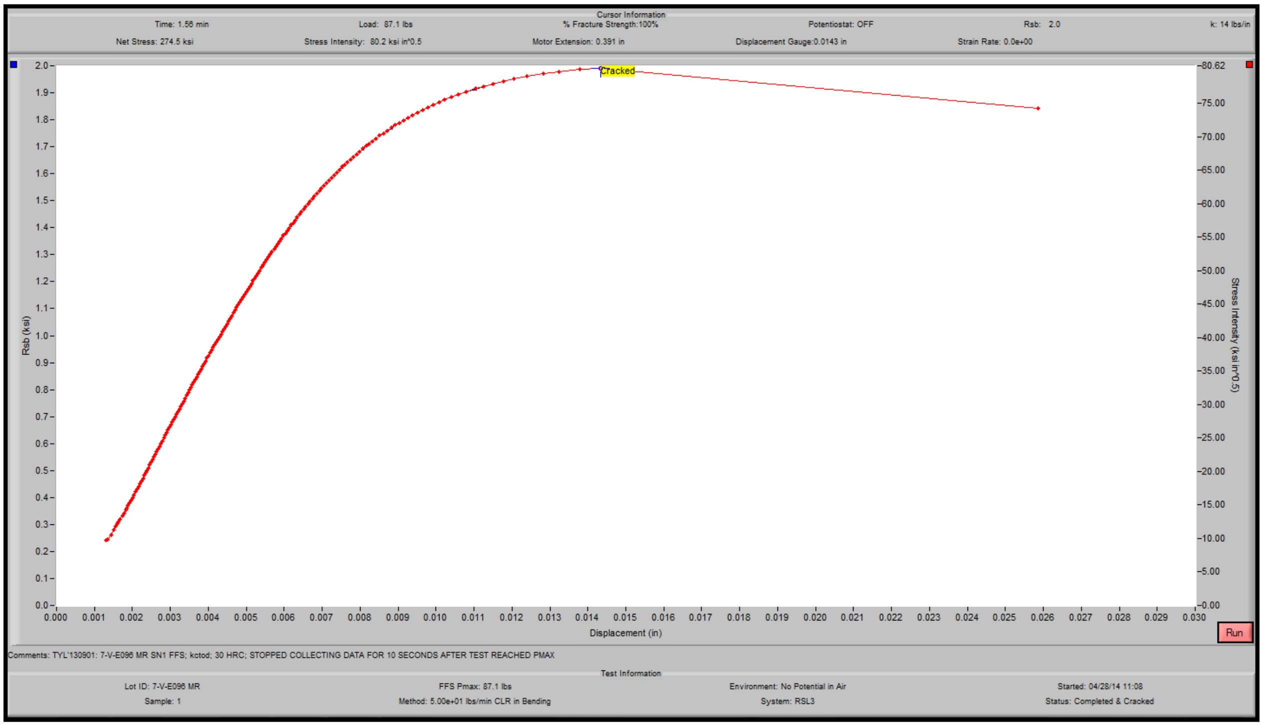


Figure Q.5-9: Rod 7-V-E096 MR 1, Graphical FFS Results

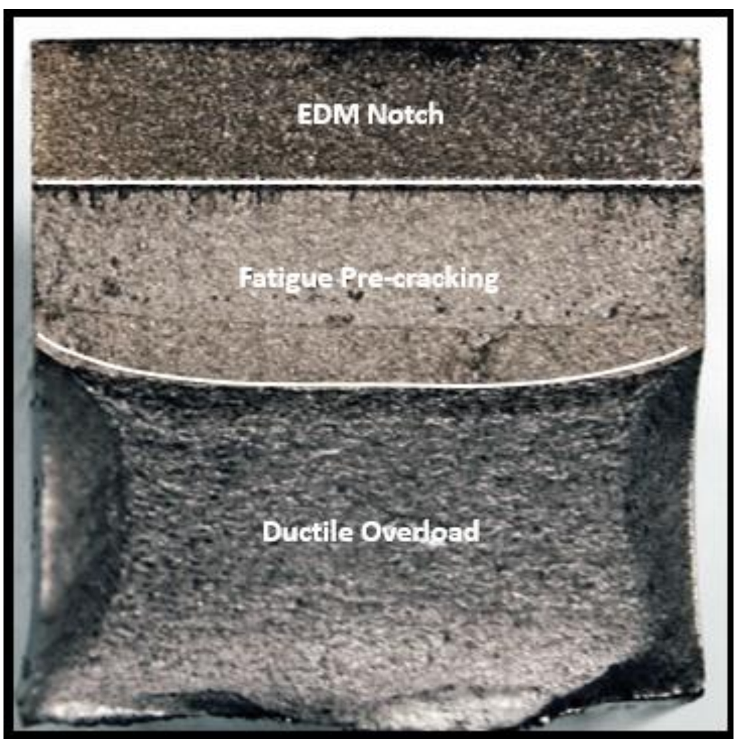


Figure Q.5-10: Fracture Face of Rod 7-V-E096 MR 1, FFS

Q.5.6 MR 3, EHE:

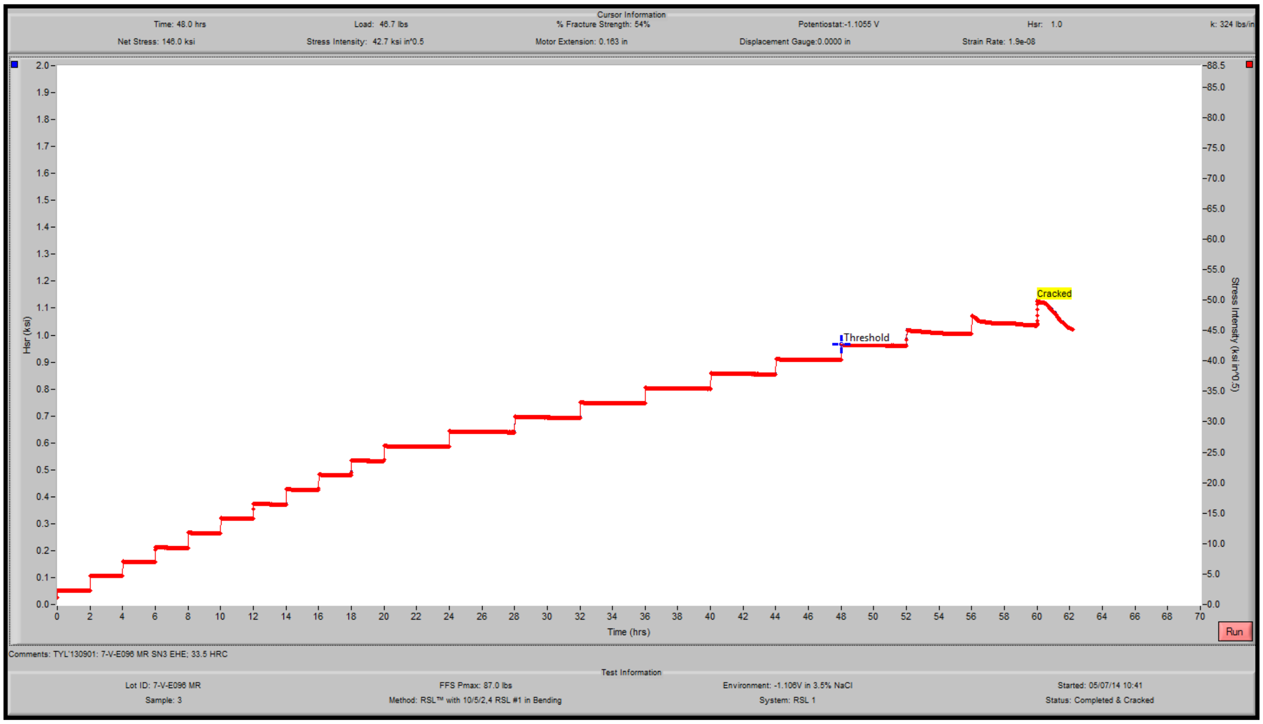


Figure Q.5-11: Rod 7-V-E096 MR 3, Graphical EHE Results

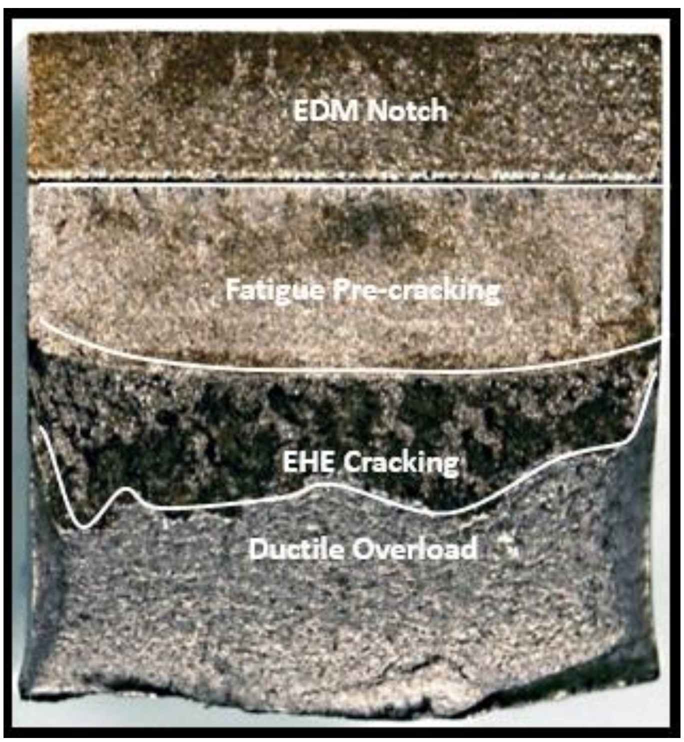


Figure Q.5-12: Fracture Face of Rod 7-V-E096 MR 3, EHE

Q.5.7 MR 4, EHE:

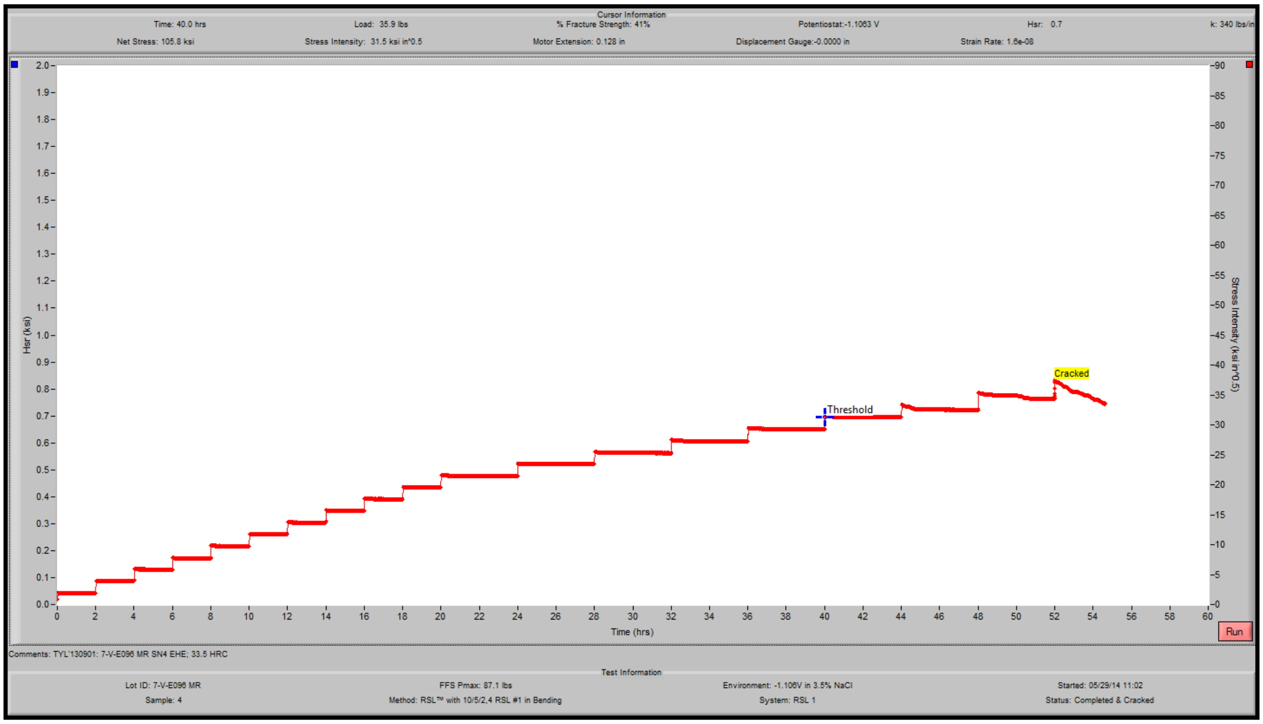


Figure Q.5-13: Rod 7-V-E096 MR 4, Graphical EHE Results

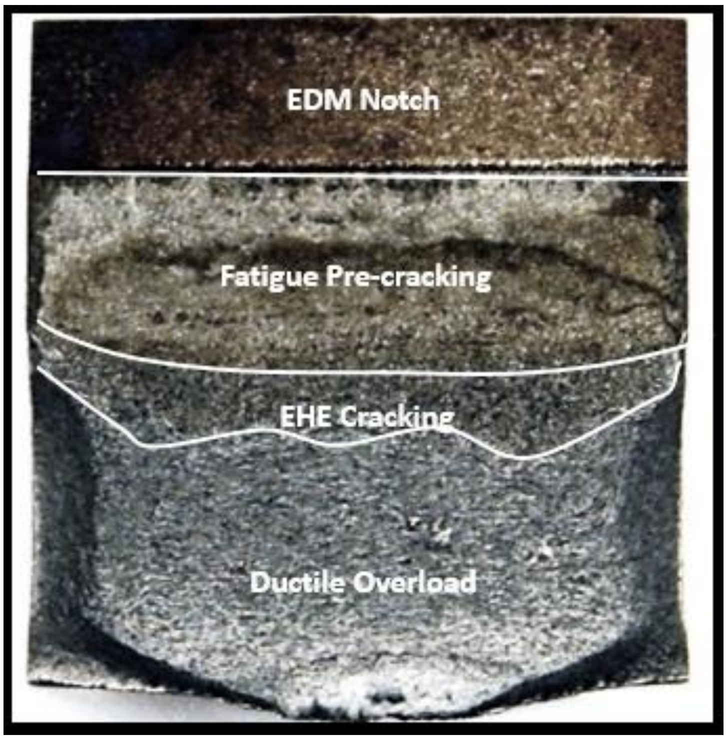


Figure Q.5-14: Fracture Face of Rod 7-V-E096 MR 4, EHE

Q.5.8 MR 5, EHE:

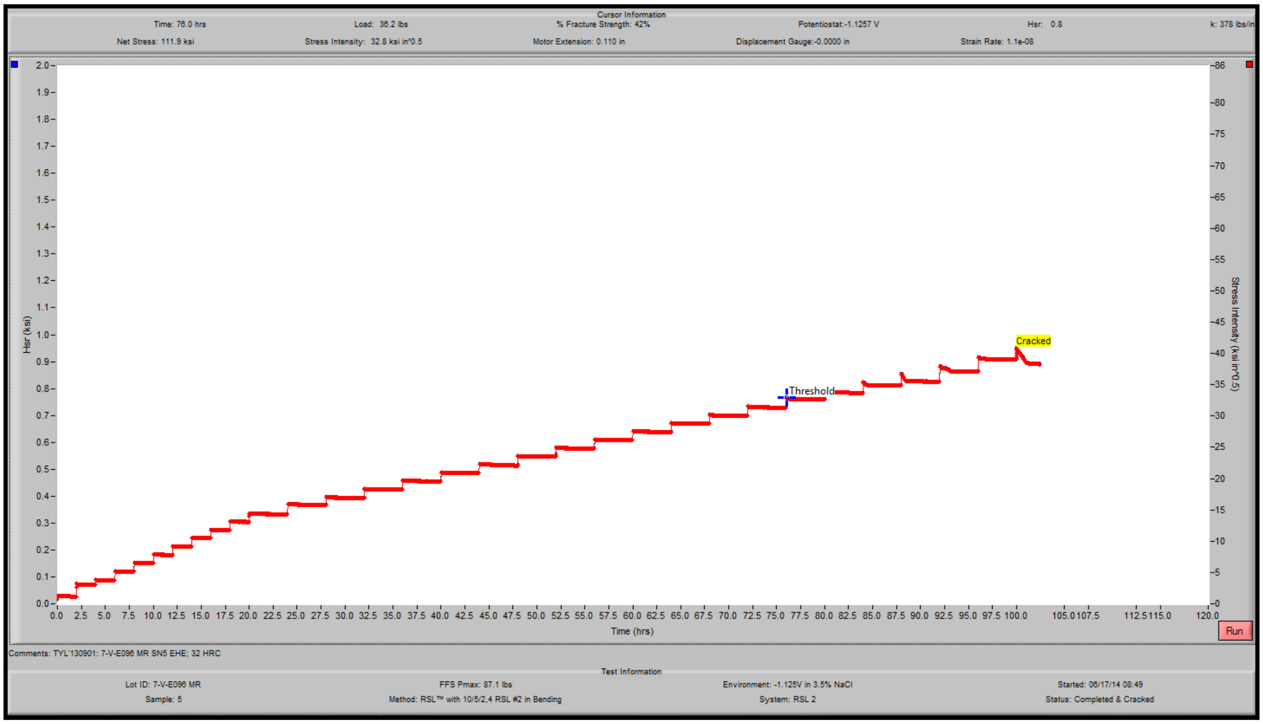


Figure Q.5-15: Rod 7-V-E096 MR 5, Graphical EHE Results

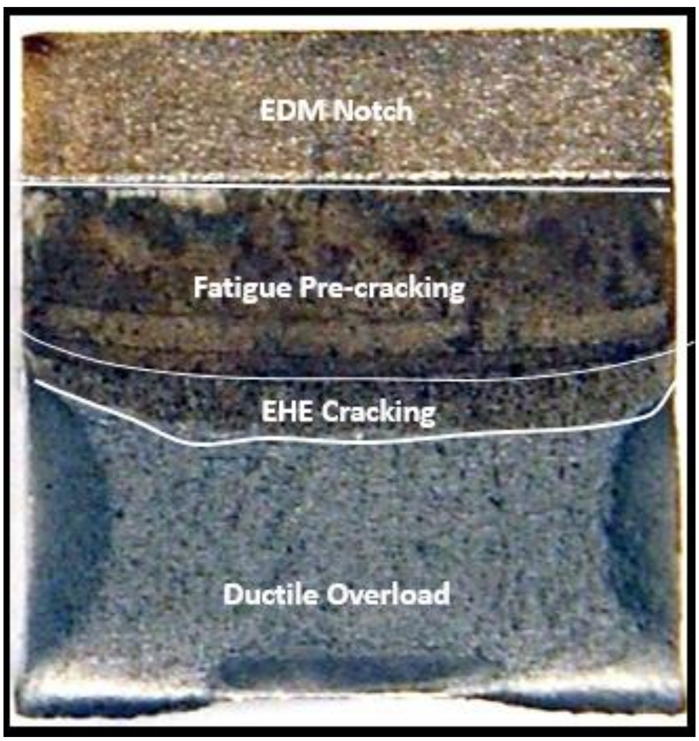


Figure Q.5-16: Fracture Face of Rod 7-V-E096 MR 5, EHE

Q.5.9 Center 1, FFS:

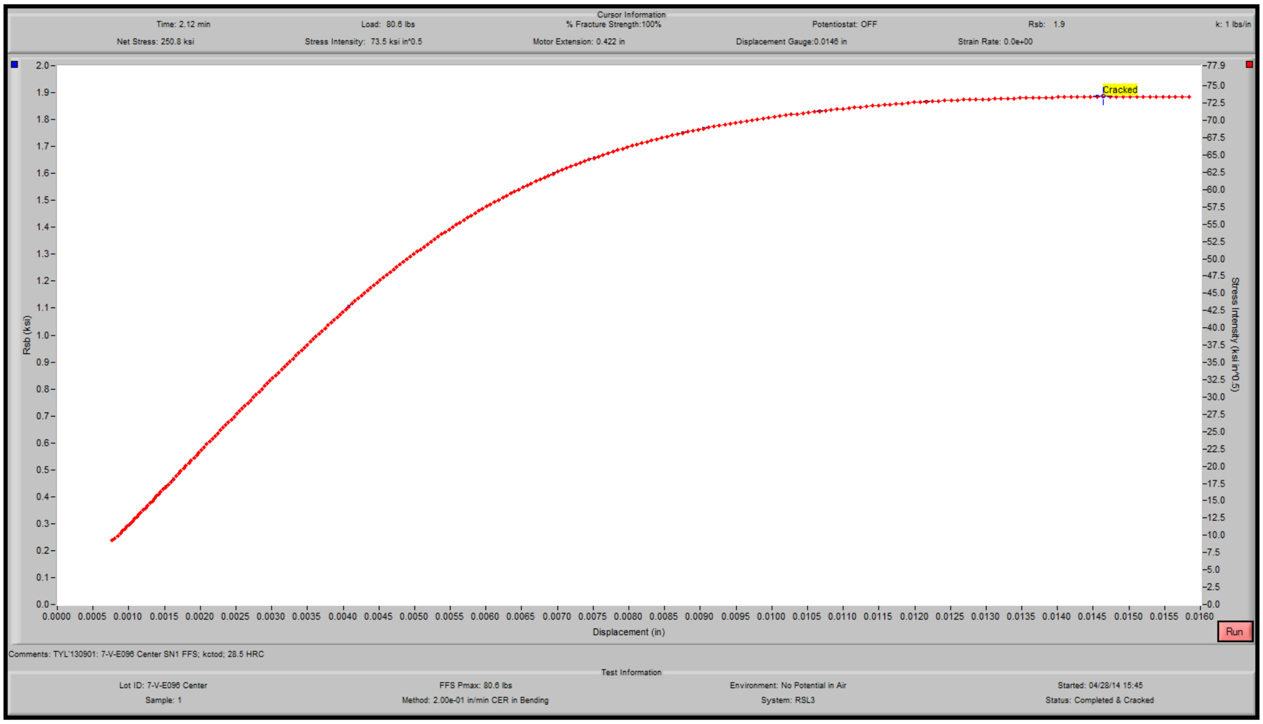


Figure Q.5-17: Rod 7-V-E096 Center 1, Graphical FFS Results

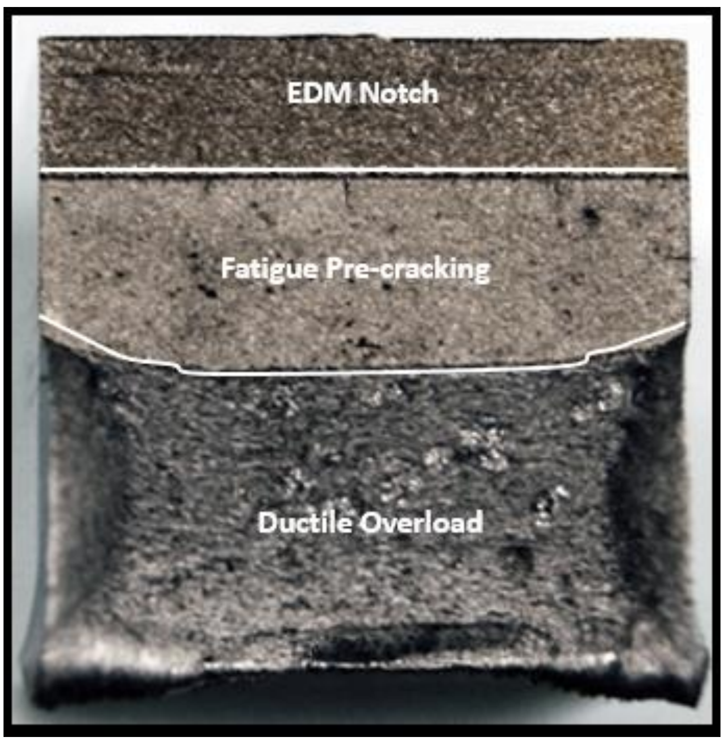


Figure Q.5-18: Fracture Face of Rod 7-V-E096 Center 1, FFS

Q.6 Threaded Specimen Test Results

Q.6.1 Thd 1, FFS:

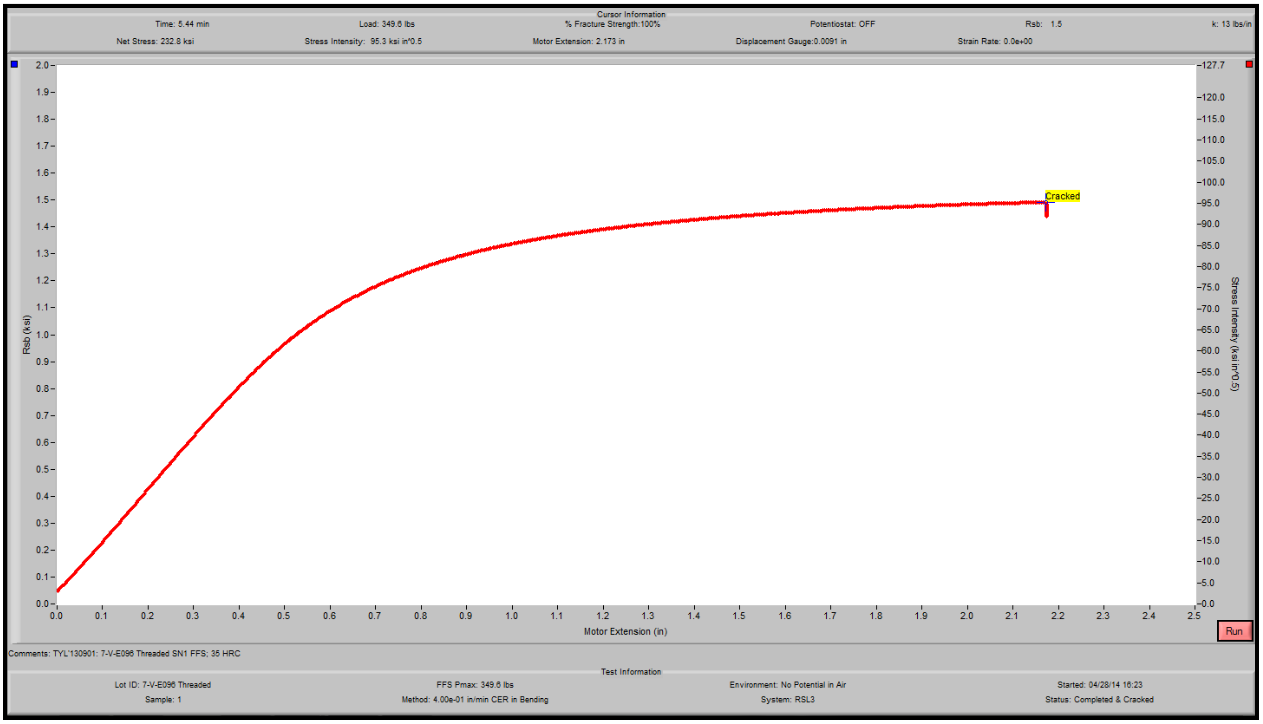


Figure Q.6-1: Rod 7-V-E096 Thd 1, Graphical FFS Results

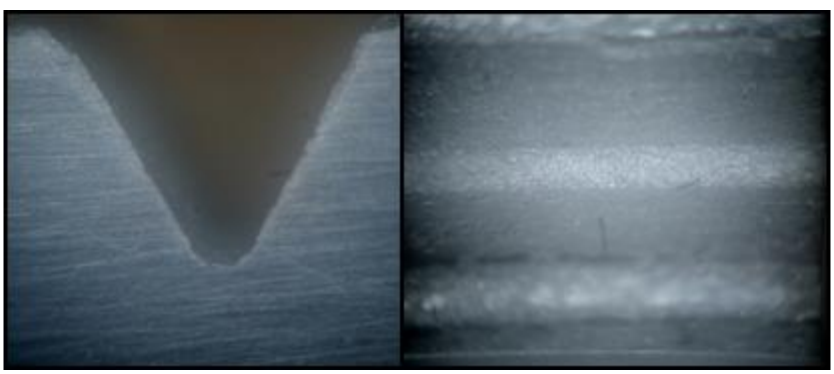


Figure Q.6-2: Rod 7-V-E096 Thd 1 Thread Root Post FFS Test V and Pre-Charpy Impact

Q.6.2 Thd 3, EHE:

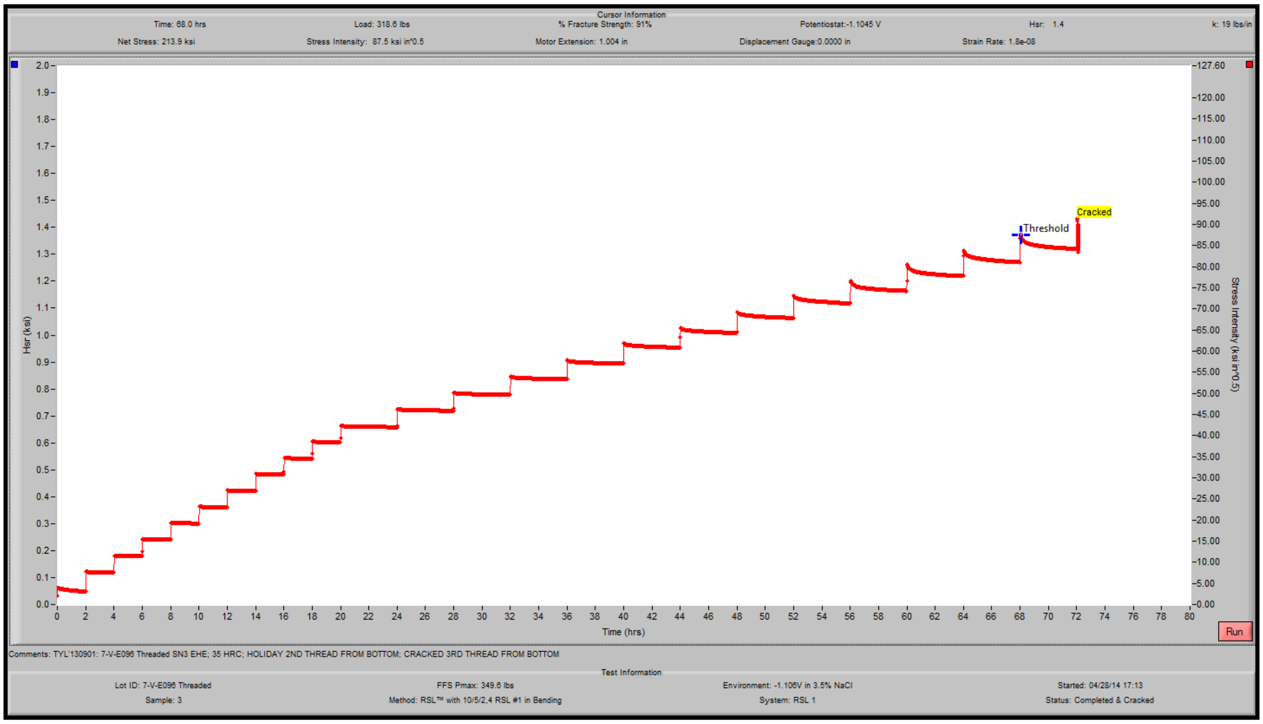


Figure Q.6-3: Rod 7-V-E096 Thd 3, Graphical EHE Results

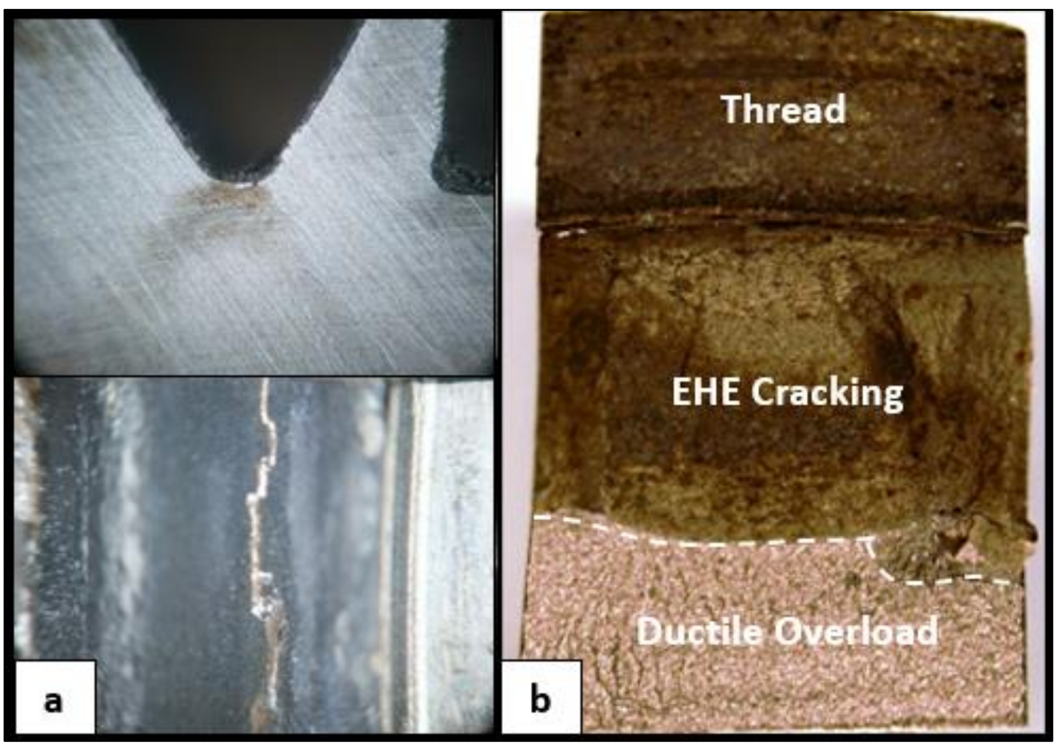
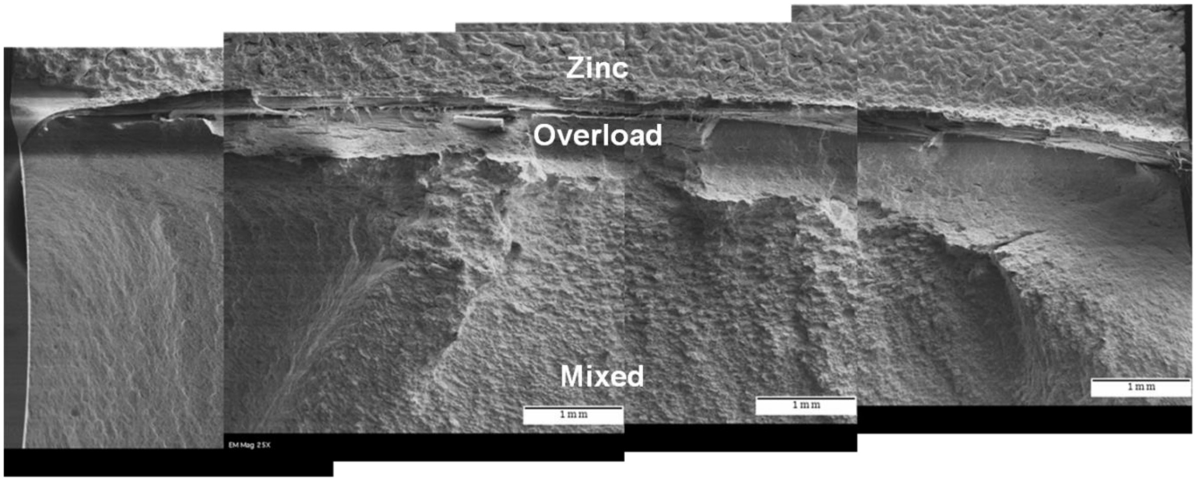
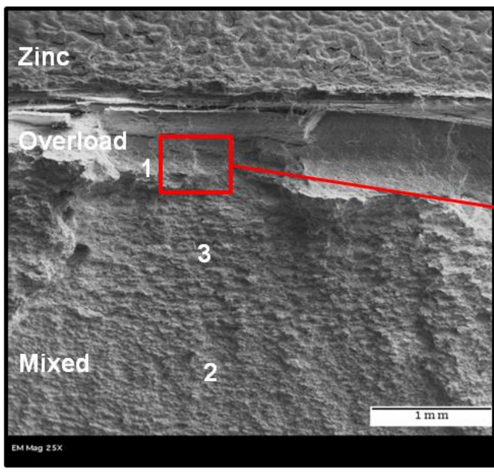


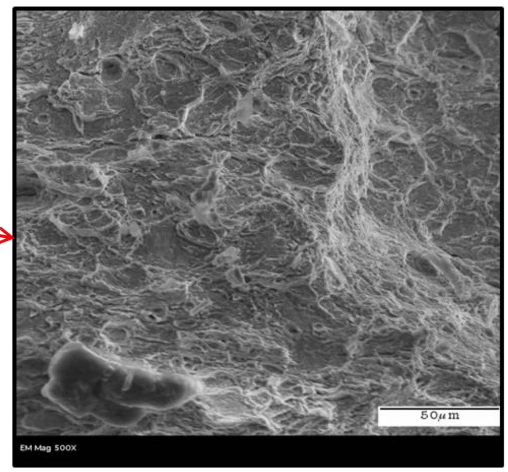
Figure Q.6-4: Rod 7-V-E096 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure Q.6-5: SEM of Rod 7-V-E096 Thd 3, EHE

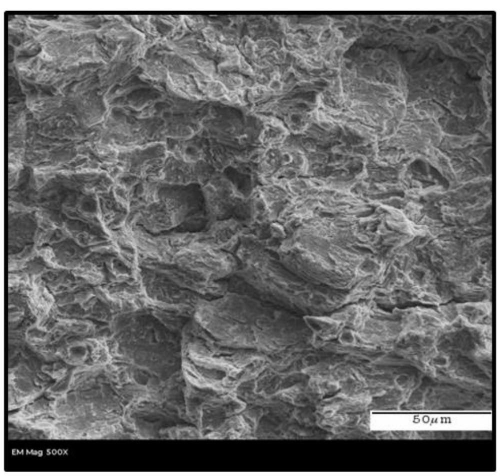




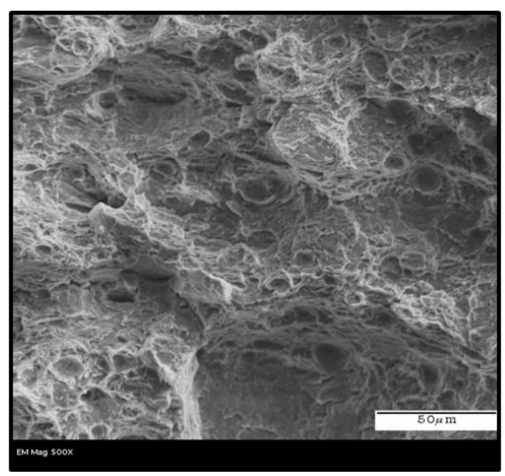
Thread Root 25X



1) Ductile Overload 500X



2) Mixed: Ductile Overload, Intergranular 500X



3) Ductile Overload 500X

Q.6.3 Thd 4, EHE:

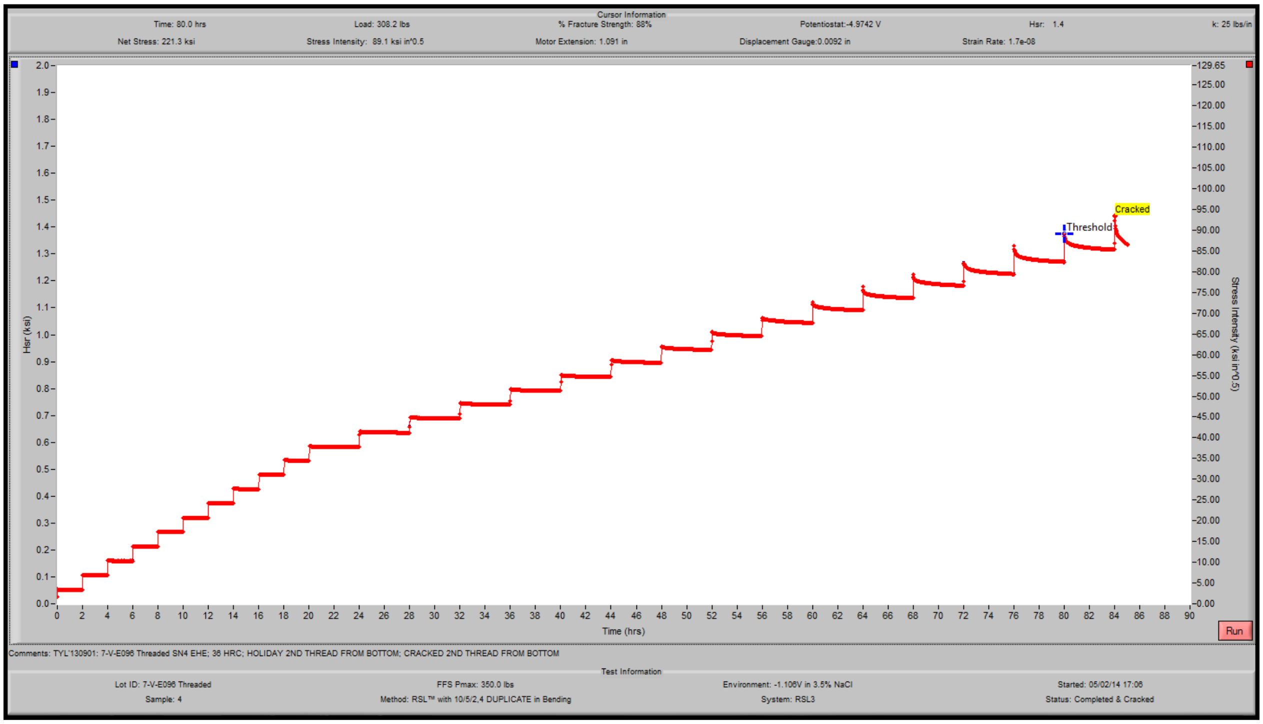


Figure Q.6-6: Rod 7-V-E096 Thd 4, Graphical EHE Results

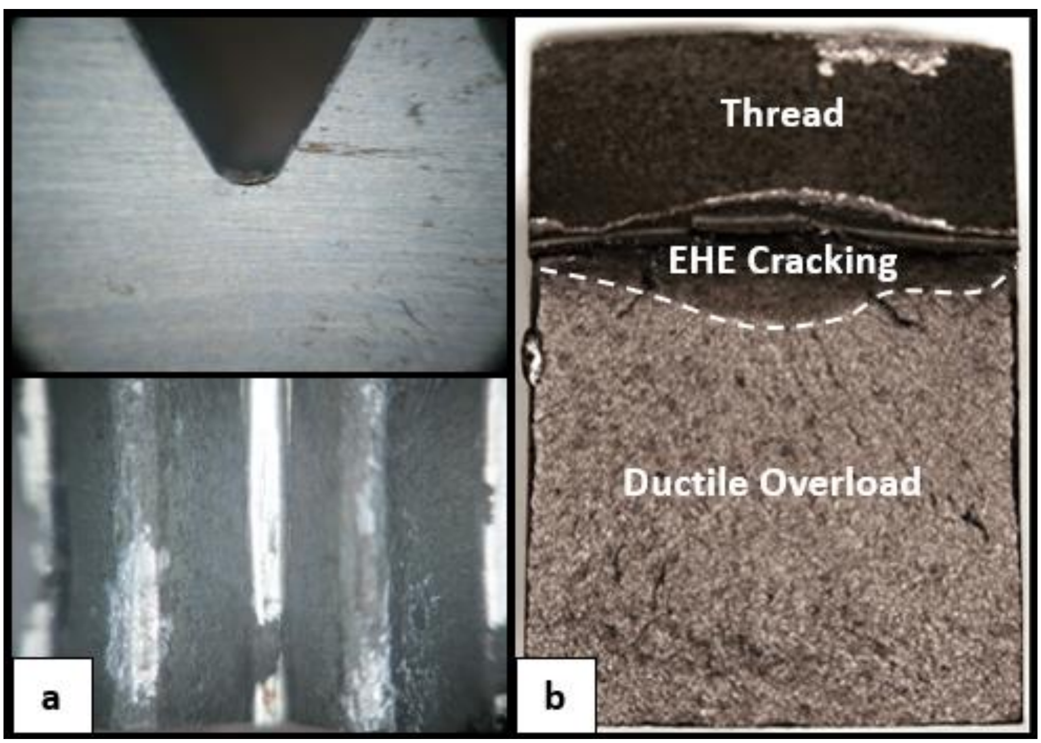
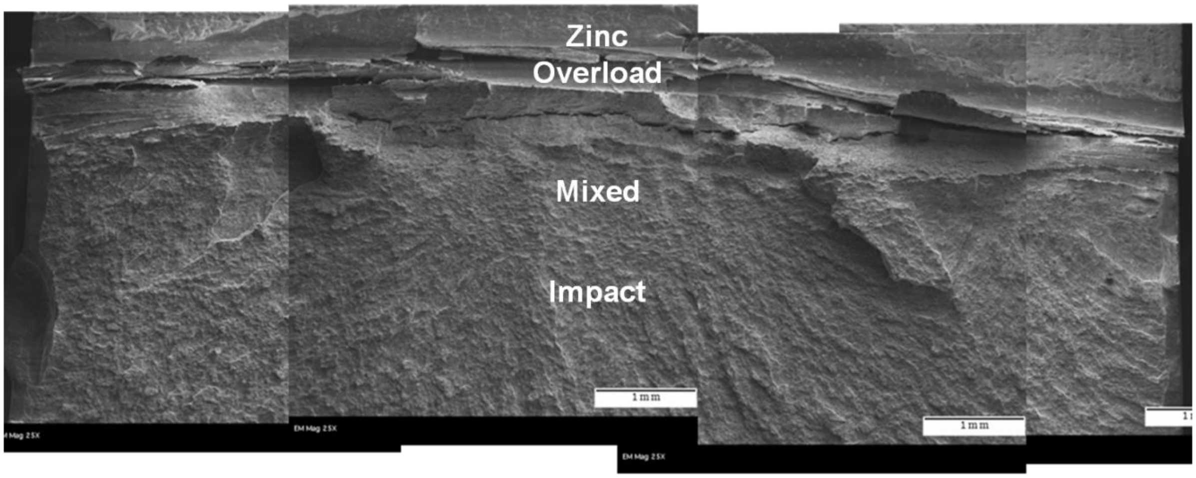
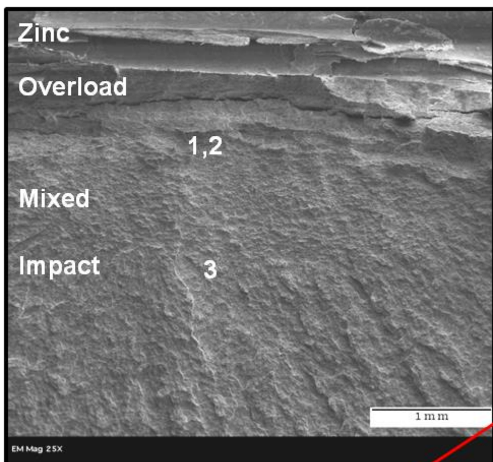


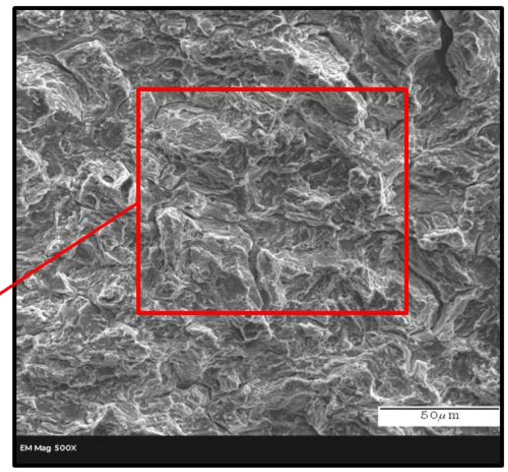
Figure Q.6-7: Rod 7-V-E096 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure Q.6-8: SEM of Rod 7-V-E096 Thd 4, EHE

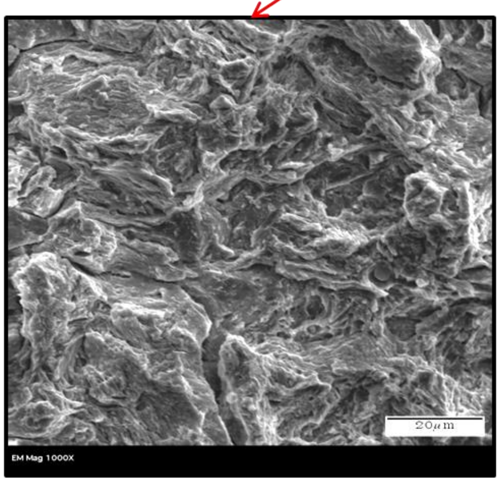




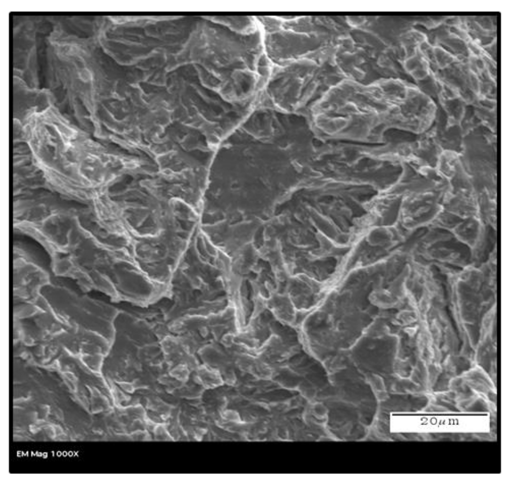
Thread Root 25X



1) Mixed Ductile Overload, Intergranular 500X



2) Mixed Ductile Overload, Intergranular 1000X



3) Impact, Cleavage 1000X

Appendix R: Rod 8-V-1

R.1 Description of Sample

Rod 8-V-1 was a Tower Saddle Tie Rod located at the top of the main tower on the SAS span from the same group of material Test Rig #7 tested in Test IV. It was made from 4140 steel to ASTM A354 Grade BD. The bolts are 4 inches in diameter with rolled threads. The segment from one of the spares from this rod provided to LRA is shown in **Figure R.1-1**.

Figure R.1-1: Tower Anchorage Anchor Bolt (Bottom), Rod 8-V-1

R.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 8-V-1 and can be seen versus time in **Figure R**.2-1. The final OCP recorded for Rod 8-V-1 was Vsce = -0.896V.

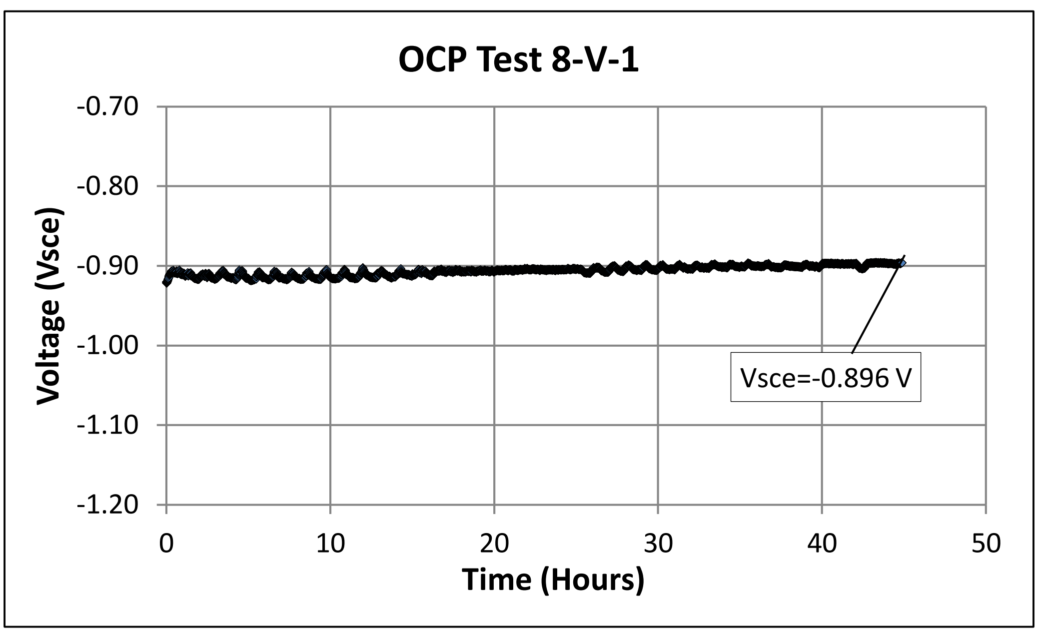


Figure R.2-1: Open Circuit Potential for Rod 8-V-1

R.3 Hardness

The hardness data and profile for sample 8-V-1 are shown in **Table R.3-1** and **Figure R.3-1**.

Table R.3-1: Hardness Data of Rod 8-V-1 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center, FFS	31.5	31.5
MR 1, FFS	34.5	34.0
MR 5, EHE	33.5	
MR 6,EHE	34.0	
OD 1, FFS	32.5	32.5
OD 3, EHE	32.5	
OD 5, EHE	32.0	
Th 1, FFS	31.0	
Th 3, EHE	34.0	
Th 4, EHE	33.0	

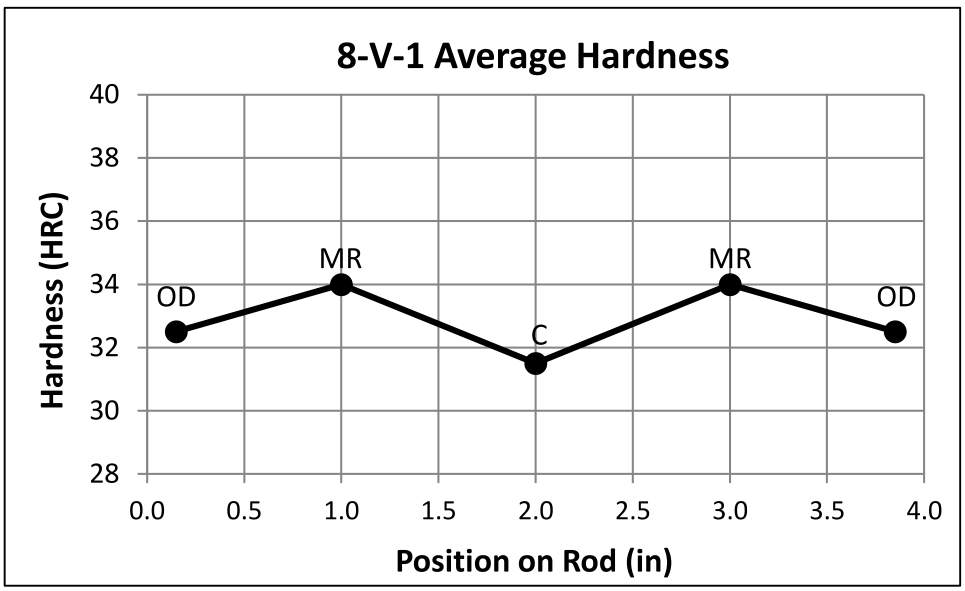


Figure R.3-1: Hardness Profile of Rod 8-V-1

R.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

R.4.1 Fatigue Pre-cracked Results:

Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 8-V-1

LRA Job No.:	**TYL130901**	**Structural Component:** Tower Saddle Tie Rods
Rod#:	**8-V-1**	
Product Form:	**1e**	**Comments**: Rolled Threads; Same Group of Material as Test Rig #7 in Test IV
Rod OD:	**4"**	

	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 1, FFS**	**32.5**	K_{max}	86.8		
			DTI_{th}	0.59		
			Fu	0.95		
			Strain Rate ($x10^{-8}$ in/in/sec)	8500		
	OD 3, EHE	**32.5**	$K_{threshold}$			33.9
			DTI_{th}			0.23
			Fu			0.37
			Strain Rate ($x10^{-8}$ in/in/sec)			2
	OD 5, EHE	**32.0**	$K_{threshold}$			36.3
			DTI_{th}			0.25
			Fu			0.40
			Strain Rate ($x10^{-8}$ in/in/sec)			1.6
	MR 1, FFS	**34.5**	K_{max}	81.5		
			DTI_{th}	0.53		
			Fu	0.89		
			Strain Rate ($x10^{-8}$ in/in/sec)	8200		
	MR 5, EHE	**33.5**	$K_{threshold}$			30.7
			DTI_{th}			0.20
			Fu			0.33
			Strain Rate ($x10^{-8}$ in/in/sec)			2.2
	MR 6,EHE	**34.0**	$K_{threshold}$			33.4
			DTI_{th}			0.22
			Fu			0.36
			Strain Rate ($x10^{-8}$ in/in/sec)			1.2
	Center 1, FFS	**31.5**	K_{max}	77.1		
			DTI_{th}	0.54		
			Fu	0.84		
			Strain Rate ($x10^{-8}$ in/in/sec)	8100		

R.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 8-V-1						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Saddle Tie Rods **Comments**: Rolled Threads; Same Group of Material as Test Rig #7 in Test IV				
Rod#:	**8-V-1**					
Product Form:	**1e**					
Rod OD:	**4"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**31.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	304.2 0.97 1.6 5000		
	Thd 3, EHE	**34.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			267.5 0.85 1.3 1.9
	Thd 4, EHE	**33.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			270.3 0.86 1.3 1.6

R.4.3 Summary Table

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 8-V-1
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**8-V-1**
Product Form:	**1e**
Rod OD:	**4"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, $KI_{p\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 1, FFS	Air	32.5	147	94.9	94.9	94.9	100.0%	86.8	0.59	296.9	2.0	8500	0.2131	154.9	50 lbs/min		0.95	
	OD 3, EHE	3.5% NaCl @ -1.106V	32.5	147	56.9	48.4	36.9	39.1%	33.9	0.23	116.3	0.8	2	0.2145		10/5/2,4		0.37	
	OD 5, EHE	3.5% NaCl @ -1.106V	32.0	145	45.0	54.0	40.4	41.8%	36.3	0.25	123.6	0.9	1.6	0.2139		10/5/2,4		0.40	
	MR 1, FFS	Air	34.5	155	92.0	92.0	92.0	100.0%	81.5	0.53	276.4	1.8	8200	0.2113	145.1	50 lbs/min		0.89	
	MR 5, EHE	3.5% NaCl @ -1.106V	33.5	151	61.0	45.8	33.5	37.7%	30.7	0.20	105.3	0.7	2.2	0.2149		10/5/2,4		0.33	
	MR 6,EHE	3.5% NaCl @ -1.106V	34.0	153	36.0	45.0	37.7	41.0%	33.4	0.22	113.1	0.7	1.2	0.2129		10/5/2,4		0.36	
	Center 1, FFS	Air	31.5	143	87.2	87.2	87.2	100.0%	77.1	0.54	261.0	1.8	8100	0.2105	128.9	50 lbs/min		0.84	
Threaded	Thd 1, FFS	Air	31.0	141	287.2	287.2	287.2	100.0%	88.7	0.63	225.4	1.6	5000	N/A	N/A	0.4 in/min	304.2	0.97	
	Thd 3, EHE	3.5% NaCl @ -1.106V	34.0	153	216.8	271.3	255.5	87.9%	78.0	0.51	197.7	1.3	1.9	N/A		10/5/2,4	267.5	0.85	Cracked in Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	33.0	149	190.0	275.5	261.9	88.8%	78.8	0.53	197.7	1.3	1.6	N/A		10/5/2,4	270.3	0.86	Cracked in Holiday

R.5 Fatigue Pre-cracked Specimen Test Results

R.5.1 OD 1, FFS:

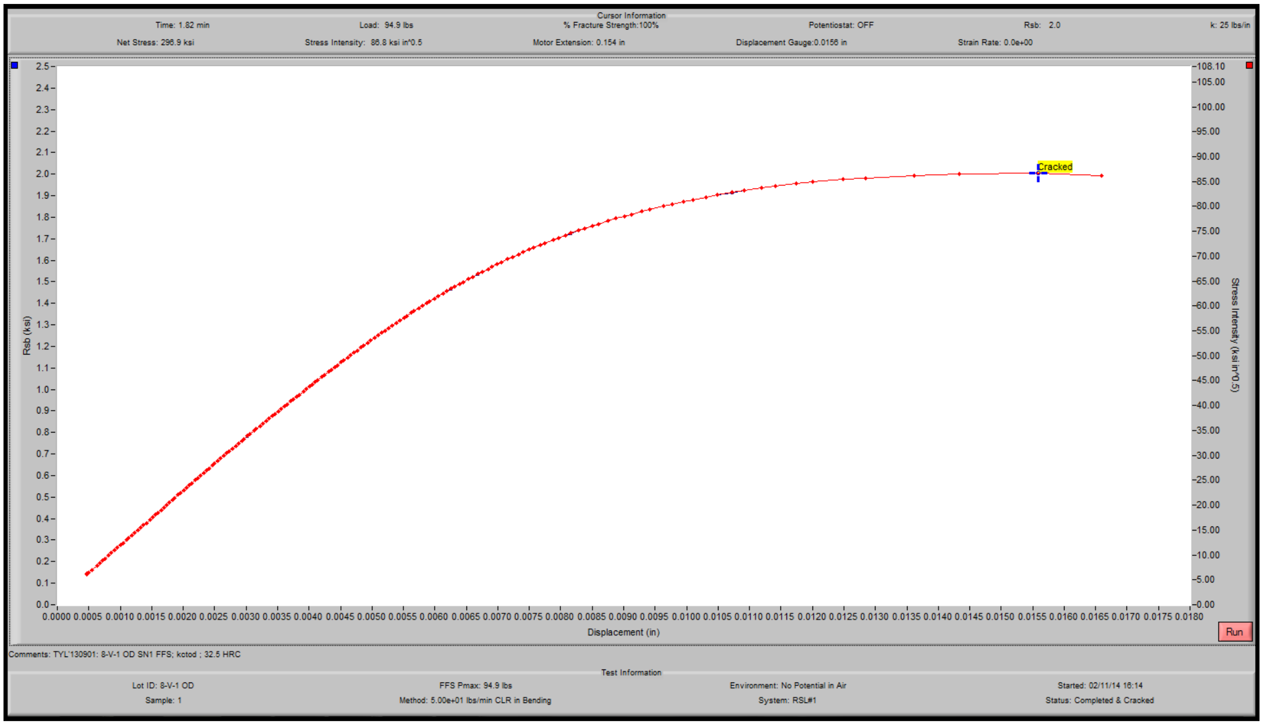


Figure R.5-1: Rod 8-V-1 OD 1, Graphical FFS Results

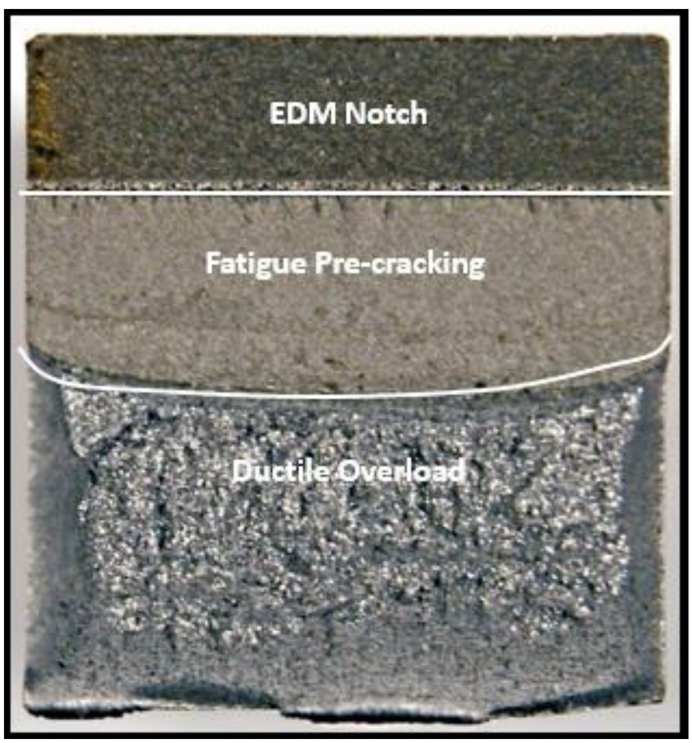


Figure R.5-2: Fracture Face of Rod 8-V-1 OD 1, FFS

R.5.2 OD 3, EHE:

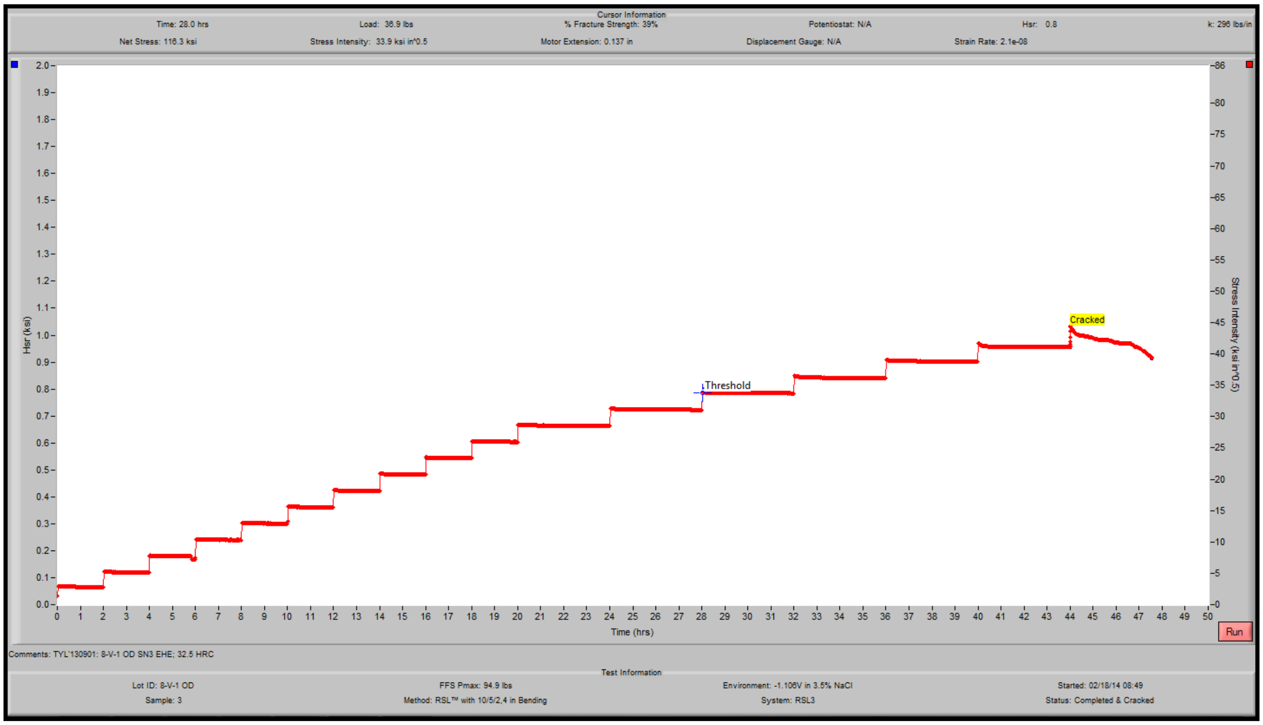


Figure R.5-3: Rod 8-V-1 OD 3, Graphical EHE Results

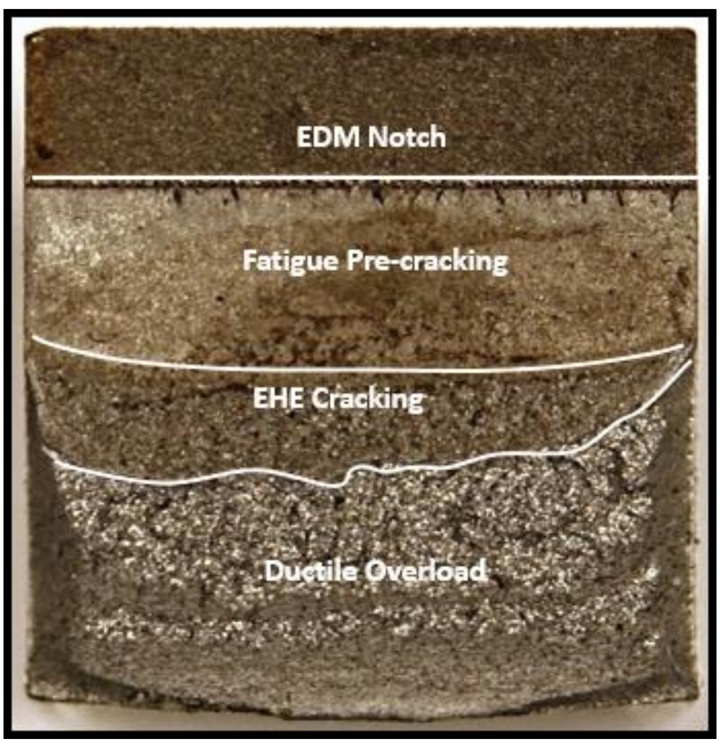


Figure R.5-4: Fracture Face of Rod 8-V-1 OD 3, EHE

R.5.3 OD 5, EHE:

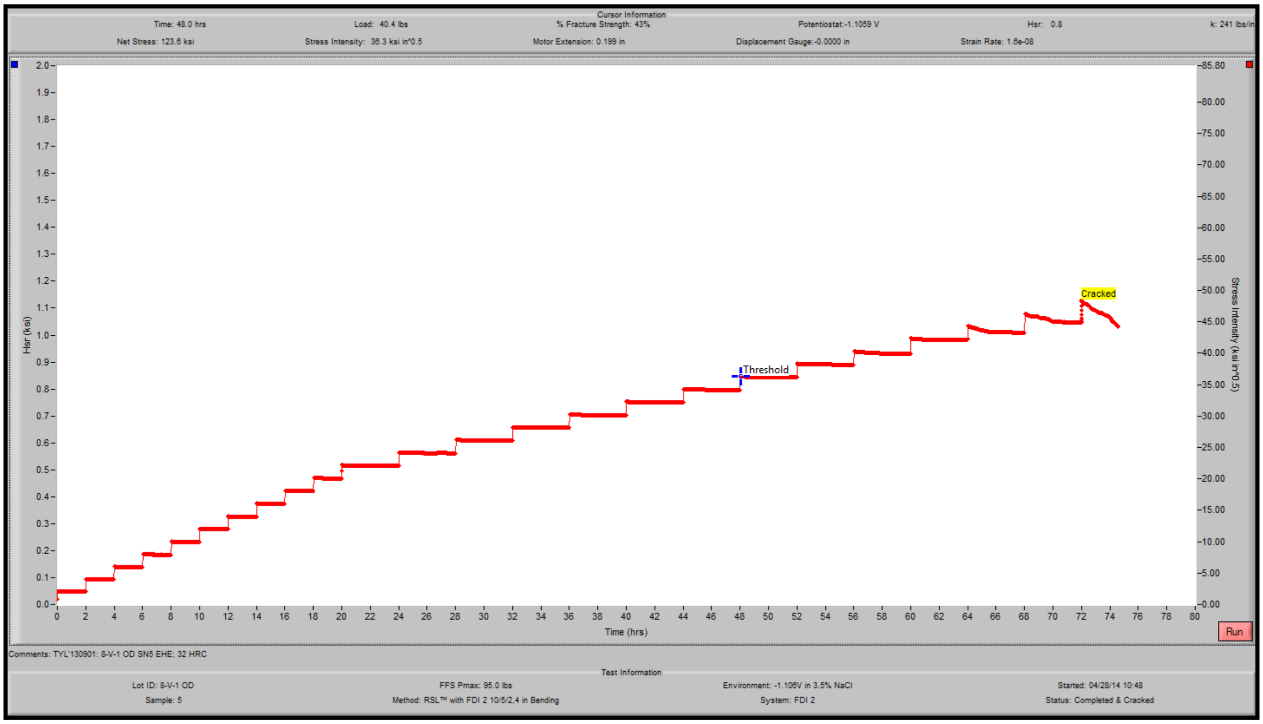


Figure R.5-5: Rod 8-V-1 OD 5, Graphical EHE Results

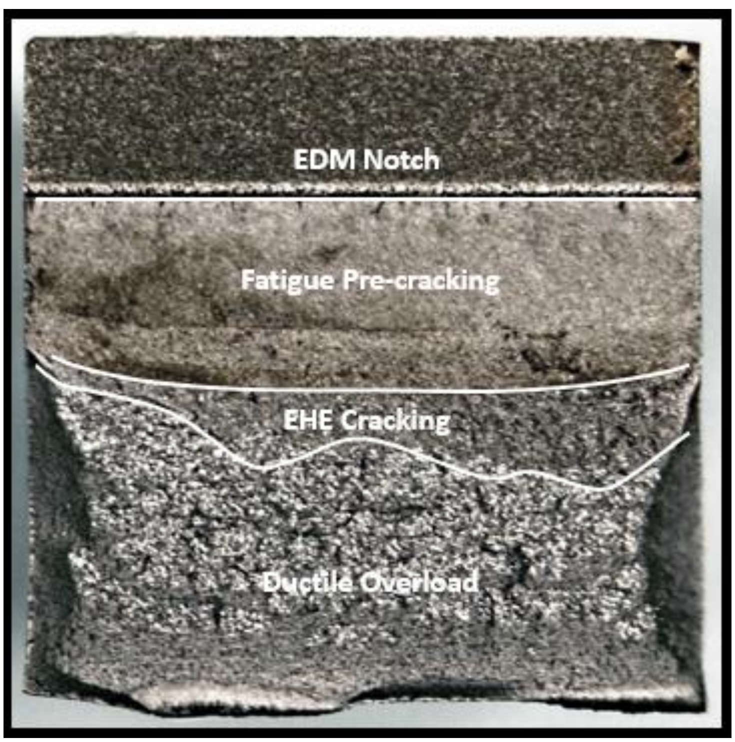


Figure R.5-6: Fracture Face of Rod 8-V-1 OD 5, EHE

R.5.4 MR 1, FFS:

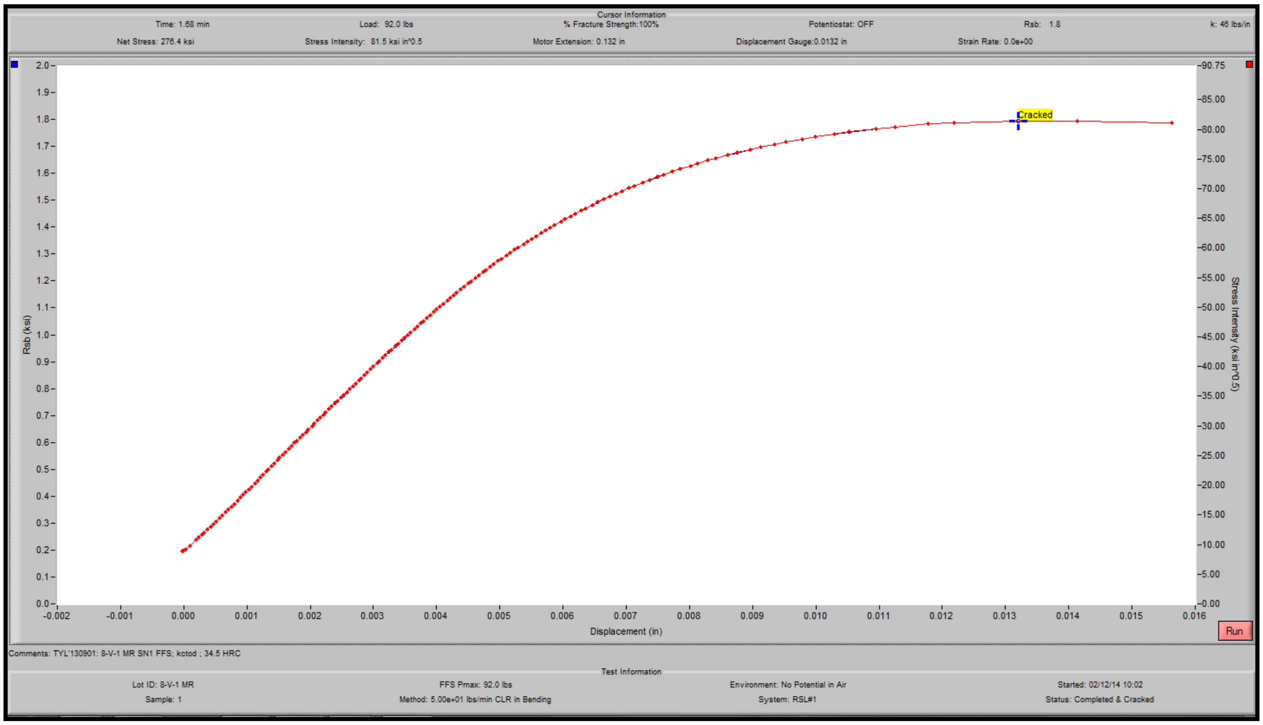


Figure R.5-7: Rod 8-V-1 MR 1, Graphical FFS Results

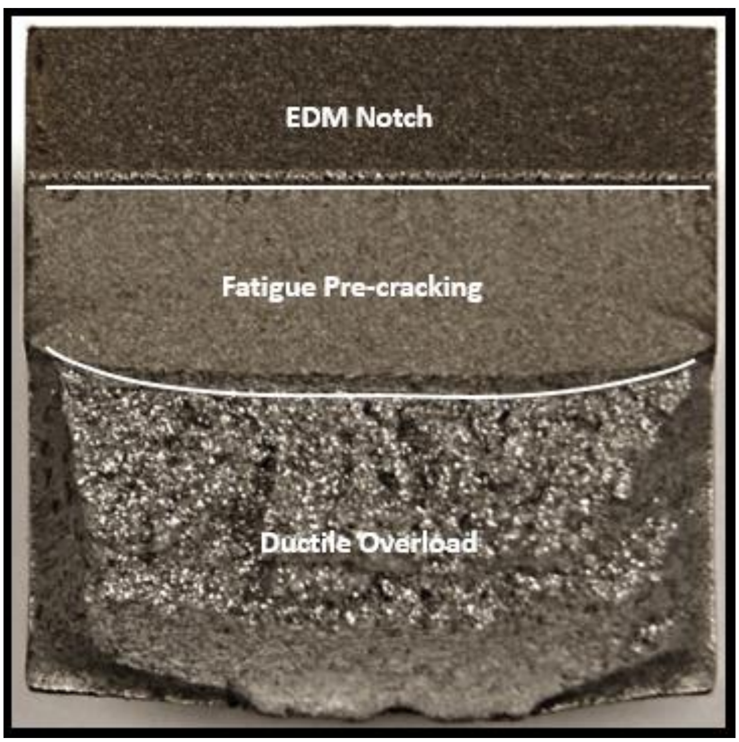


Figure R.5-8: Fracture Face of Rod 8-V-1 MR 1, FFS

R.5.5 MR 5, EHE:

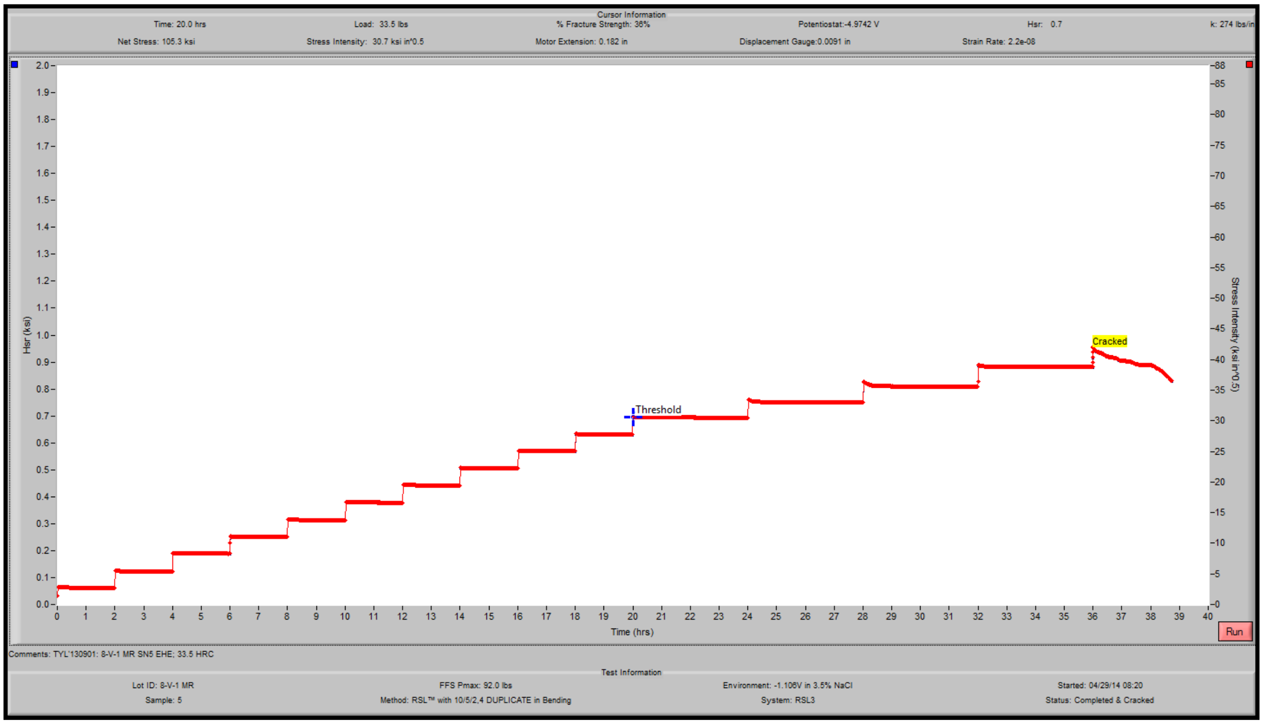


Figure R.5-9: Rod 8-V-1 MR 5, Graphical EHE Results

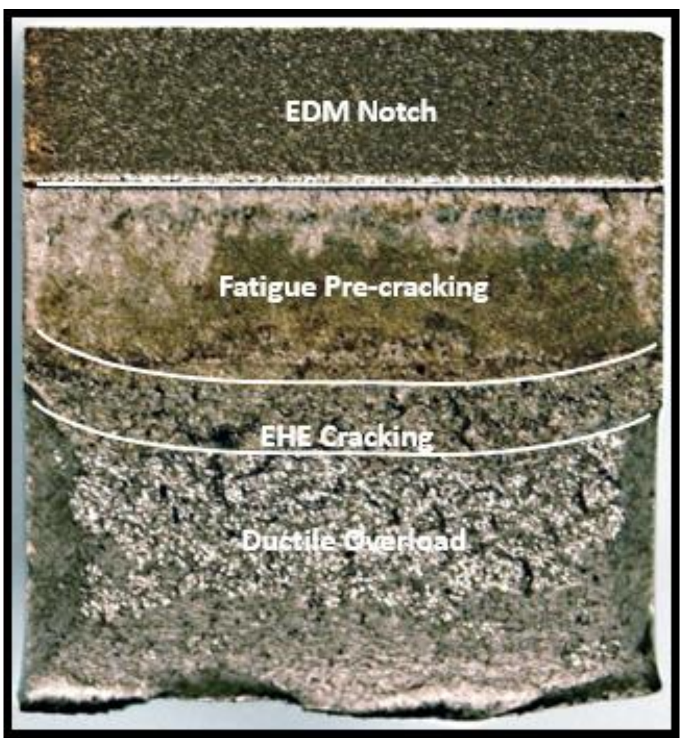


Figure R.5-10: Fracture Face of Rod 8-V-1 MR 5, EHE

R.5.6 MR 6, EHE:

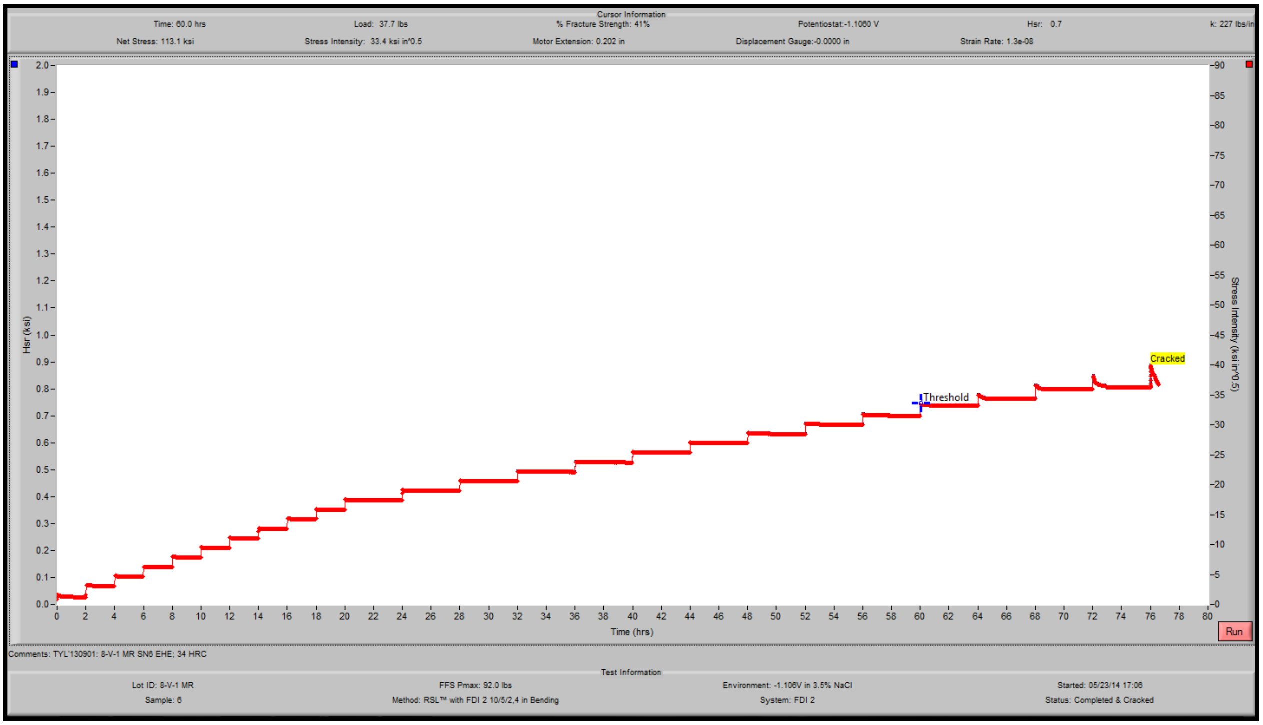


Figure R.5-11: Rod 8-V-1 MR 6, Graphical EHE Results

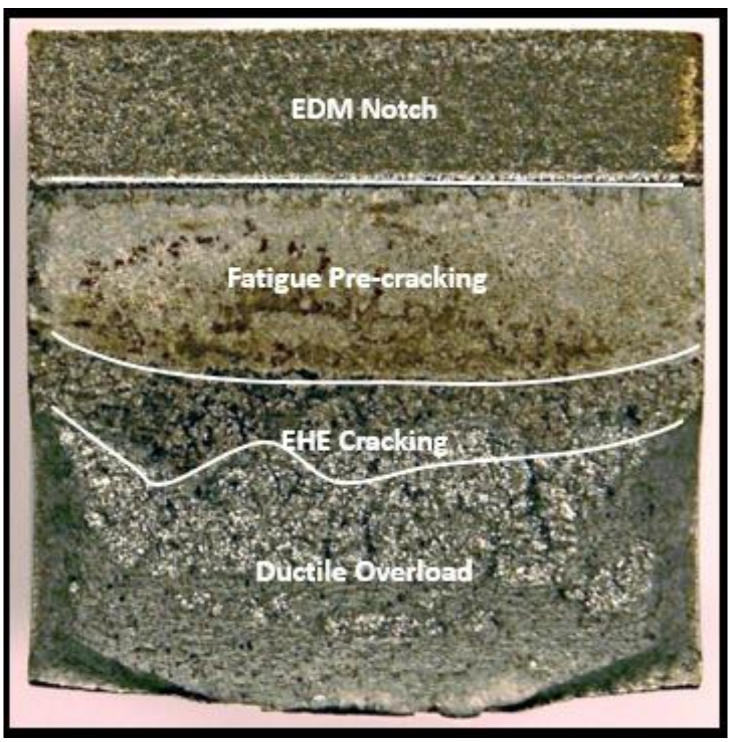


Figure R.5-12: Fracture Face of Rod 8-V-1 MR 6, EHE

R.5.7 Center 1, FFS:

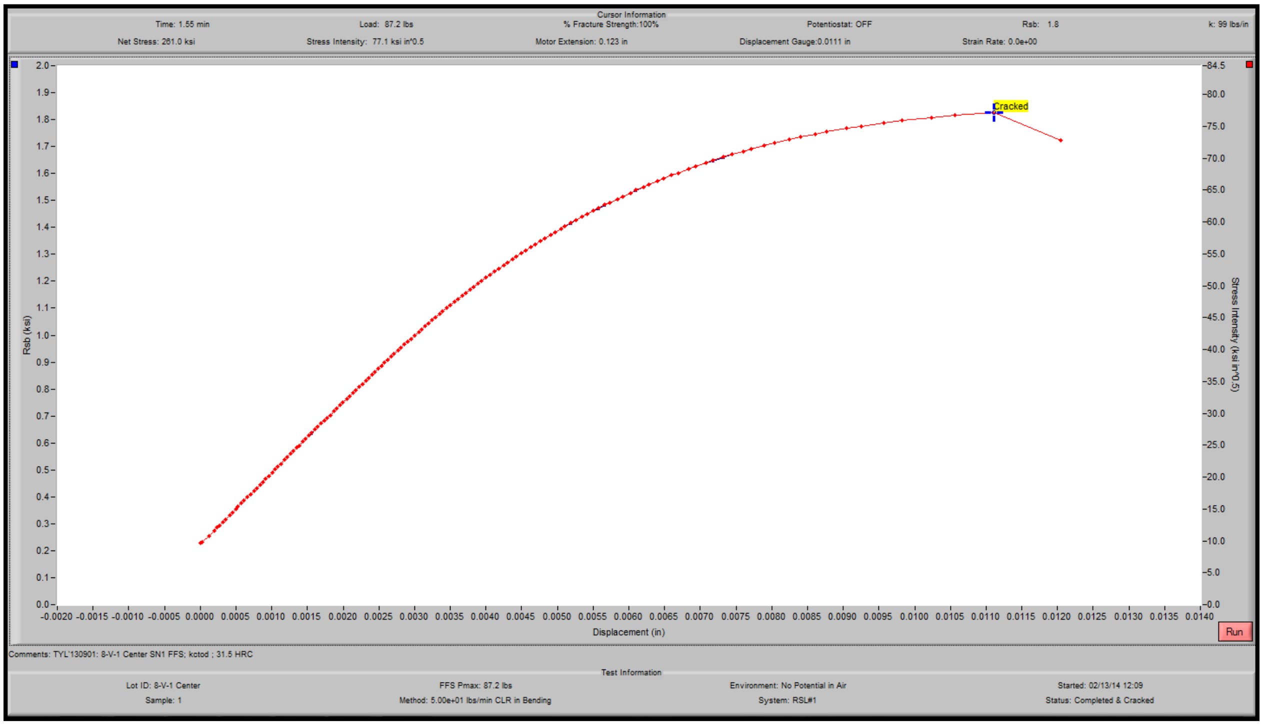


Figure R.5-13: Rod 8-V-1 Center 1, Graphical FFS Results

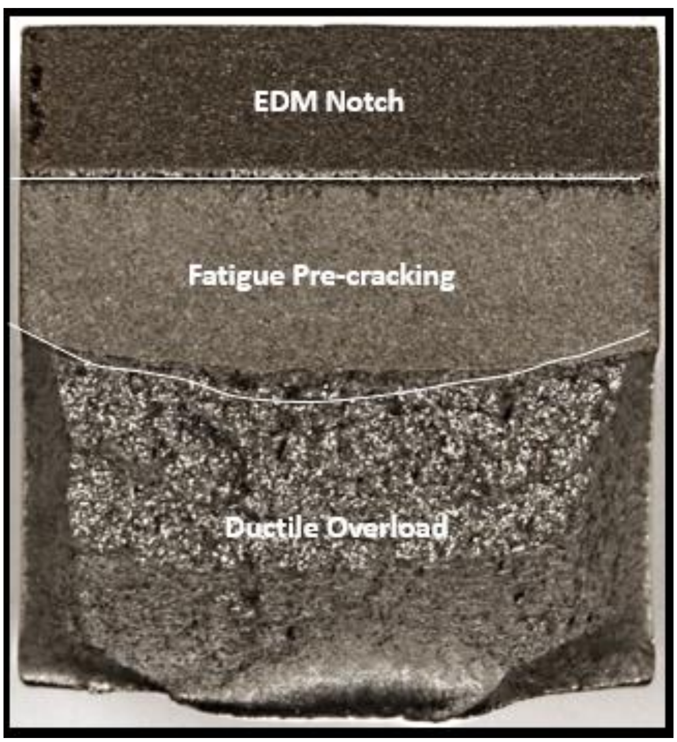


Figure R.5-14: Fracture Face of Rod 8-V-1 Center 1, FFS

R.6 Threaded Specimen Test Results

R.6.1 Thd 1, FFS:

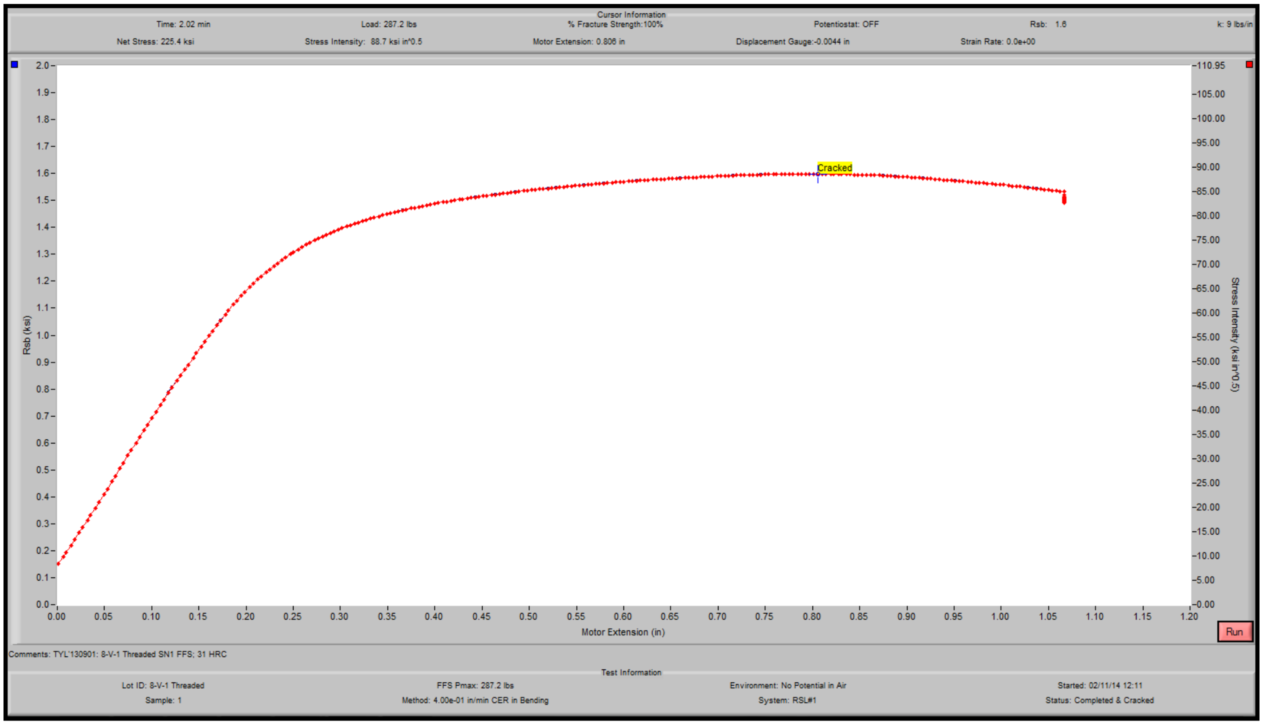


Figure R.6-1: Rod 8-V-1 Thd 1, Graphical FFS Results

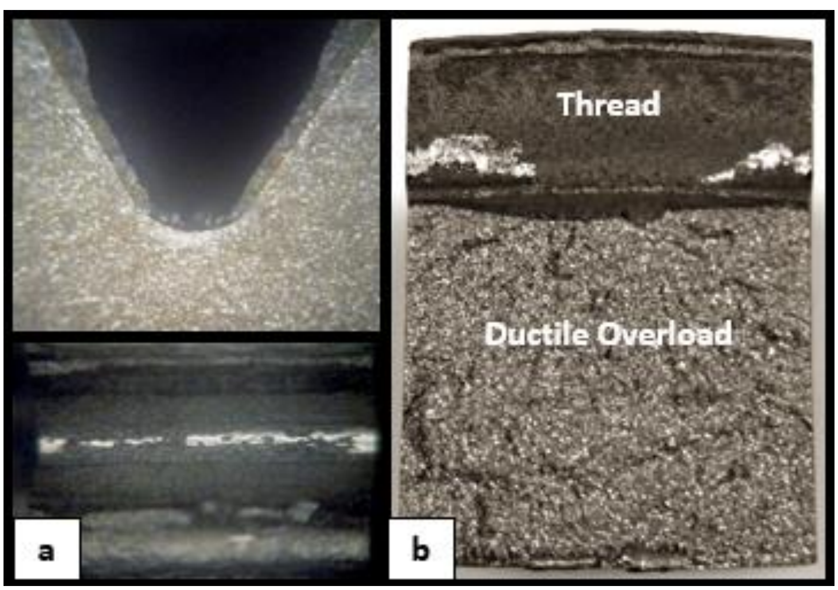


Figure R.6-2: Rod 8-V-1 Thd 1 a) Thread Root Post FFS Test V and Pre-Charpy Impact and b) FFS Fracture Face

R.6.2 Thd 3, EHE:

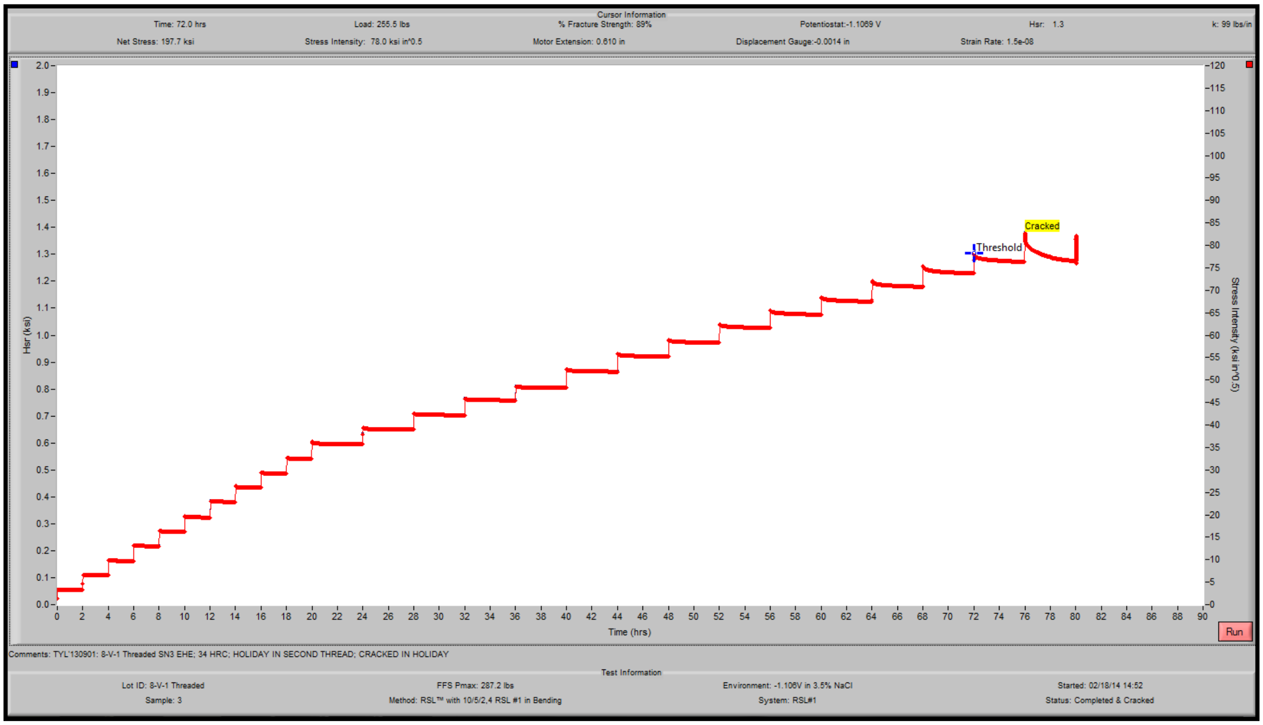


Figure R.6-3: Rod 8-V-1 Thd 3 Graphical EHE Results

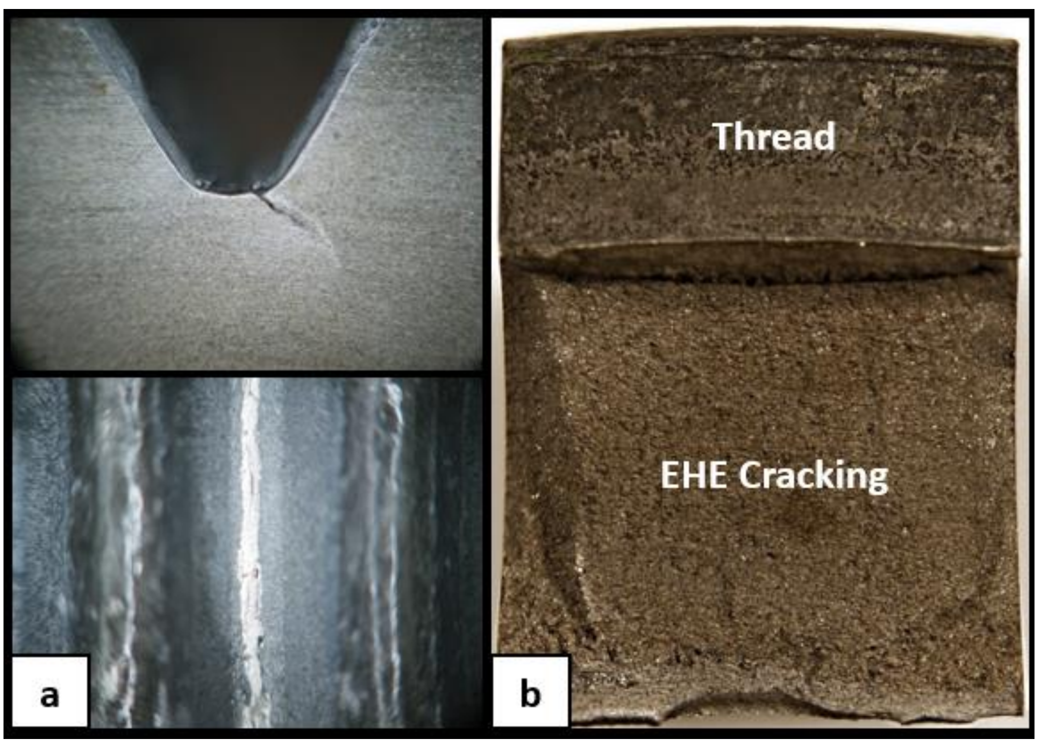
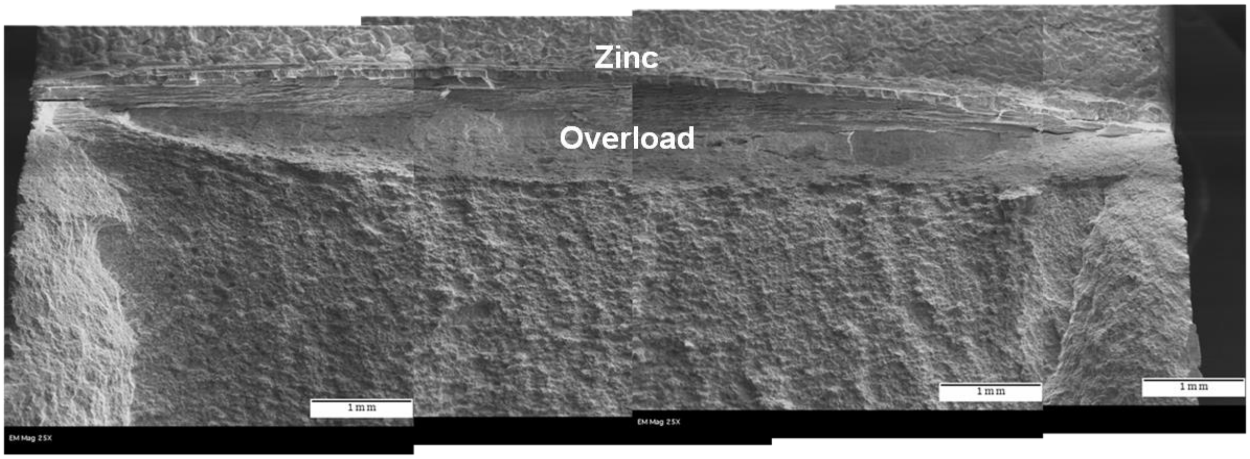
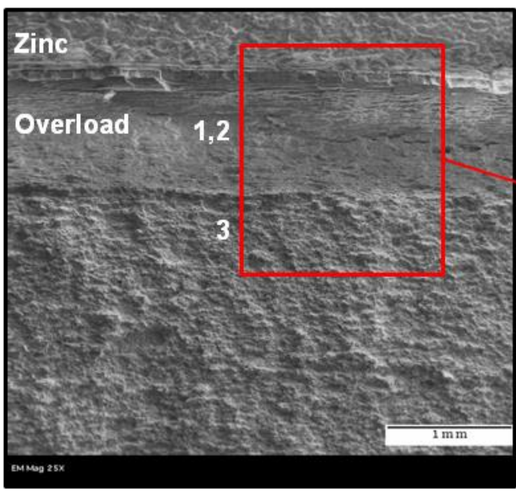


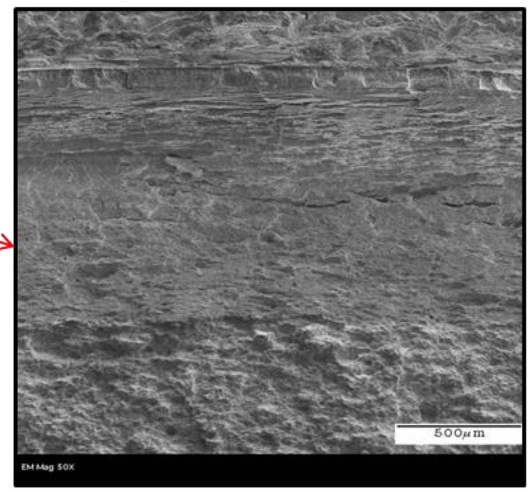
Figure R.6-4: Rod 8-V-1 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Figure R.6-5: SEM of Rod 8-V-1 Thd 3, EHE

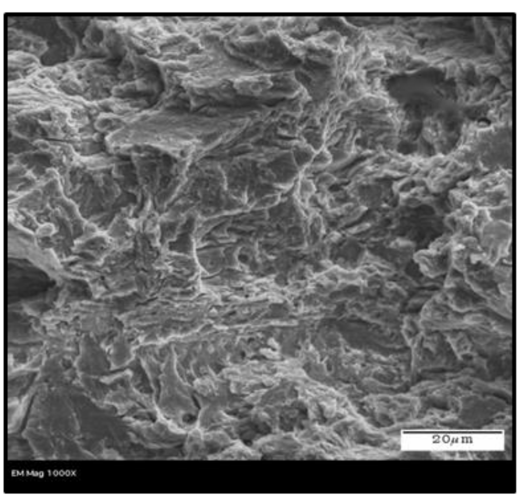




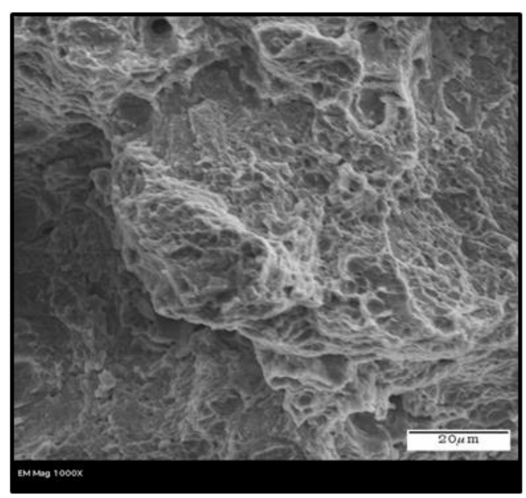
Thread Root 25X



1) Ductile Overload 50X



2) Ductile Overload 1000X



3) Ductile Overload 1000X

R.6.3 Thd 4, EHE:

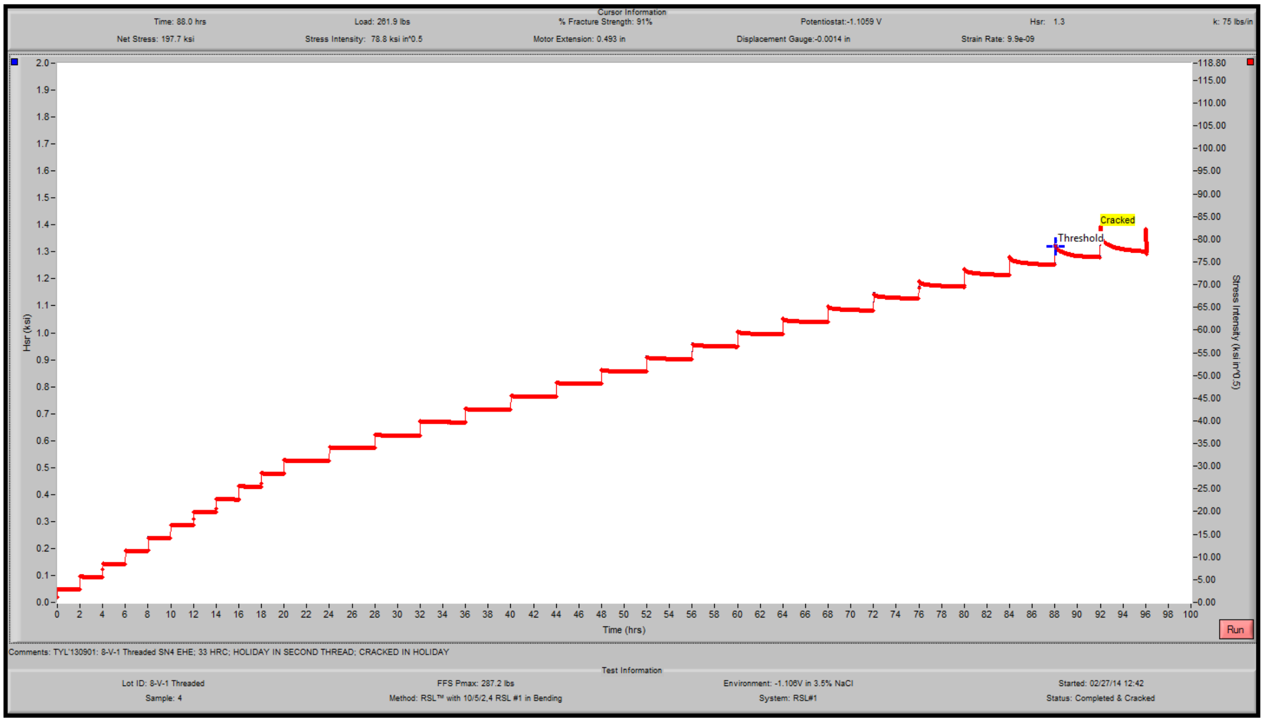


Figure R.6-6: Rod 8-V-1 Thd 4 Graphical EHE Results

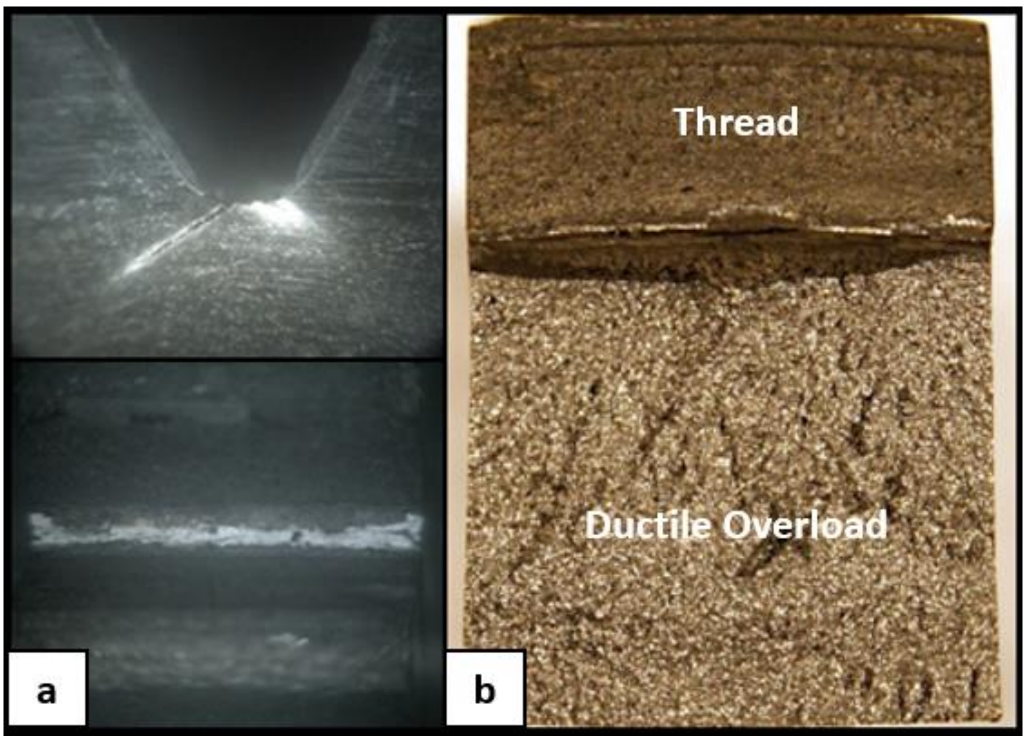
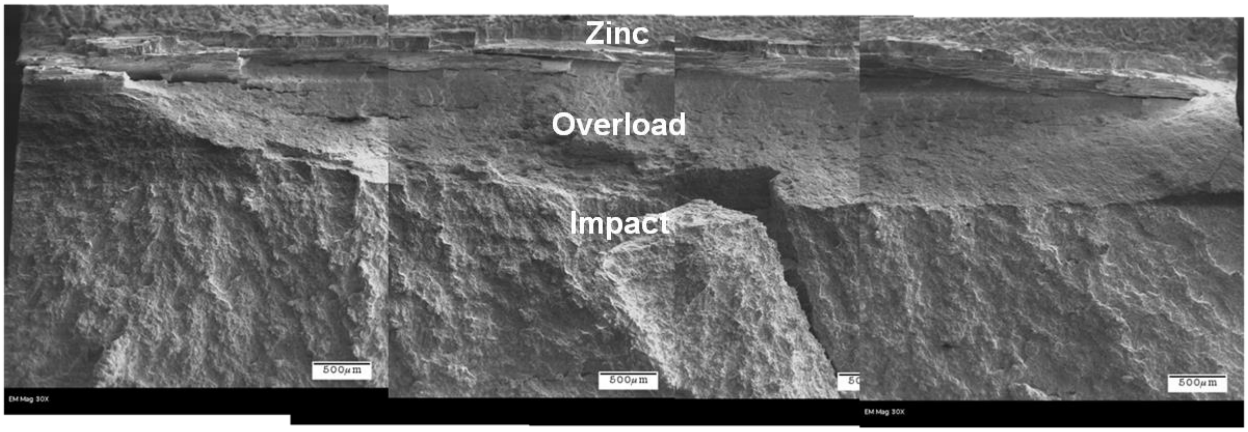
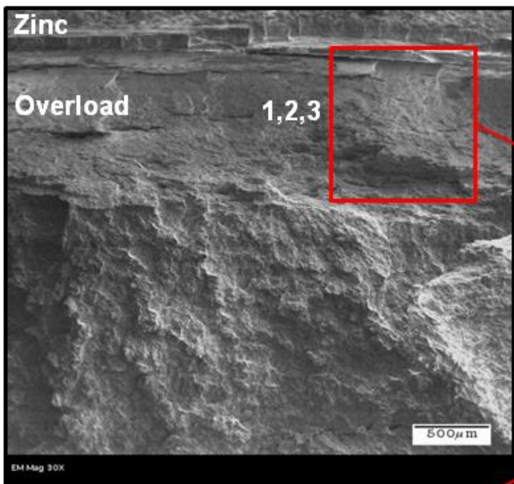


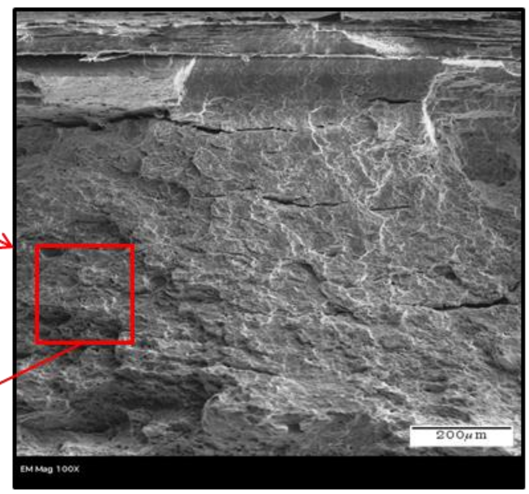
Figure R.6-7: Rod 8-V-1 Thd 4 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Figure R.6-8: SEM of Rod 8-V-1 Thd 4, EHE

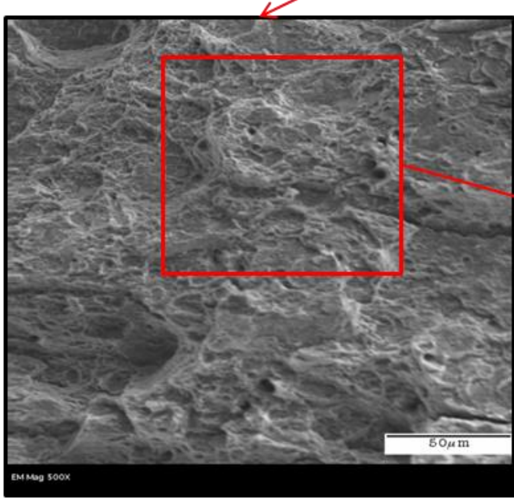




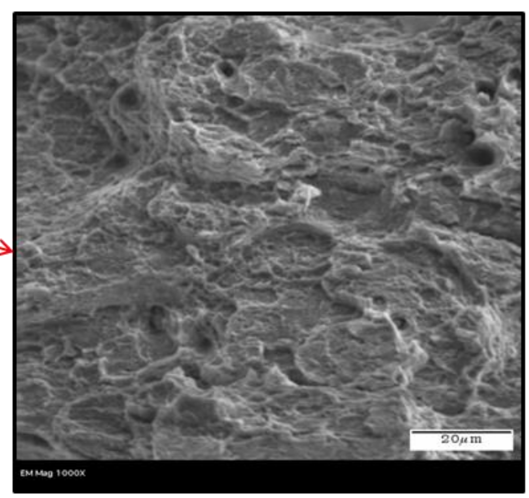
Thread Root 30X



1) Ductile Overload, Intergranular 100X



2) Ductile Overload 500X



3) Ductile Overload 1000X

Appendix S: Rod 13-V-CW-4

S.1 Description of Sample

Rod 13-V-CW-4 was a Tower Anchorage Anchor Bolt. No material from the same or similar heat as Rod 13-V-CW-4 was tested in Test IV. The rod was made from 4140 steel to ASTM A354 Grade BD. The bolts are 4 inches in diameter with machined threads. The segment from this rod provided to LRA is shown in **Figure S.1-1**.

Figure S.1-1: Tower Anchorage Anchor Bolt, Rod 13-V-CW-4

S.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod 13-V-CW-4 and can be seen versus time in **Figure S**.2-1. The final OCP recorded for Rod 13-V-CW-4 was Vsce=-0.893 V.

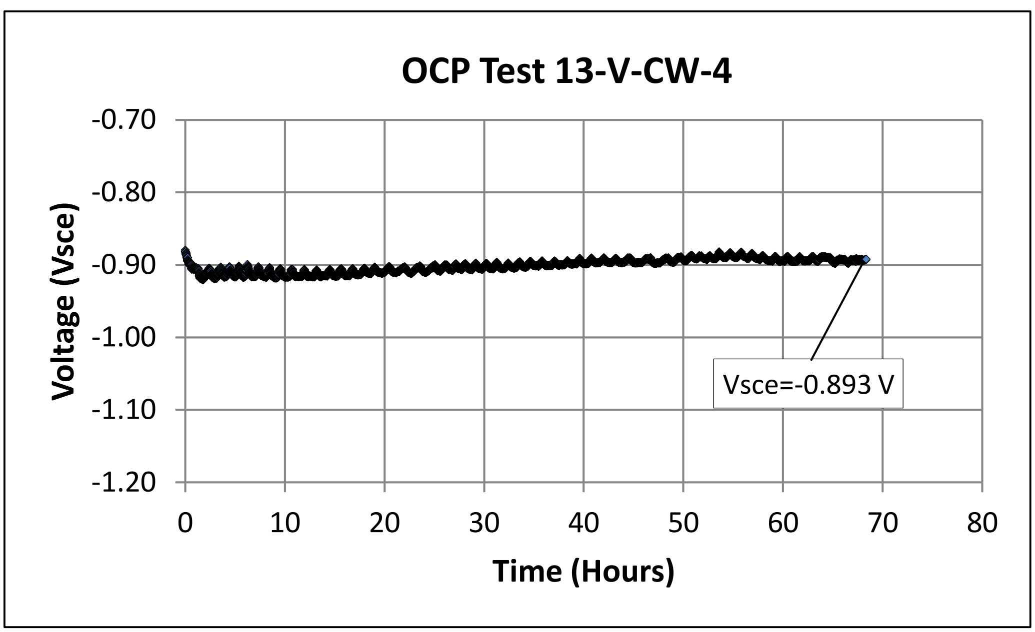


Figure S.2-1: Open Circuit Potential for Rod 13-V-CW-4

S.3 Hardness

The hardness data and profile for sample 13-V-CW-4 are shown in **Table S.3-1** and **Figure S.3-1**.

Table S.3-1: Hardness Data of Rod 13-V-CW-4 Specimen

S/N	Hardness (HRC)	Average (HRC)
Center 1, FFS	30.5	30.5
MR 1, FFS	35.0	36.1
MR 3, EHE	35.5	
MR 5, EHE	36.5	
MR 6, EHE	36.5	
MR 7, EHE	37.0	
OD 2, FFS	37.0	36.6
OD 4, EHE	36.0	
OD 5, EHE	36.5	
Th 1, FFS	35.5	
Th 3, EHE	37.0	
Th 4, EHE	37.5	

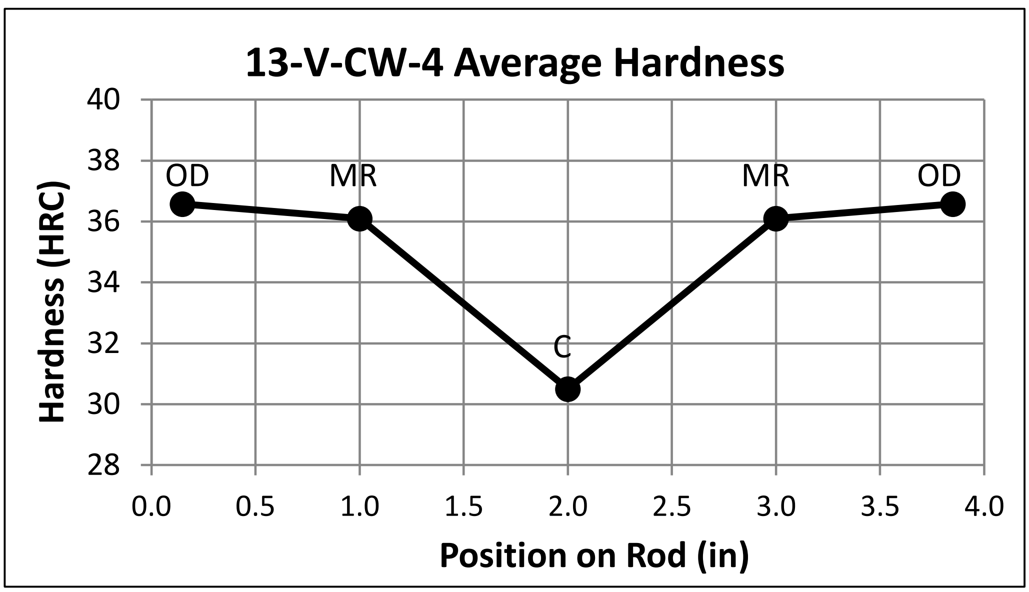


Figure S.3-1: Hardness Profile of Rod 13-V-CW-4

S.4 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables.

S.4.1 Fatigue Pre-crack Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 13-V-cW-4						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (100 Dia. Anchor Bolts) **Comments**: Cut Threads				
Rod#:	**13-V-cW-4**					
Product Form:	**1e**					
Rod OD:	**4"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**OD 2, FFS**	**37.0**	K_{max}	92.8		
			DTI_{th}	0.56		
			Fu	1.01		
			Strain Rate ($x10^{-8}$ in/in/sec)	8400		
	OD 4, EHE	**36.0**	$K_{threshold}$			25.8
			DTI_{th}			0.16
			Fu			0.28
			Strain Rate ($x10^{-8}$ in/in/sec)			4.5
	OD 5, EHE	**36.5**	$K_{threshold}$			21.4
			DTI_{th}			0.13
			Fu			0.23
			Strain Rate ($x10^{-8}$ in/in/sec)			1.2
	MR 1, FFS	**35.0**	K_{max}	79.8		
			DTI_{th}	0.51		
			Fu	0.87		
			Strain Rate ($x10^{-8}$ in/in/sec)	8100		

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 13-V-cW-4						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (100 Dia. Anchor Bolts) **Comments**: Cut Threads				
Rod#:	**13-V-cW-4**					
Product Form:	**1e**					
Rod OD:	**4"**					
	Sample #/ID	**HRC**		**K-FFS**	**K-IHE**	**K-EHE**
Fatigue Pre-cracked	**MR 3, EHE**	**35.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			40.6 0.25 0.44 2.3
	MR 5, EHE	**36.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			24.1 0.15 0.26 1.4
	MR 6, EHE	**36.5**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			32.1 0.20 0.35 1.2
	MR 7, EHE	**37.0**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)			25.1 0.15 0.27 0.9
	Center 1, FFS	**30.5**	K_{max} DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	76.3 0.55 0.83 8100		

S.4.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 13-V-cW-4						
LRA Job No.:	**TYL130901**	**Structural Component:** Tower Anchorage Anchor Bolts (100 Dia. Anchor Bolts) **Comments**: Cut Threads				
Rod#:	**13-V-cW-4**					
Product Form:	**1e**					
Rod OD:	**4"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.5**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	331.3 1.05 1.6 2750		
	Thd 3, EHE	**37.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			198.9 0.63 0.9 2.2
	Thd 4, EHE	**37.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			221.9 0.71 1.0 1.9

S.4.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 13-V-cW-4
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**13-V-cW-4**
Product Form:	**1e**
Rod OD:	**4"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, K_{Iscc}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	KIctod (ksi√in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	OD 2, FFS	Air	37.0	167	103.4	103.4	103.4	100.0%	92.8	0.56	316.4	1.9	8400	0.2022	132.5	50 lbs/min		1.01	
	OD 4, EHE	3.5% NaCl @ -1.106V	36.0	162	65.5	36.0	29.4	27.8%	25.8	0.16	87.0	0.5	4.5	0.2091		10/5/2,4		0.28	Threshold in Two Hour Steps
	OD 5, EHE	3.5% NaCl @ -1.106V	36.5	164	33.0	28.1	23.1	23.1%	21.4	0.13	73.6	0.4	1.2	0.2168		10/5/2,4		0.23	
	MR 1, FFS	Air	35.0	157	91.5	91.5	91.5	100.0%	79.8	0.51	269.2	1.7	8100	0.2114	129.5	50 lbs/min		0.87	
	MR 3, EHE	3.5% NaCl @ -1.106V	35.5	159	64.1	51.3	44.7	50.9%	40.6	0.25	138.5	0.9	2.3	0.215		10/5/2,4		0.44	
	MR 5, EHE	3.5% NaCl @ -1.106V	36.5	164	50.0	35.0	27.5	30.2%	24.1	0.15	81.3	0.5	1.4	0.2097		10/5/2,4		0.26	
	MR 6, EHE	3.5% NaCl @ -1.106V	36.5	164	35.0	43.8	34.9	40.2%	32.1	0.20	110.2	0.7	1.2	0.2166		10/5/2,4		0.35	
	MR 7, EHE	3.5% NaCl @ -1.106V	37.0	167	25.0	31.3	28.7	31.5%	25.1	0.15	84.7	0.5	0.9	0.2099		10/5/2,4		0.27	
	Center 1, FFS	Air	30.5	139	86.6	86.6	86.6	100.0%	76.3	0.55	258.3	1.9	8100	0.2114	146.3	50 lbs/min		0.83	
Threaded	Thd 1, FFS	Air	35.5	159	302.0	302.0	302.0	100.0%	96.6	0.61	247.7	1.6	2750	N/A		0.4 in/min	331.3	1.05	
	Thd 3, EHE	3.5% NaCl @ -1.106V	37.0	167	232.7	244.6	173.7	60.0%	58.0	0.35	149.7	0.9	2.2	N/A		10/5/2,4	198.9	0.63	Did not crack in Holiday.
	Thd 4, EHE	3.5% NaCl @ -1.106V	37.5	169	200.0	240.0	199.5	67.0%	64.7	0.38	166.4	1.0	1.9	N/A		10/5/2,4	221.9	0.71	Cracked in Holiday. Threshold Reached.

S.5 Fatigue Pre-cracked Specimen Test Results

S.5.1 OD 2, FFS:

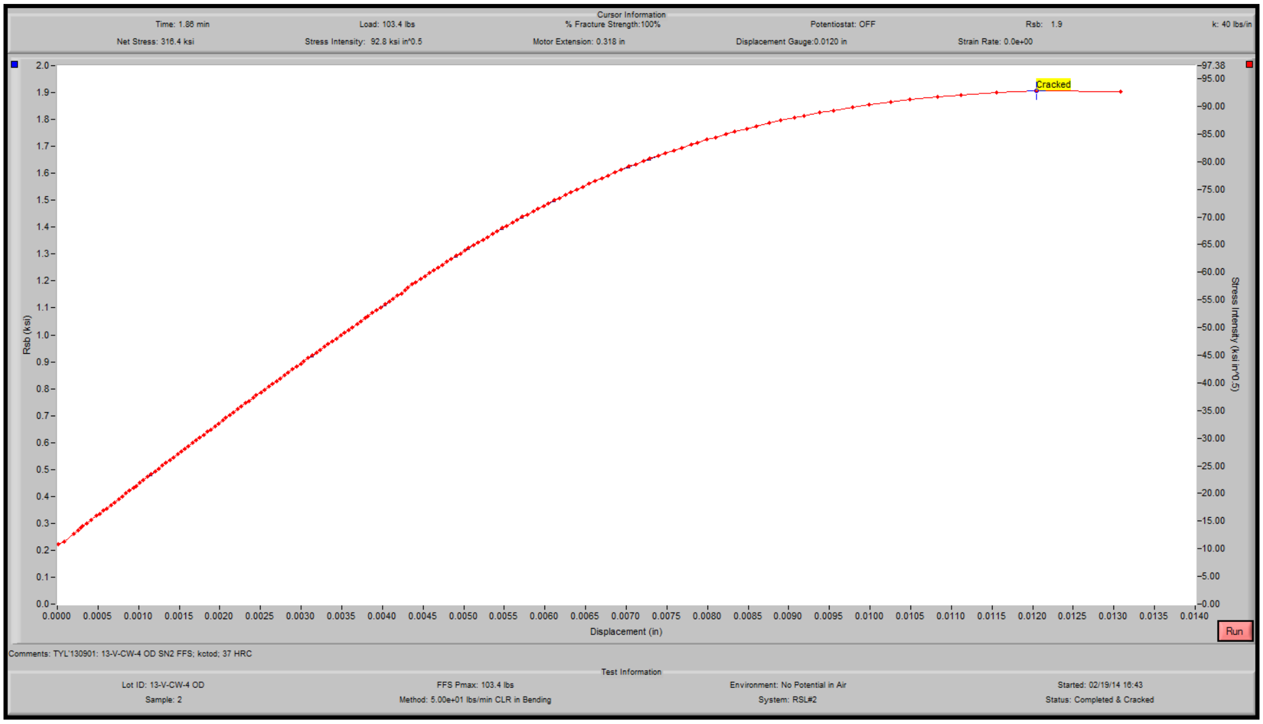
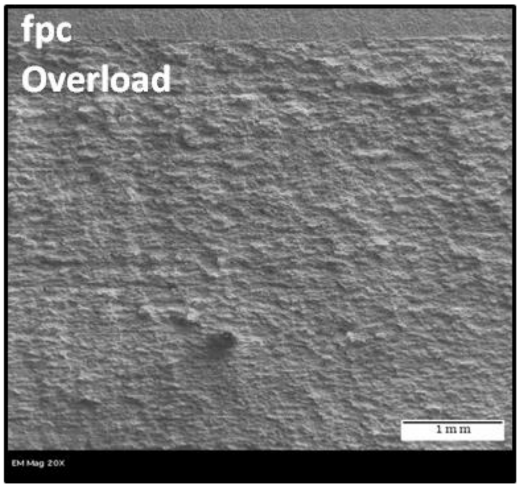


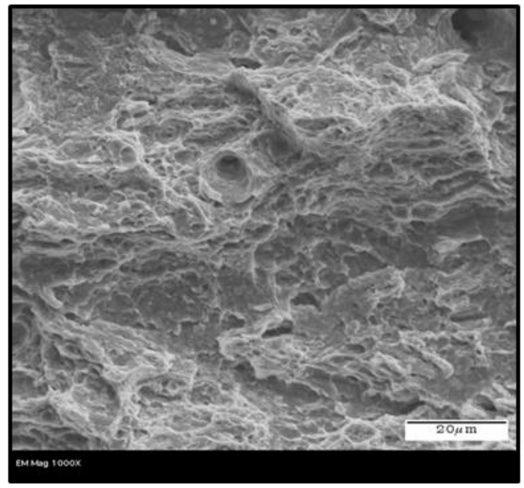
Figure S.5-1: Rod 13-V-CW-4 OD 2, Graphical FFS Results

Figure S.5-2: Fracture Face of Rod 13-V-CW-4 OD 2, FFS

Figure S.5-3: SEM of Rod 13-V-CW-4 OD 2, FFS



Macro 20X



Overload 1000X

S.5.2 OD 4, EHE:

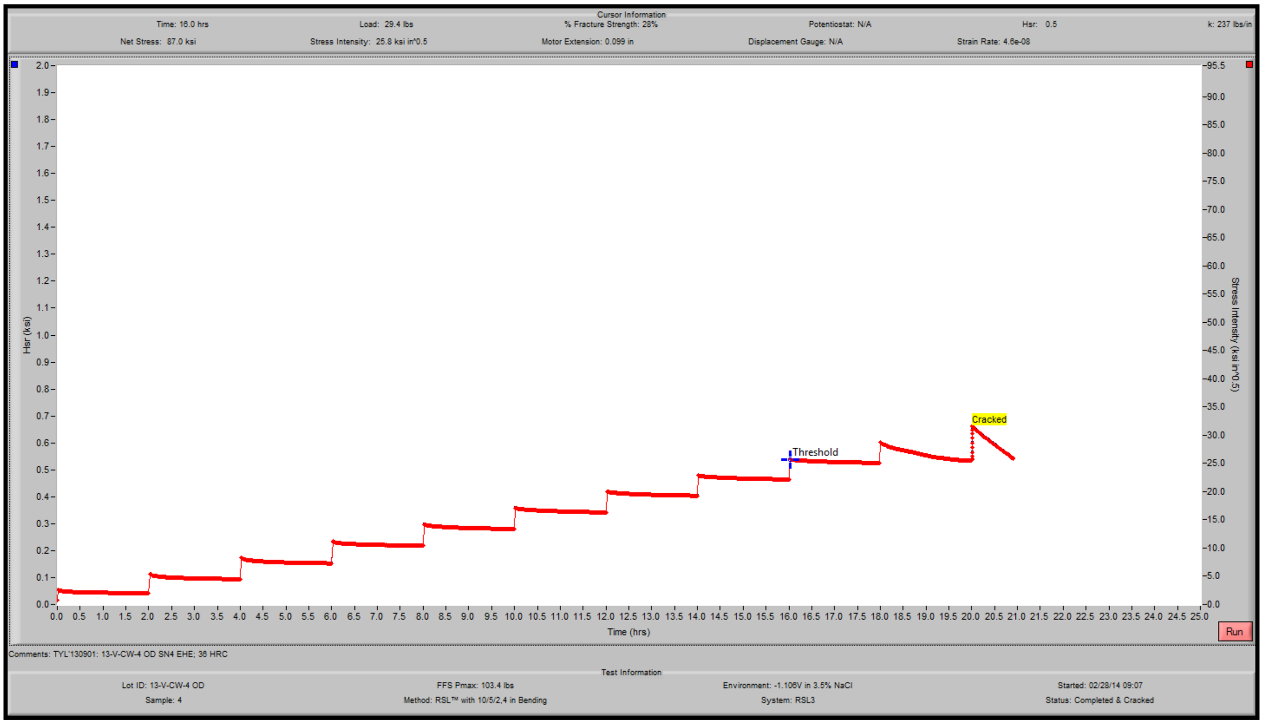


Figure S.5-4: Rod 13-V-CW-4 OD 4, Graphical EHE Results

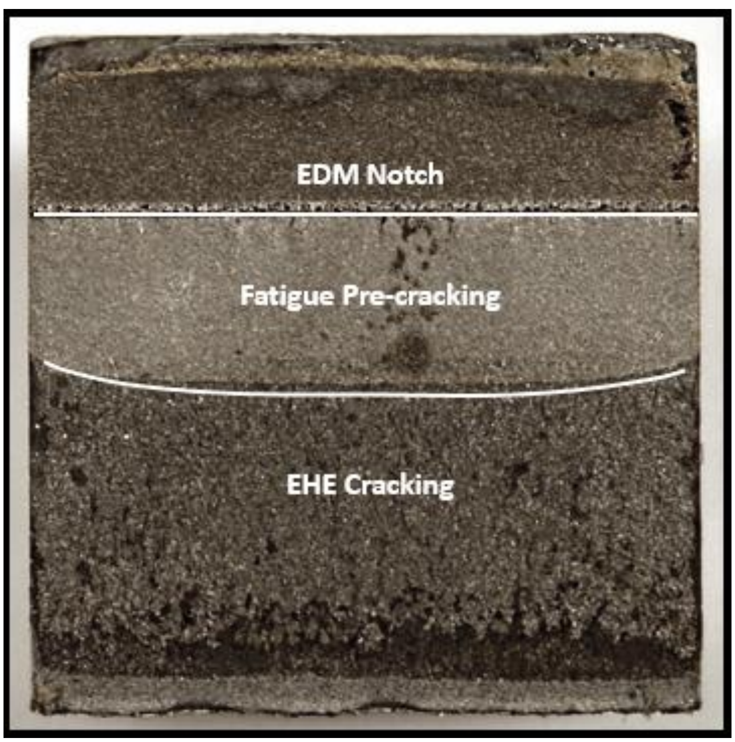


Figure S.5-5: Fracture Face of Rod 13-V-CW-4 OD 4, EHE

S.5.3 OD 5, EHE:

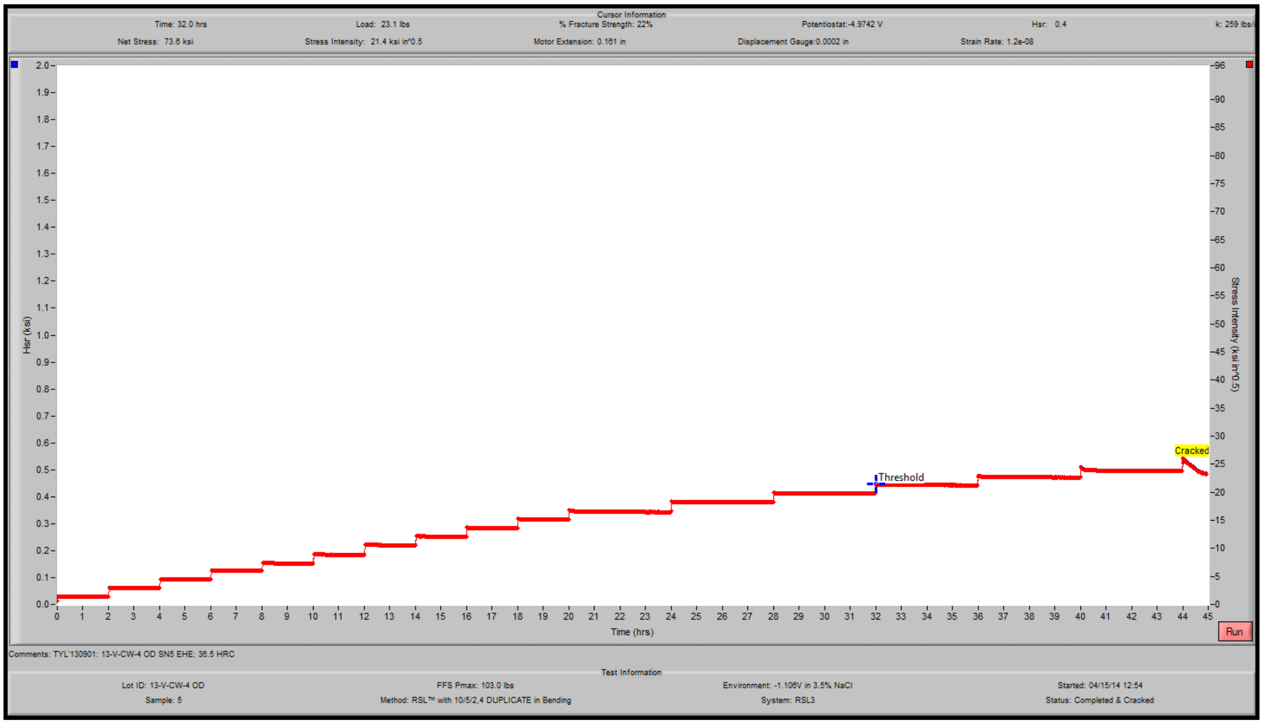


Figure S.5-6: Rod 13-V-CW-4 OD 5, Graphical EHE Results

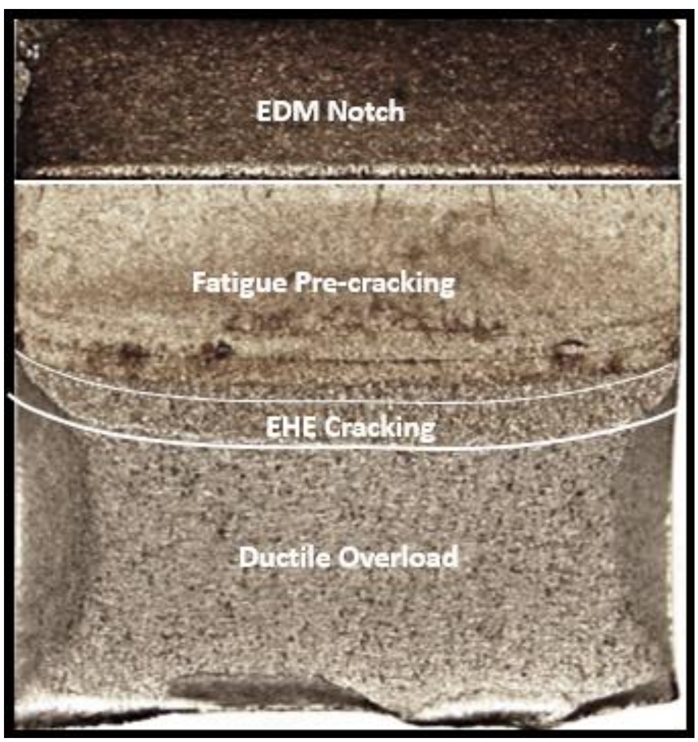


Figure S.5-7: Fracture Face of Rod 13-V-CW-4 OD 5, EHE

S.5.4 MR 1, FFS:

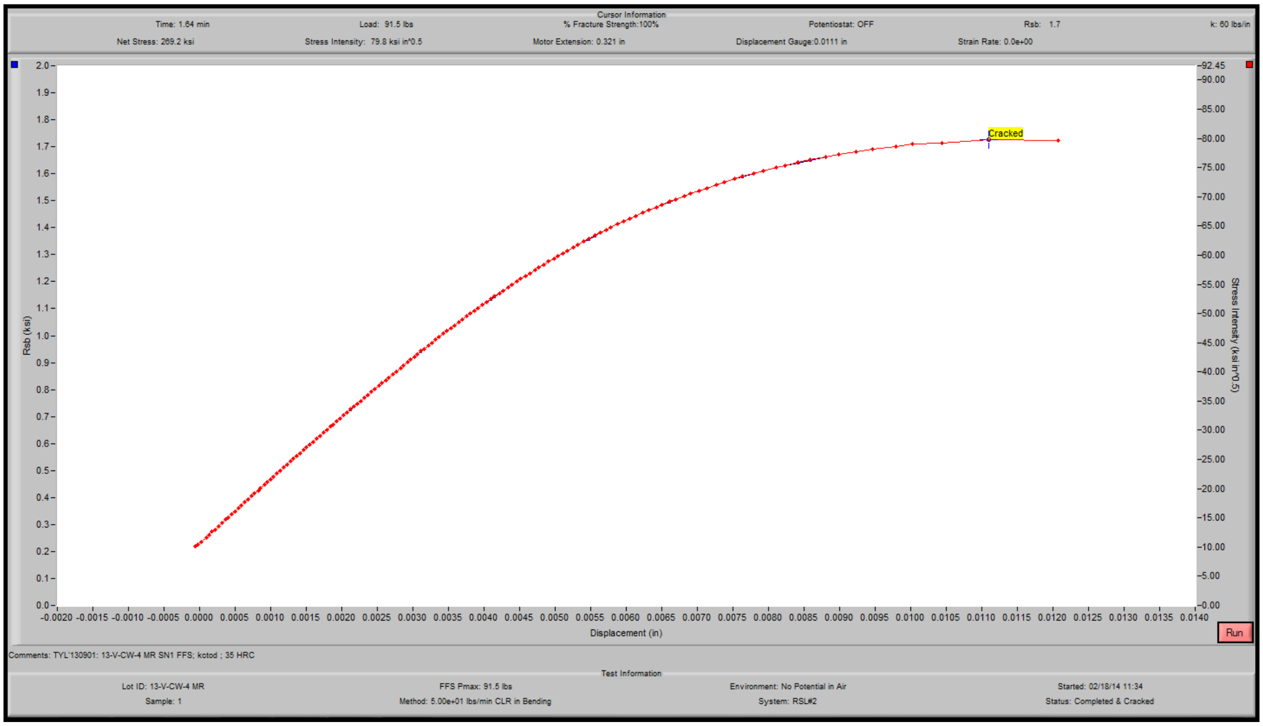


Figure S.5-8: Rod 13-V-CW-4 MR 1, Graphical FFS Results

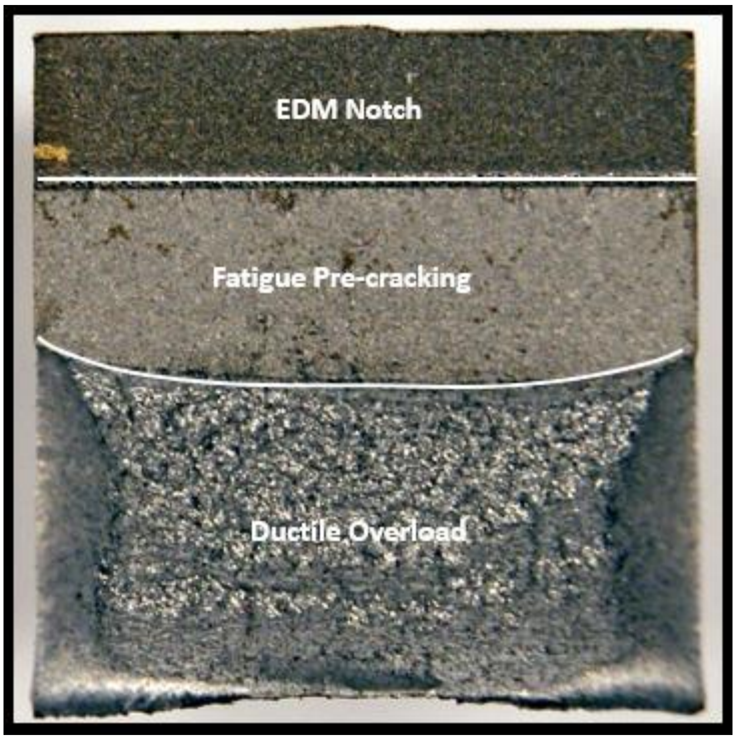


Figure S.5-9: Fracture Face of Rod 13-V-CW-4 MR 1, FFS

S.5.5 MR 3, EHE:

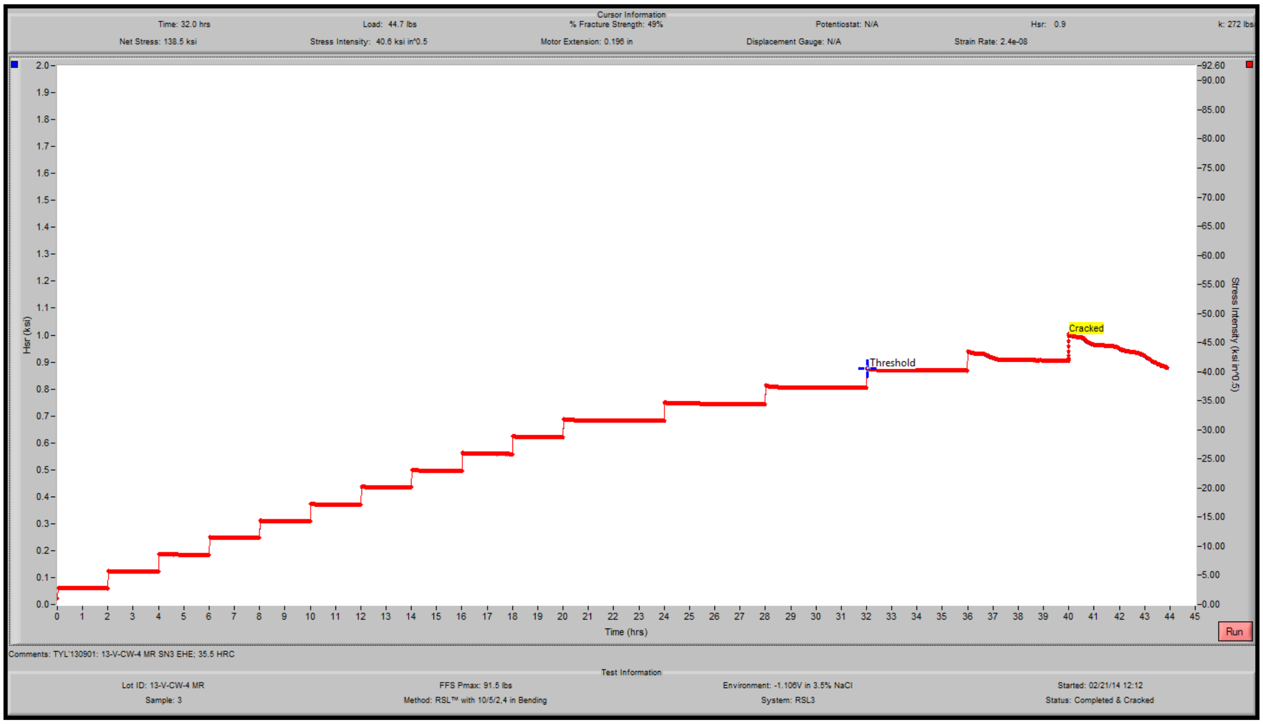


Figure S.5-10: Rod 13-V-CW-4 MR 3, Graphical EHE Results

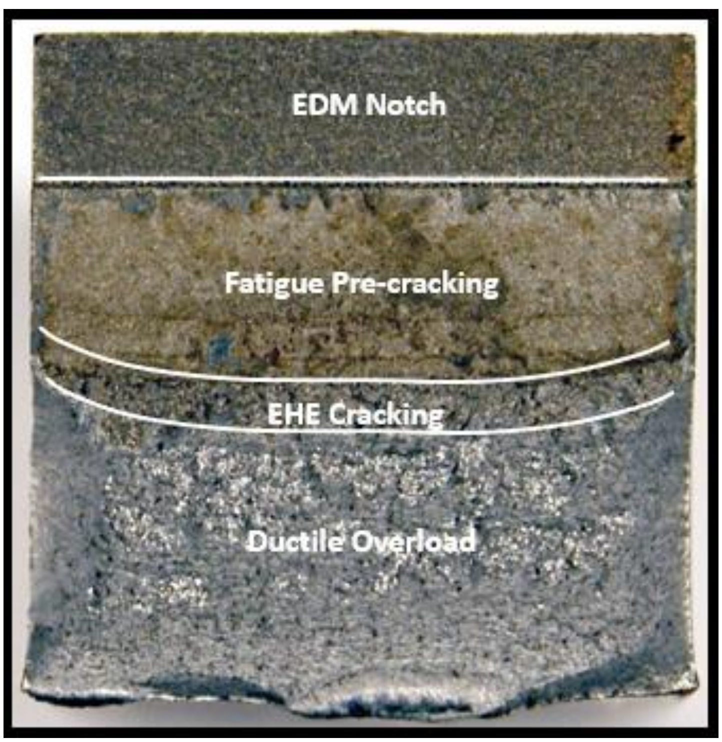


Figure S.5-11: Fracture Face of Rod 13-V-CW-4 MR 3, EHE

S.5.6 MR 5, EHE:

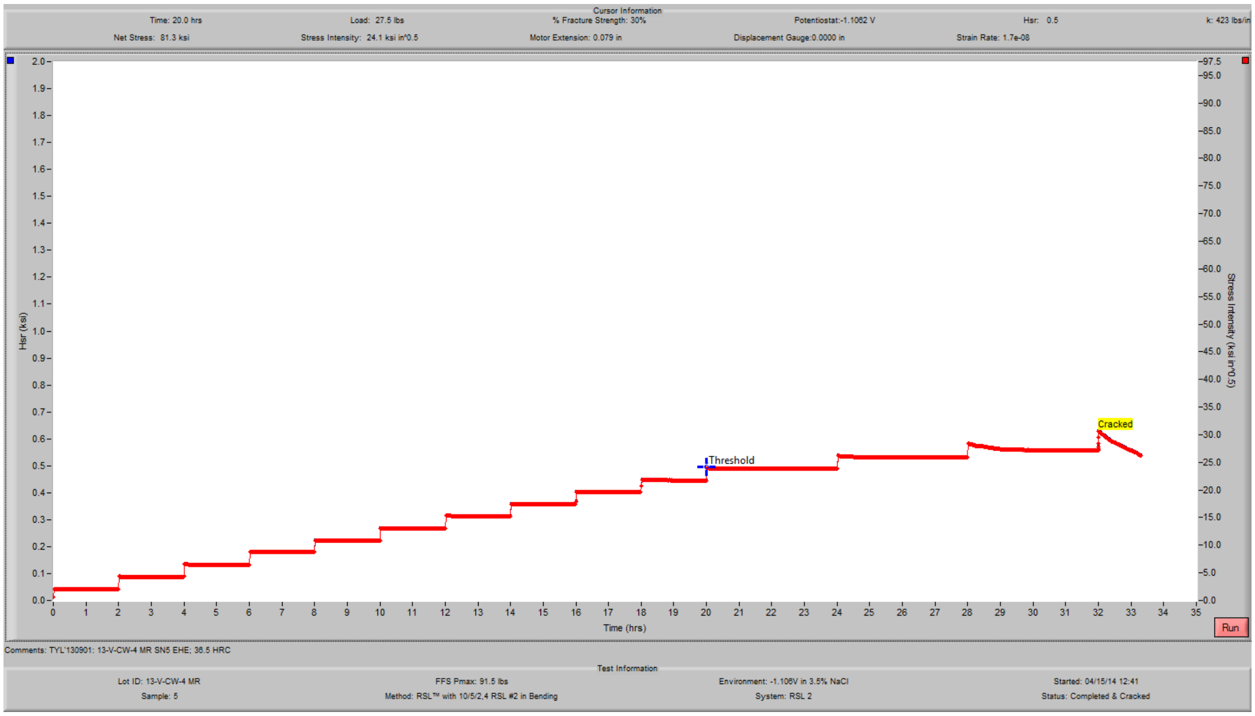


Figure S.5-12: Rod 13-V-CW-4 MR 5, Graphical EHE Results

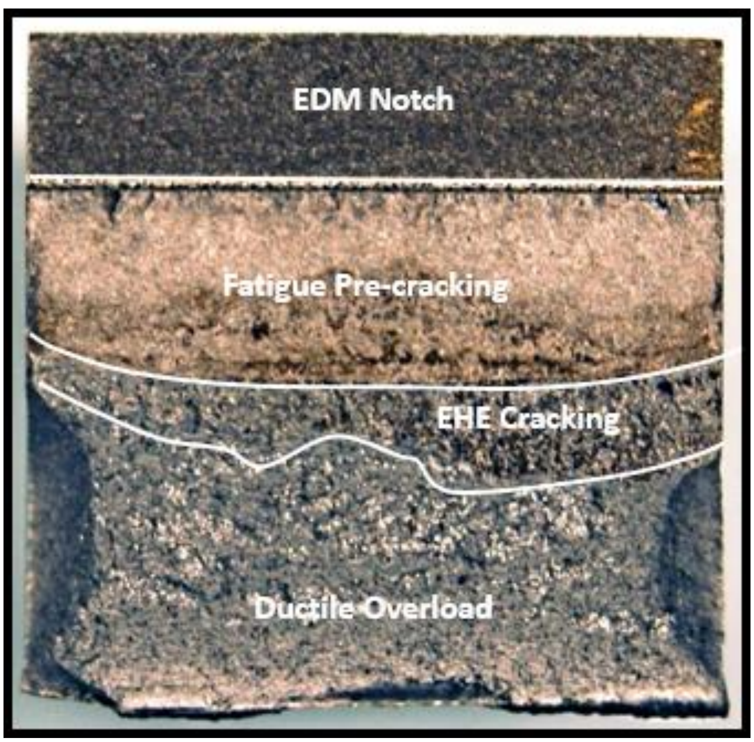


Figure S.5-13: Fracture Face of Rod 13-V-CW-4 MR 5, EHE

S.5.7 MR 6, EHE:

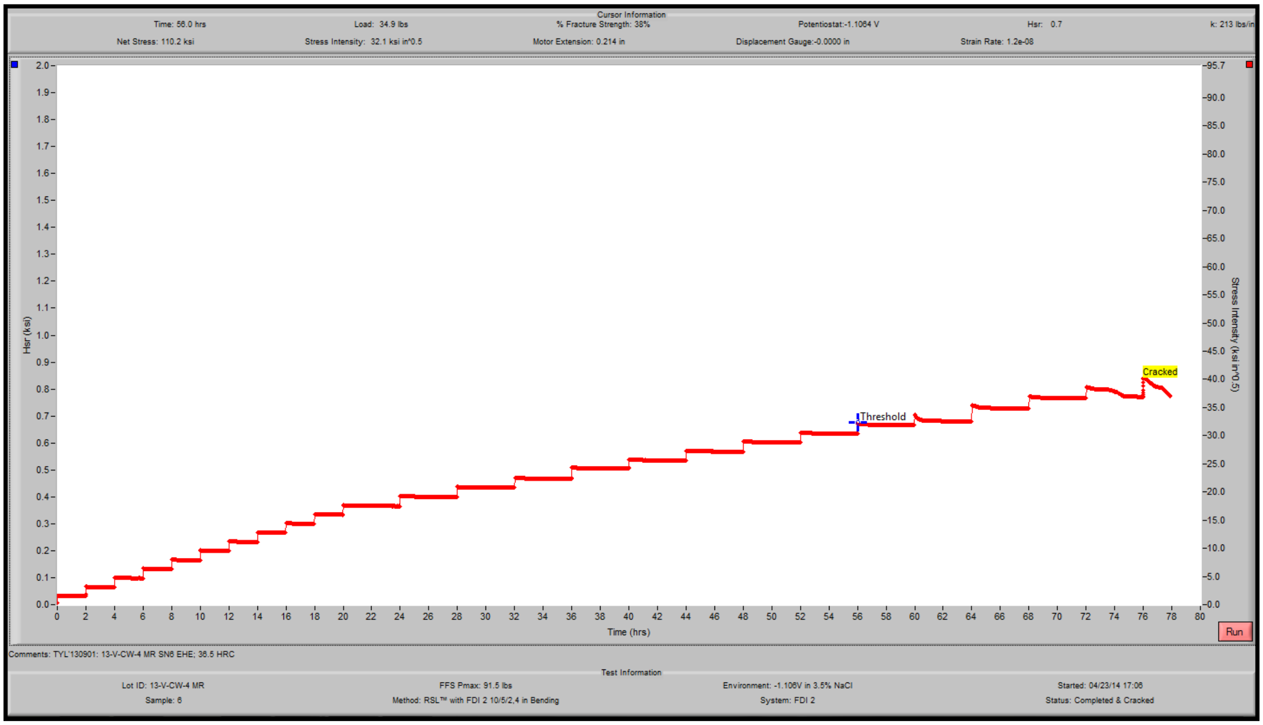


Figure S.5-14: Rod 13-V-CW-4 MR 6, Graphical EHE Results

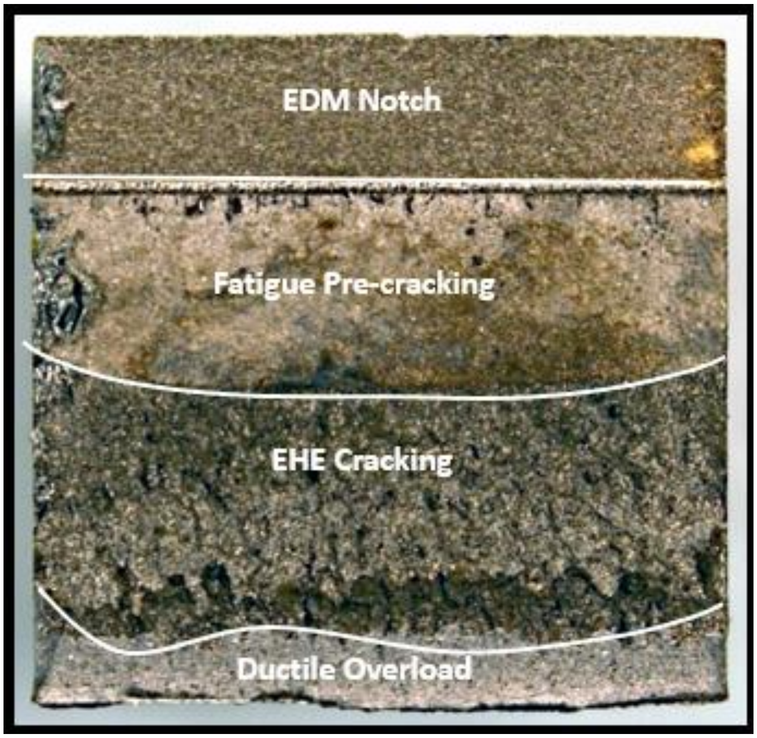


Figure S.5-15: Fracture Face of Rod 13-V-CW-4 MR 6, EHE

S.5.8 MR 7, EHE:

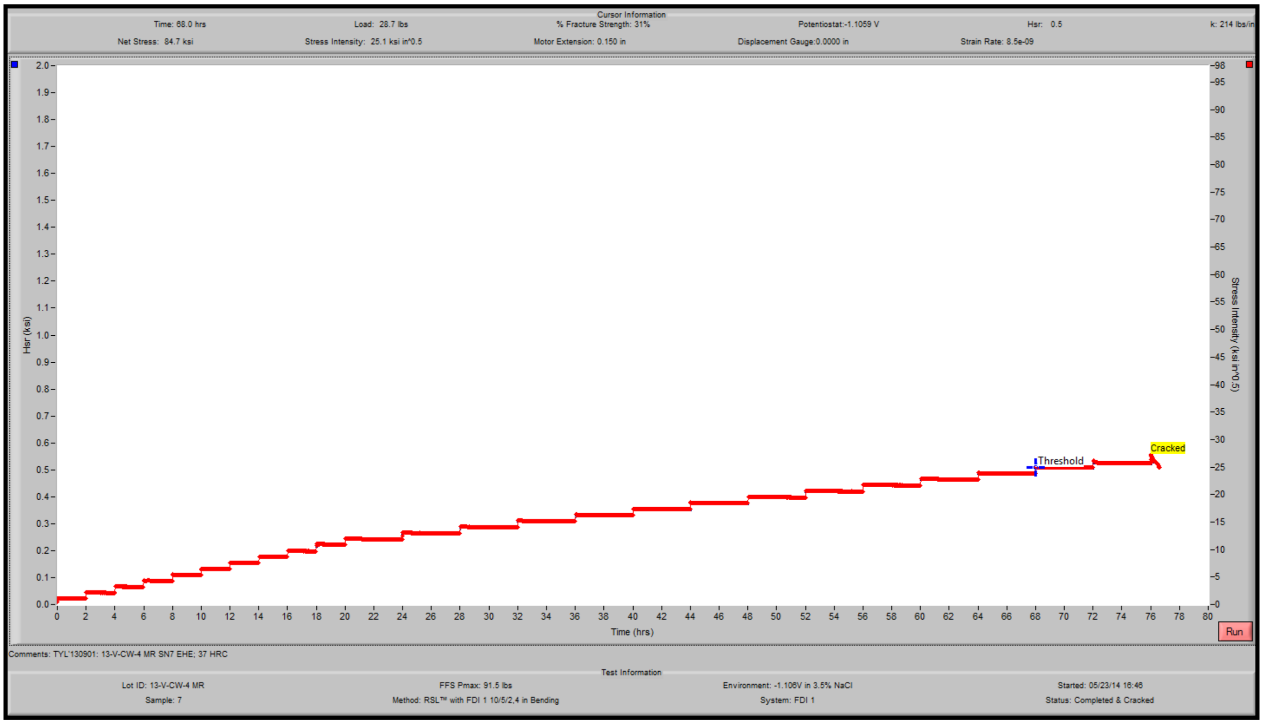


Figure S.5-16: Rod 13-V-CW-4 MR 7, Graphical EHE Results

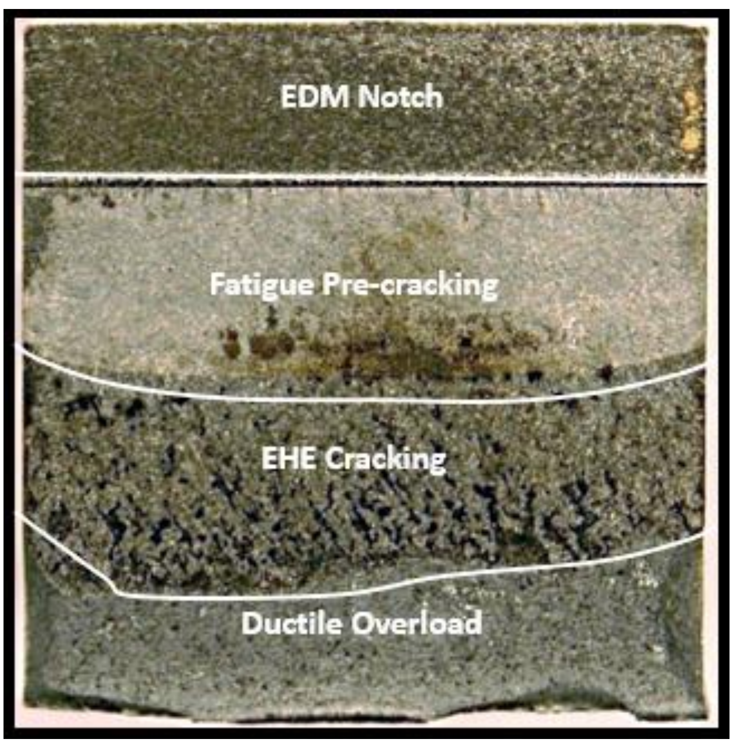


Figure S.5-17: Fracture Face of Rod 13-V-CW-4 MR 7, EHE

S.5.9 Center 1, FFS:

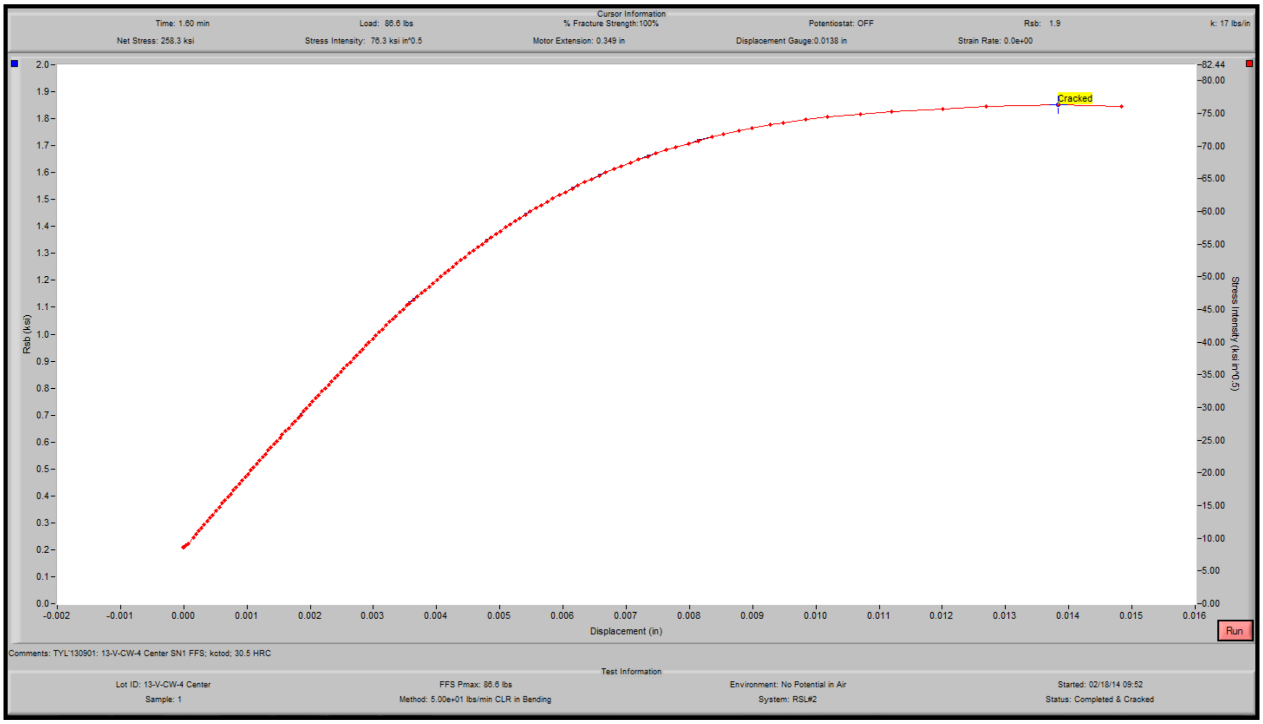


Figure S.5-18: Rod 13-V-CW-4 Center 1, Graphical FFS Results

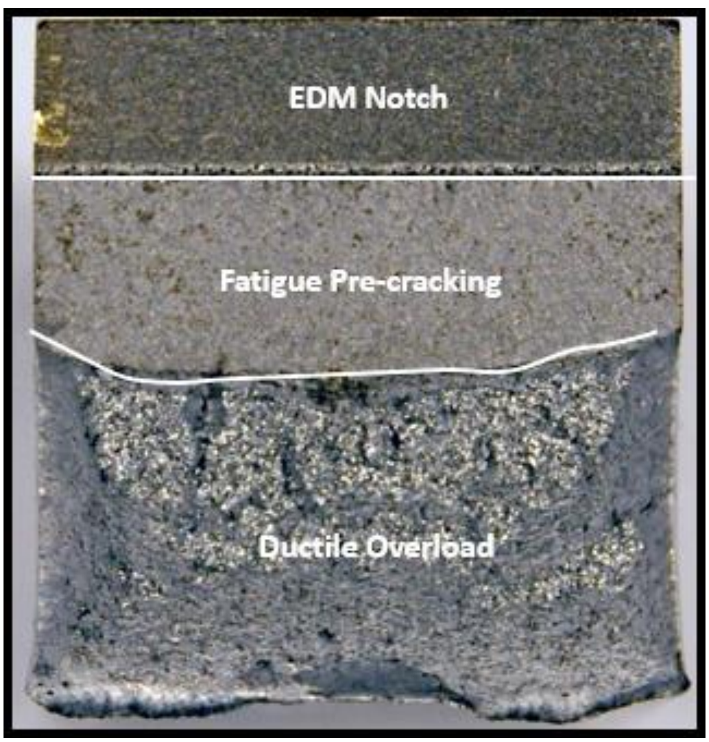


Figure S.5-19: Fracture Face of Rod 13-V-CW-4 Center 1, FFS

S.6 Threaded Specimen Test Results

S.6.1 Thd 1, FFS:

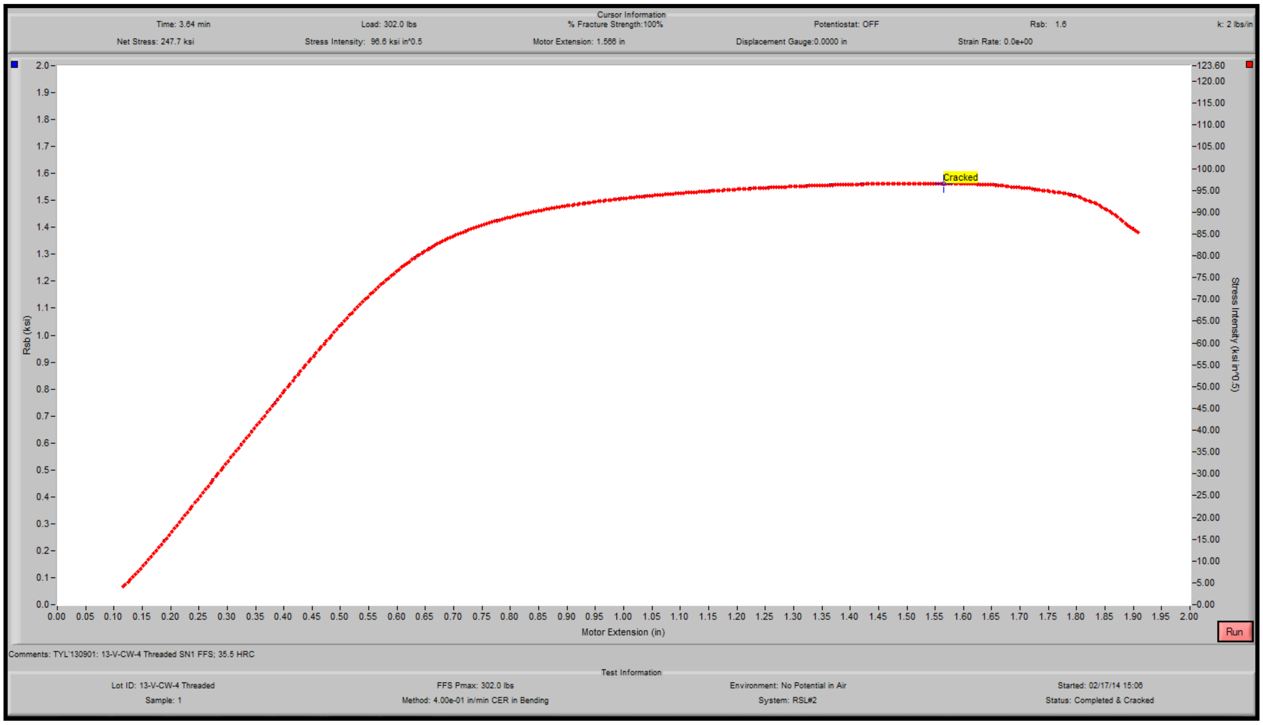


Figure S.6-1: Rod 13-V-CW-4 Thd 1, Graphical FFS Results

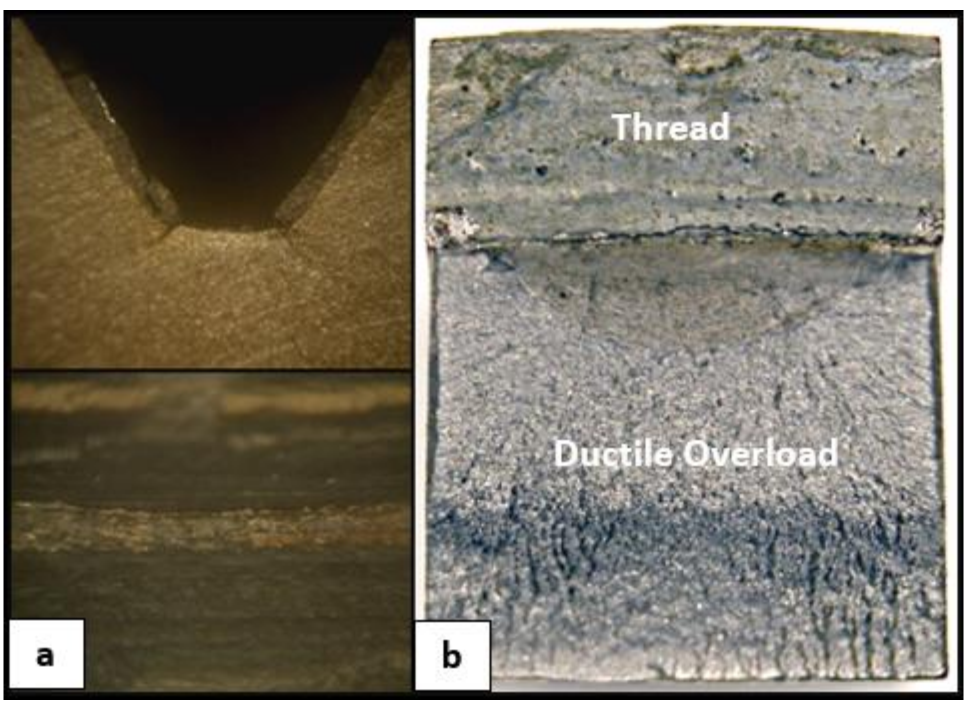


Figure S.6-2: Rod 13-V-CW-4 Thd 1 a) Thread Root Post FFS Test V and Pre-Charpy Impact and b) FFS Fracture Face

S.6.2 Thd 3, EHE:

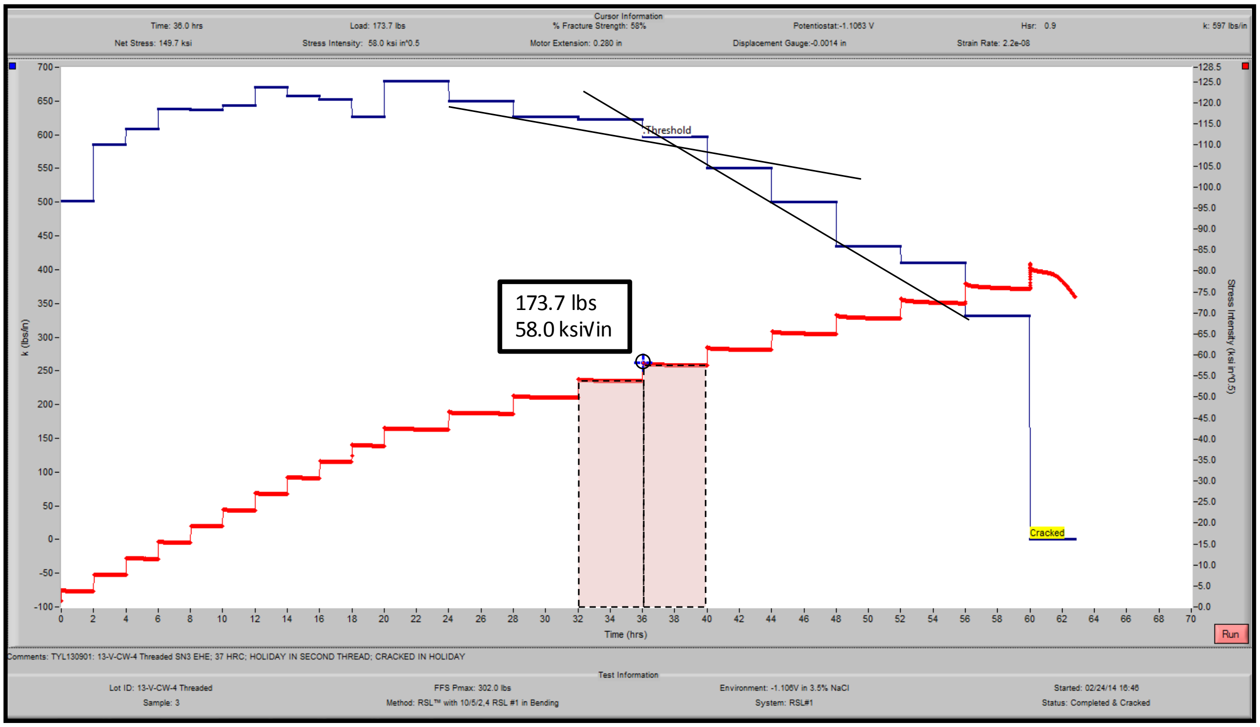


Figure S.6-3: Rod 13-V-CW-4 Thd 3, Graphical EHE Results

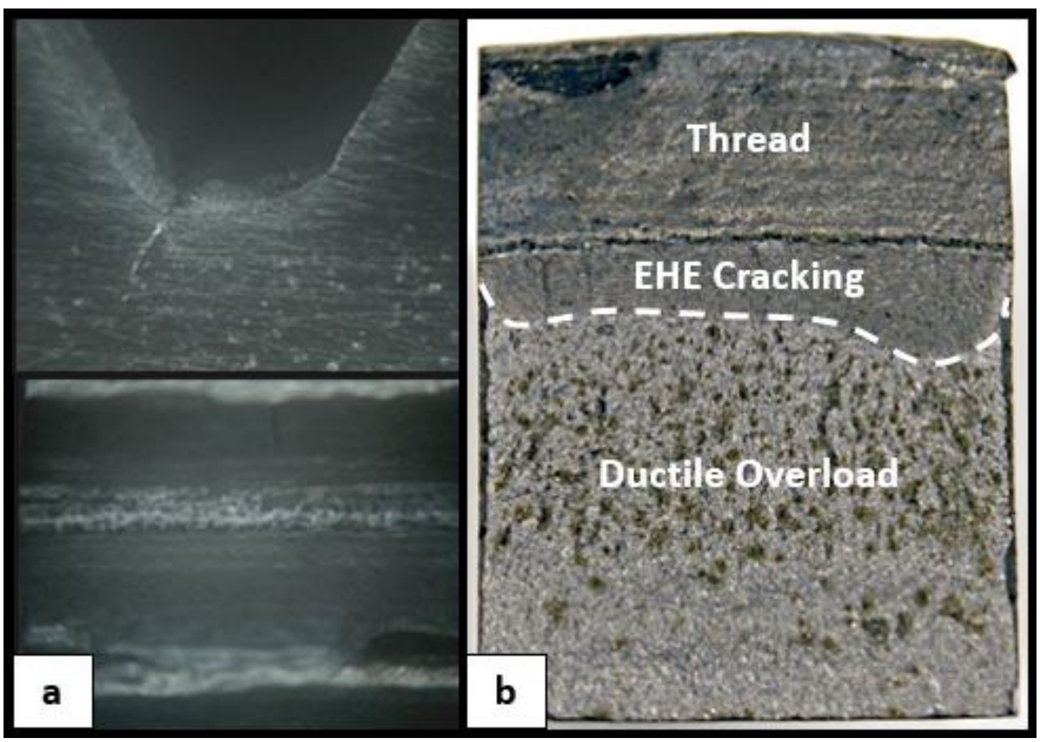


Figure S.6-4: Rod 13-V-CW-4 Thd 3 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

S.6.3 Thd 4, EHE:

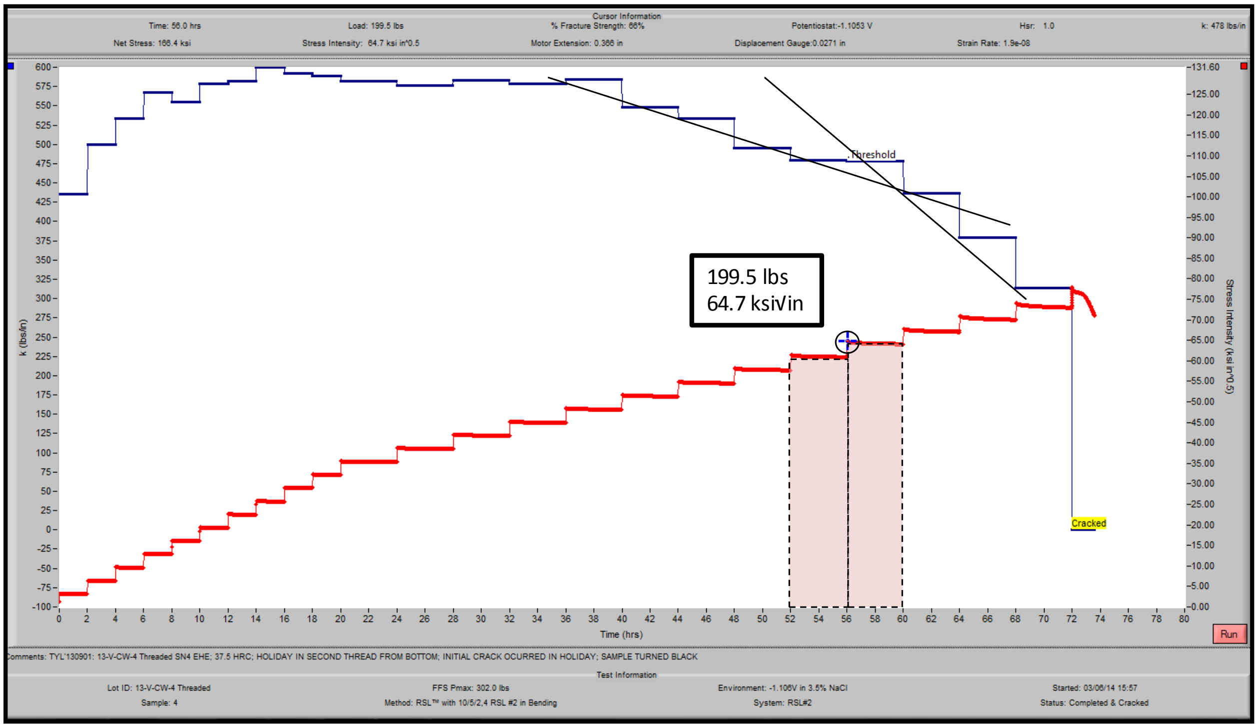


Figure S.6-5: Rod 13-V-CW-4 Thd 4, Graphical EHE Results

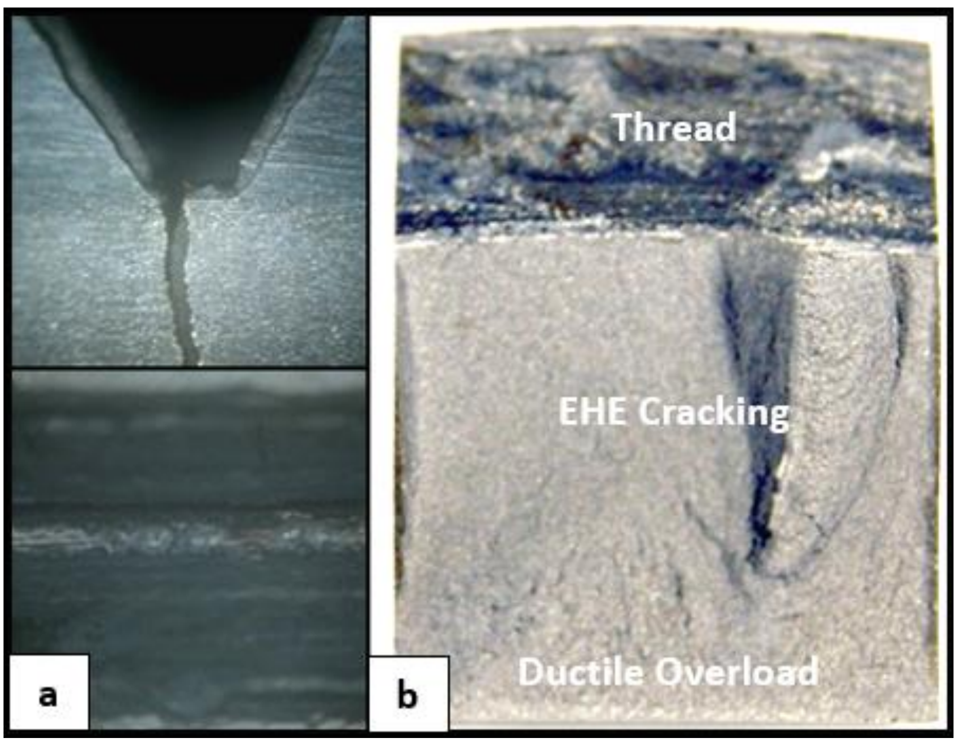


Figure S.6-6: Rod 13-V-CW-4 Thd 4 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Appendix T: Rod Remnant B1-F4

T.1 Description of Sample

The Remnant B1-F4 test specimens were taken from the unstressed portion above the nut of the rod tested in Test Rig 1 in Test IV. The specimens were used to specify a design limit at the zinc potential and verify the results of Test IV.

T.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod Remnant B1-F4 and can be seen versus time in **Figure T.2-1**. The final OCP recorded for Rod Remnant B1-F4 was Vsce=-0.902 V.

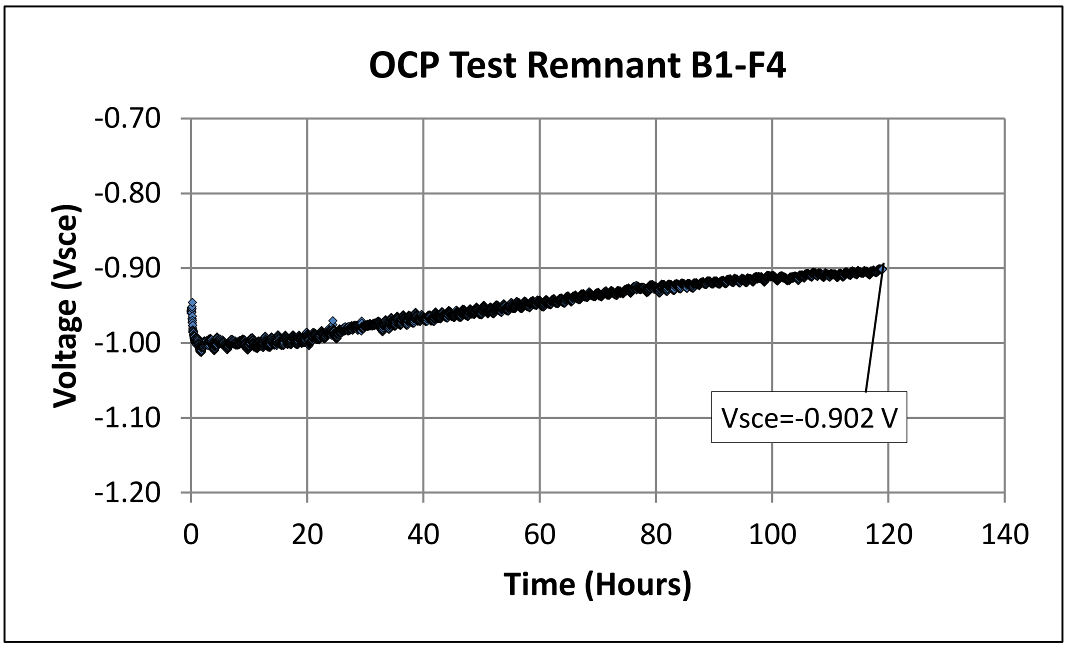


Figure T.2-1: Open Circuit Potential for Rod Remnant B1-F4

T.3 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" table.

T.3.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Remnant ID # B1-F4					
LRA Job No.:	**TYL130901**	**Structural Components:** Pier E2 Bearing Bolts (Spare)			
Rod#:	**B1-F4**				
Product Form:	**1e**	**Comments:** Machined Threads			
Rod OD:	**3"**	Dead End of Rod from Test Rig #1 in Test IV			
	Sample #/ID	**HRC**		**P-FFS**	**P-EHE**
Threaded	**Thd 1, FFS**	**36**	Pmax* (lbs)	341.2	
			Fu	1.12	
			Rsb	1.5	
			Strain Rate ($x10^{-8}$ in/in/sec)	3000	
	Thd 5, EHE	**36.5**	$P_{threshold}$* (lbs)		210.9
			Fu		0.69
			Hsr		0.9
			Strain Rate ($x10^{-8}$ in/in/sec)		1.2

T.3.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Remnant ID # B1-F4
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**B1-F4**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	Thd 1, FFS	Air	36	162	413.0	413.0	413.0	100.0%	99.5	0.62	236.9	1.5	3000	0.4 in/min	341.2	1.12	
	Thd 5, EHE	3.5% NaCl @ -1.106V	36.5	164	300.0	285.5	209.0	61.8%	61.5	0.37	153.8	0.9	1.2	10/5/1,8	210.9	0.69	Did Not Crack In Holiday

T.4 Threaded Specimen Test Results

T.4.1 Thd 1, FFS:

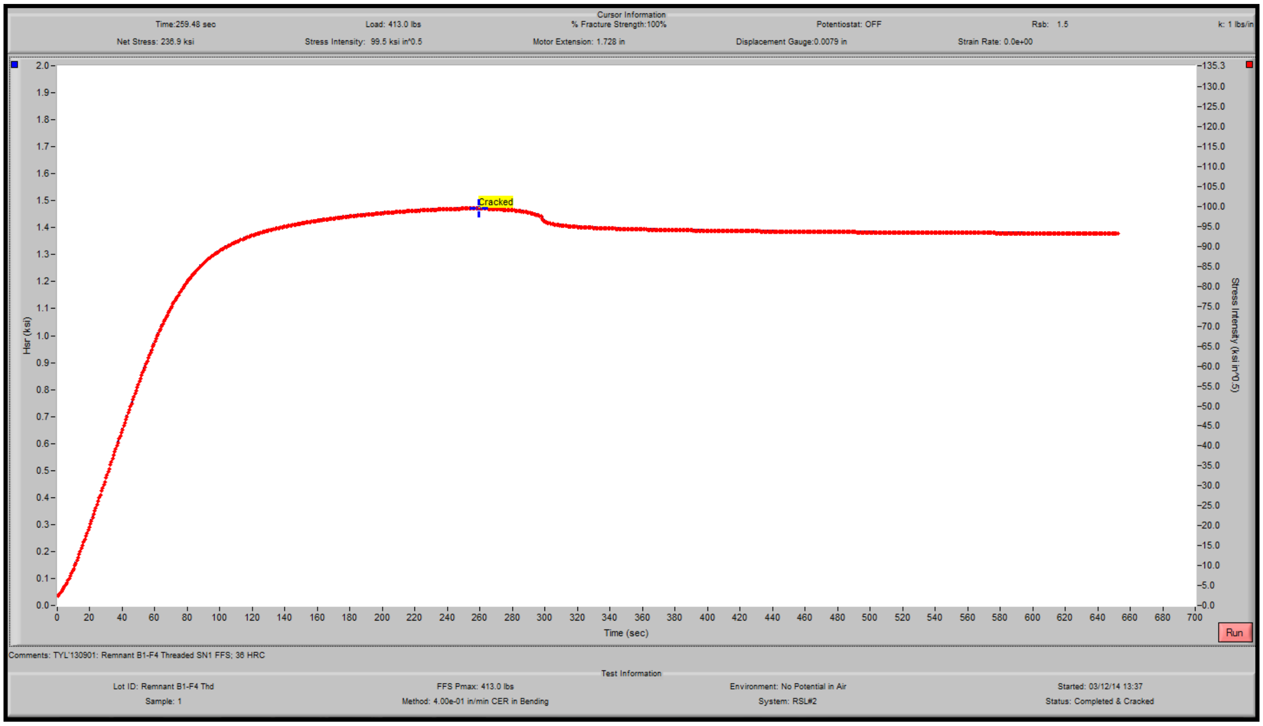


Figure T.4-1: Rod Remnant B1-F4 Thd 1, Graphical FFS Results

Figure T.4-2: Rod Remnant B1-F4 Thd 1 FFS Fracture Face

T.4.2 Thd 5, EHE:

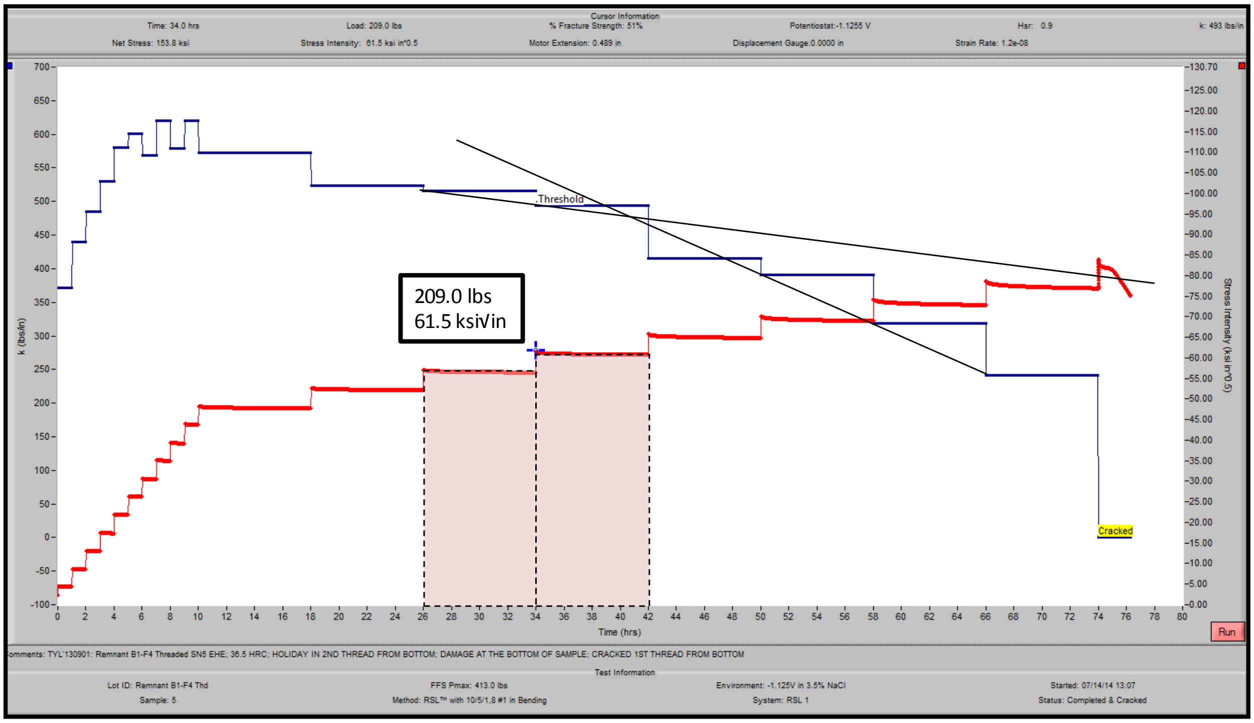


Figure T.4-3: Rod Remnant B1-F4 Thd 5, Graphical EHE Results

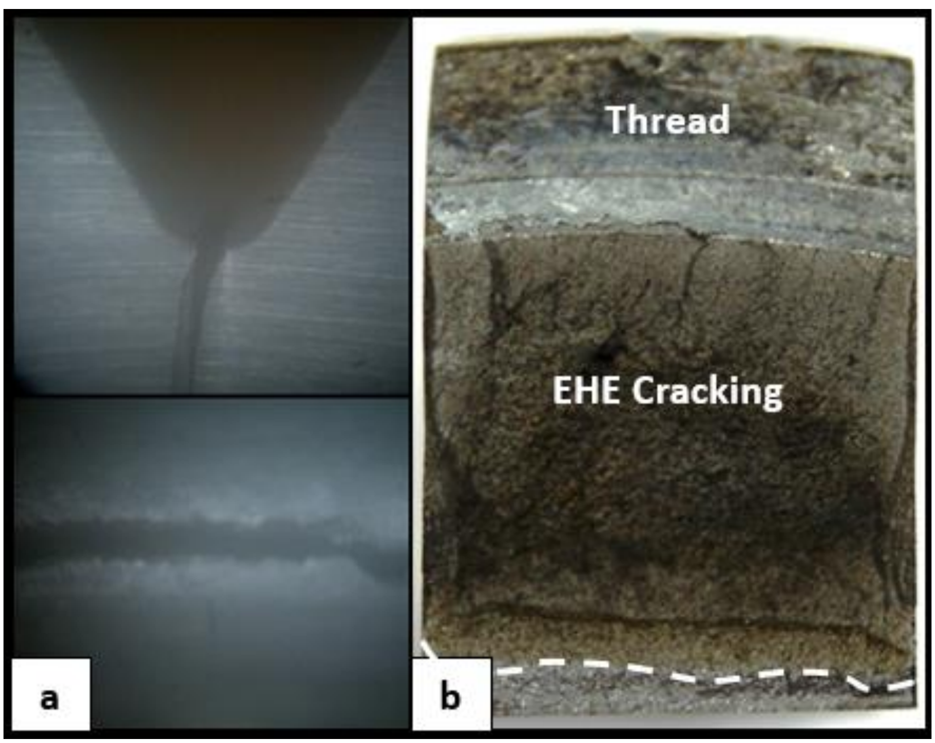


Figure T.4-4: Rod Remnant B1-F4 Thd 5 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Appendix U: Rod Remnant B2-F5

U.1 Description of Sample

The Remnant B2-F5 test specimens were taken from the unstressed portion above the nut of the rod tested in Test Rig 2 in Test IV. The specimens were used to specify a design limit at the zinc potential and verify the results of Test IV.

U.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod Remnant B2-F5 and can be seen versus time in **Figure U.2-1**. The final OCP recorded for Rod Remnant B2-F5 was Vsce=-0.886 V.

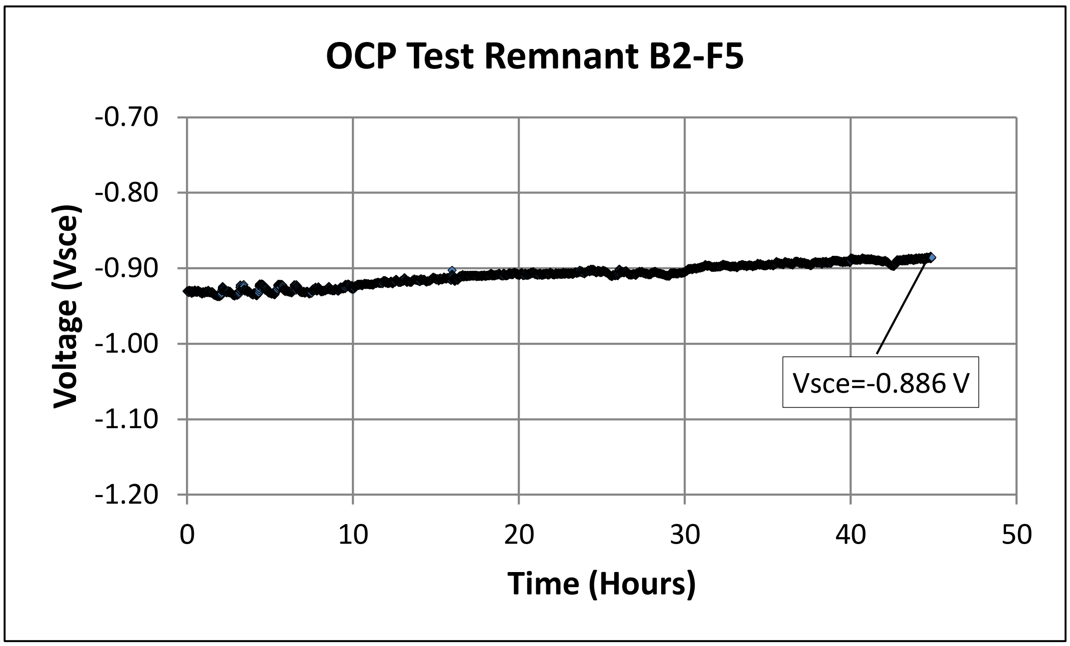


Figure U.2-1: Open Circuit Potential for Rod Remnant B2-F5

U.3 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following “checker board” table.

U.3.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Remnant ID # B2-F5					
LRA Job No.:	**TYL130901**	**Structural Components:** Pier E2 Bearing Bolts (Spare) **Comments:** Machined Threads Dead End of Rod from Test Rig #2 in Test IV			
Rod #:	**B2-F5**				
Product Form:	**1e**				
Rod OD:	**3"**				
	Sample #/ID	**HRC**		**P-FFS**	**P-EHE**
Threaded	**Thd 1, FFS**	**36.0**	Pmax* (lbs)	335.4	
			Fu	1.10	
			Rsb	1.5	
			Strain Rate ($x10^{-8}$ in/in/sec)	3500	
	Thd 3, EHE	**35.5**	$P_{threshold}$* (lbs)		217.8
			Fu		0.72
			Hsr		0.9
			Strain Rate ($x10^{-8}$ in/in/sec)		1.8
	Thd 5, EHE	**36.0**	$P_{threshold}$* (lbs)		253.1
			Fu		0.83
			Hsr		1.1
			Strain Rate ($x10^{-8}$ in/in/sec)		1.1

U.3.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Remnant ID # B2-F5
RSL™ (B) 4-pt Bend Test

LRA Job No.:	TYL130901
Rod #:	B2-F5
Product Form:	1e
Rod OD:	3"

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	$\delta\varepsilon/\delta t$ $(10^{-8}s^{-1})$	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	Thd 1, FFS	Air	36.0	162	375.0	375.0	375.0	100.0%	97.8	0.60	240.1	1.5	3500	0.4 in/min	335.4	1.10	
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.5	159	302.0	317.1	285.6	64.9%	63.5	0.40	148.6	0.9	1.8	10/5/2,4	217.8	0.72	Did Not Crack In Holiday
	Thd 5, EHE	3.5% NaCl @ -1.106V	36.0	162	270.0	270.4	254.9	75.5%	73.8	0.46	183.1	1.1	1.1	10/5/1,8	253.1	0.83	Did Crack in Holiday. Kept Visual Threshold.

U.4 Threaded Specimen Test Results

U.4.1 Thd 1, FFS:

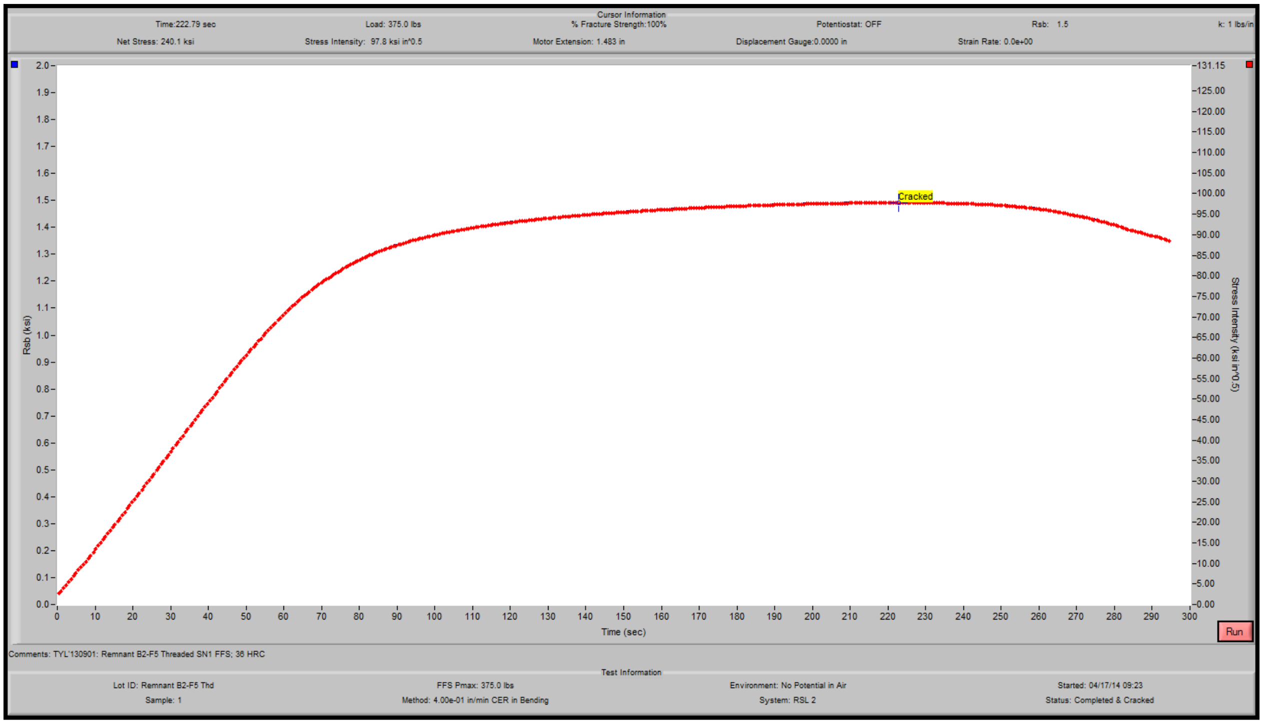


Figure U.4-1: Rod Remnant B2-F5 Thd 1, Graphical FFS Results

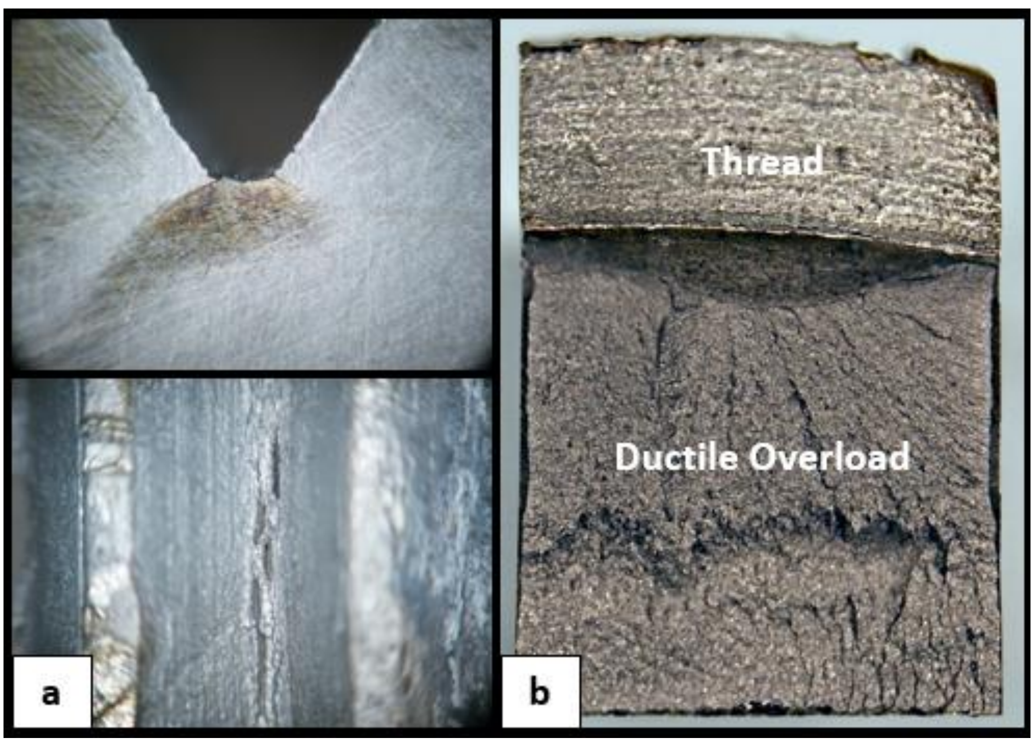


Figure U.4-2: Rod Remnant B2-F5 Thd 1 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

U.4.2 Thd 3, EHE:

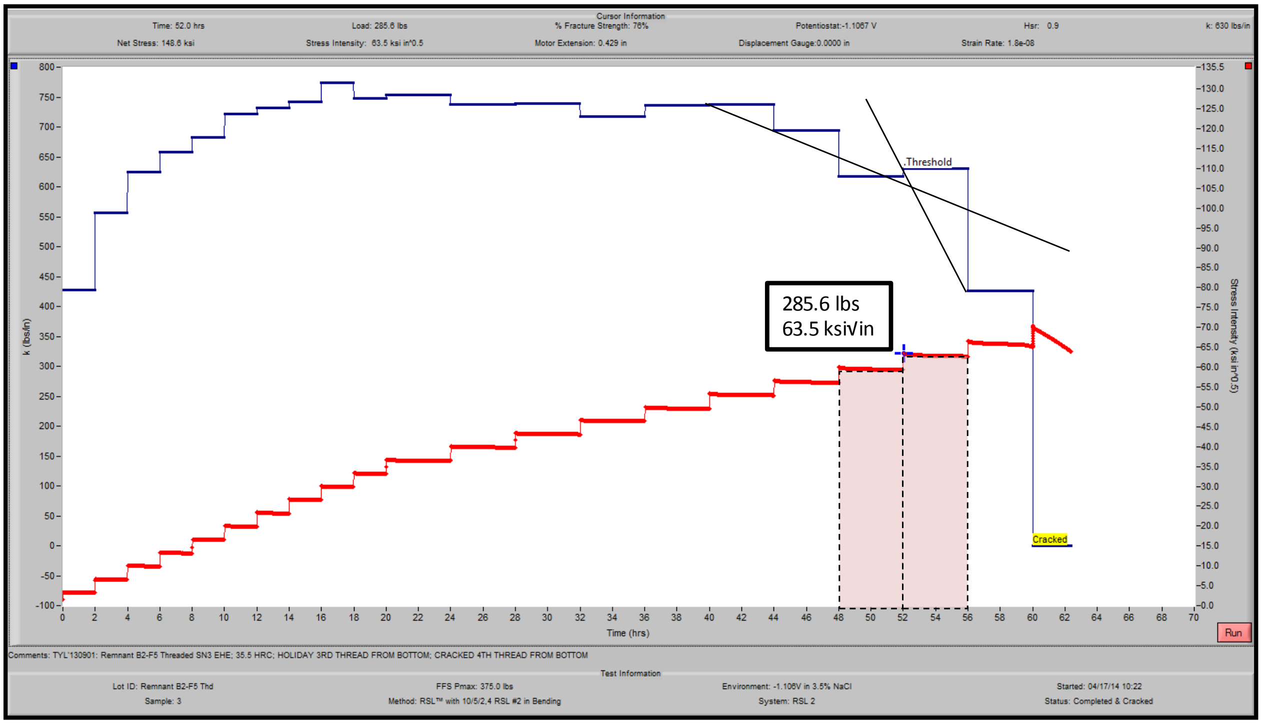


Figure U.4-3: Rod Remnant B2-F5 Thd 3, Graphical EHE Results

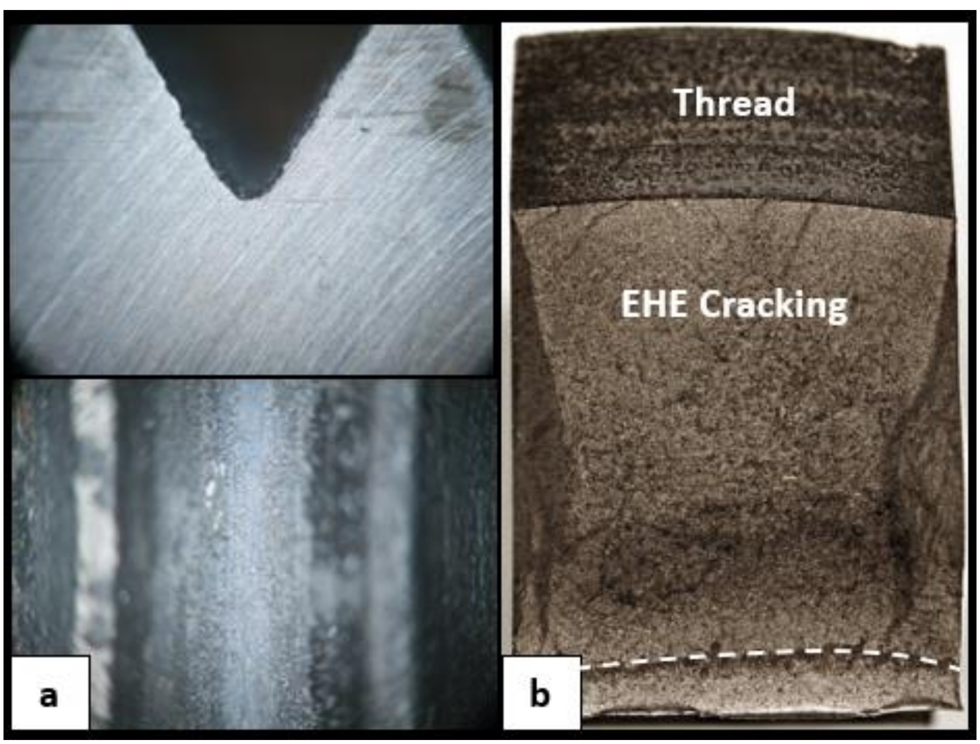


Figure U.4-4: Rod Remnant B2-F5 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

U.4.3 Thd 5, EHE:

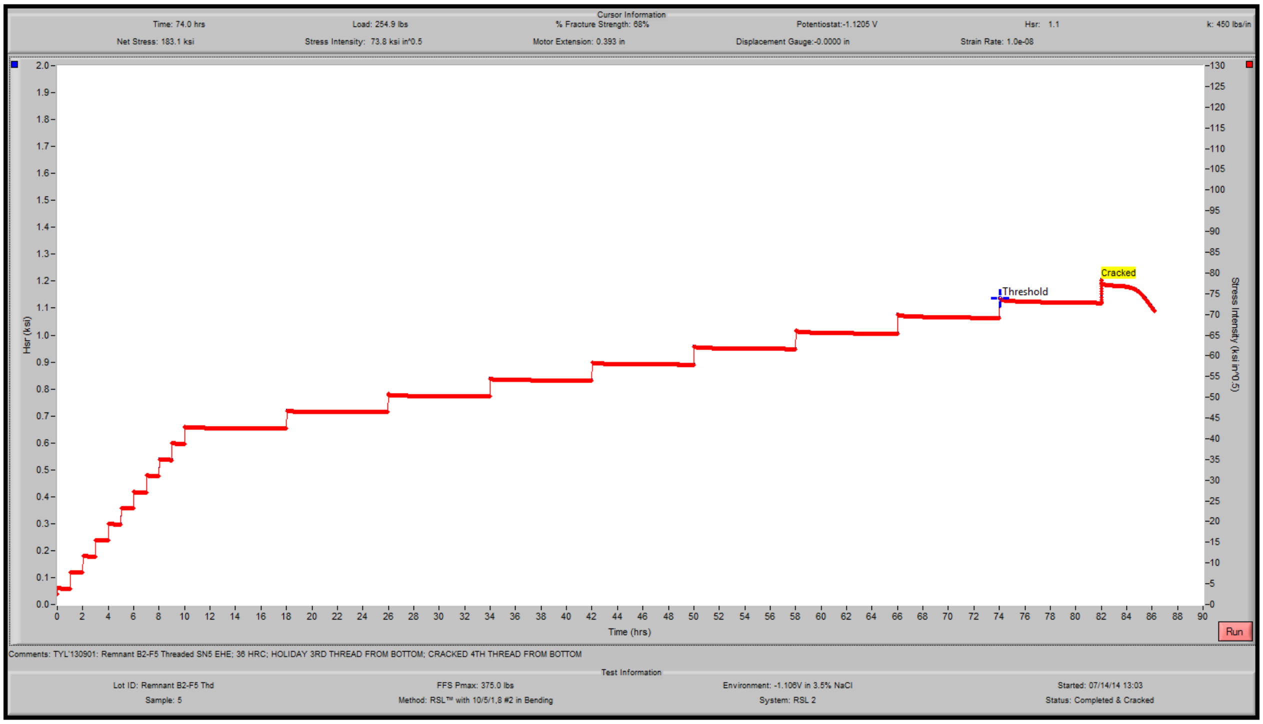


Figure U.4-5: Rod Remnant B2-F5 Thd 5, Graphical EHE Results

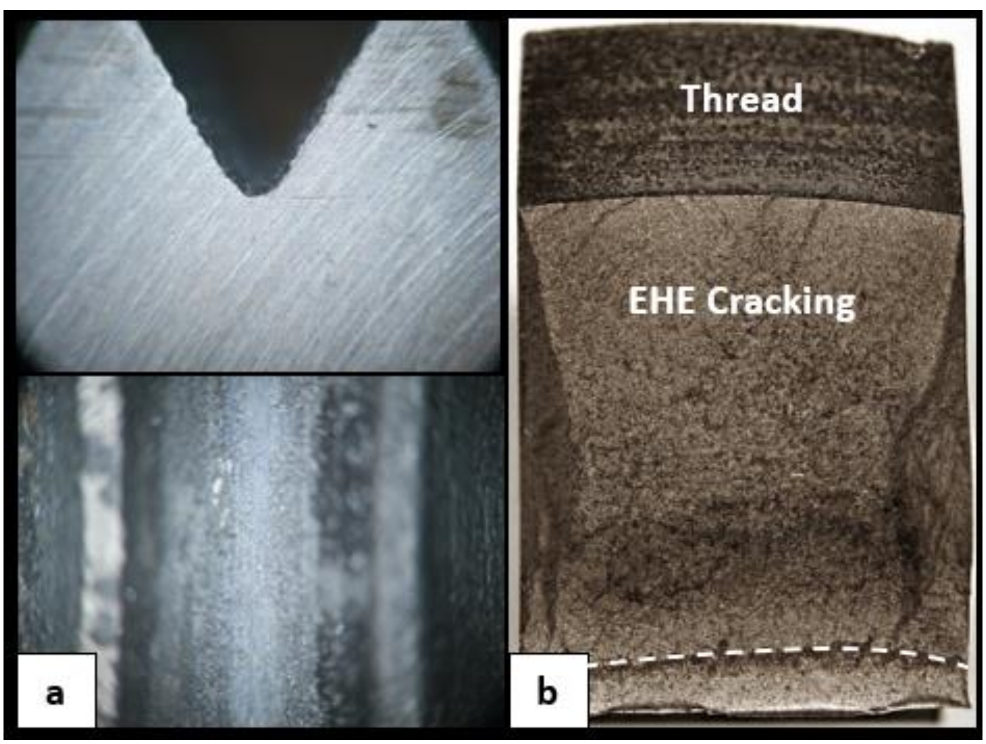


Figure U.4-6: Rod Remnant B2-F5 Thd 5 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix V: Rod Remnant S3-D2

V.1 Description of Sample

The Remnant S3-D2 test specimens were taken from the unstressed portion above the nut of the rod tested in Test Rig 3 in Test IV. The specimens were used to specify a design limit at the zinc potential and verify the results of Test IV.

V.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod Remnant S3-D2 and can be seen versus time in **Figure V.2-1**. The final OCP recorded for Rod Remnant S3-D2 was Vsce=-0.817 V.

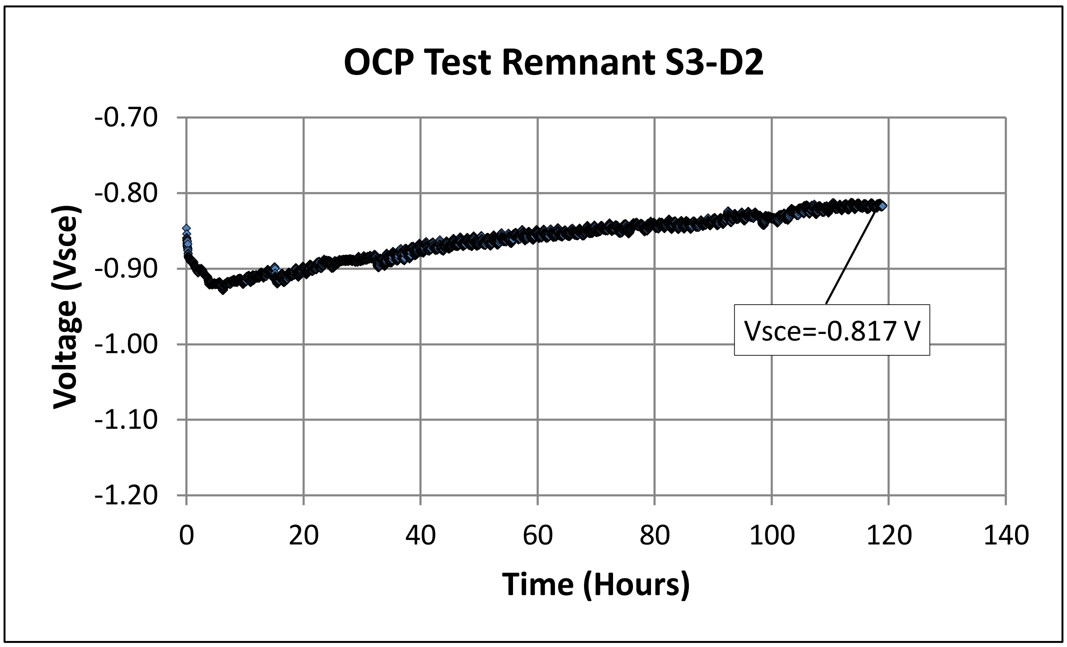


Figure V.2-1: Open Circuit Potential for Rod Remnant S3-D2

V.3 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" table.

V.3.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Remnant ID # S3-D2					
LRA Job No.:	**TYL130523**	**Structural Components:** Pier E2 Shear Key Bolts (Spare) **Comments:** Machined Threads Dead End of Rod from Test Rig #3 in Test IV			
Rod#:	**S3-D2**				
Product Form:	**1e**				
Rod OD:	**3"**				
	Sample #/ID	**HRC**		**P-FFS**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.5**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	338.5 1.12 1.5 3200	
	Thd 3, EHE	**36**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		222.9 0.73 1.0 2.5
	Thd 4, EHE	**36**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)		224.3 0.74 1.0 2.0

V.3.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Remnant ID # S3-D2
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130523**
Rod #:	**S3-D2**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $KI_{P\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	Thd 1, FFS	Air	35.5	159	369.9	369.9	369.9	100.0%	98.7	0.62	242.3	1.5	3200	0.4 in/min	338.5	1.12	
	Thd 3, EHE	3.5% NaCl @ -1.106V	36.0	162	290.0	275.6	216.5	65.9%	65.0	0.40	164.6	1.0	2.5	10/5/2,4	222.9	0.73	Did Crack In Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	36.0	162	250.0	300.1	224.0	66.3%	65.4	0.40	164.1	1.0	2	10/5/2,4	224.3	0.74	Did Not Crack in Holiday

V.4 Threaded Specimen Test Results

V.4.1 Thd 1, FFS:

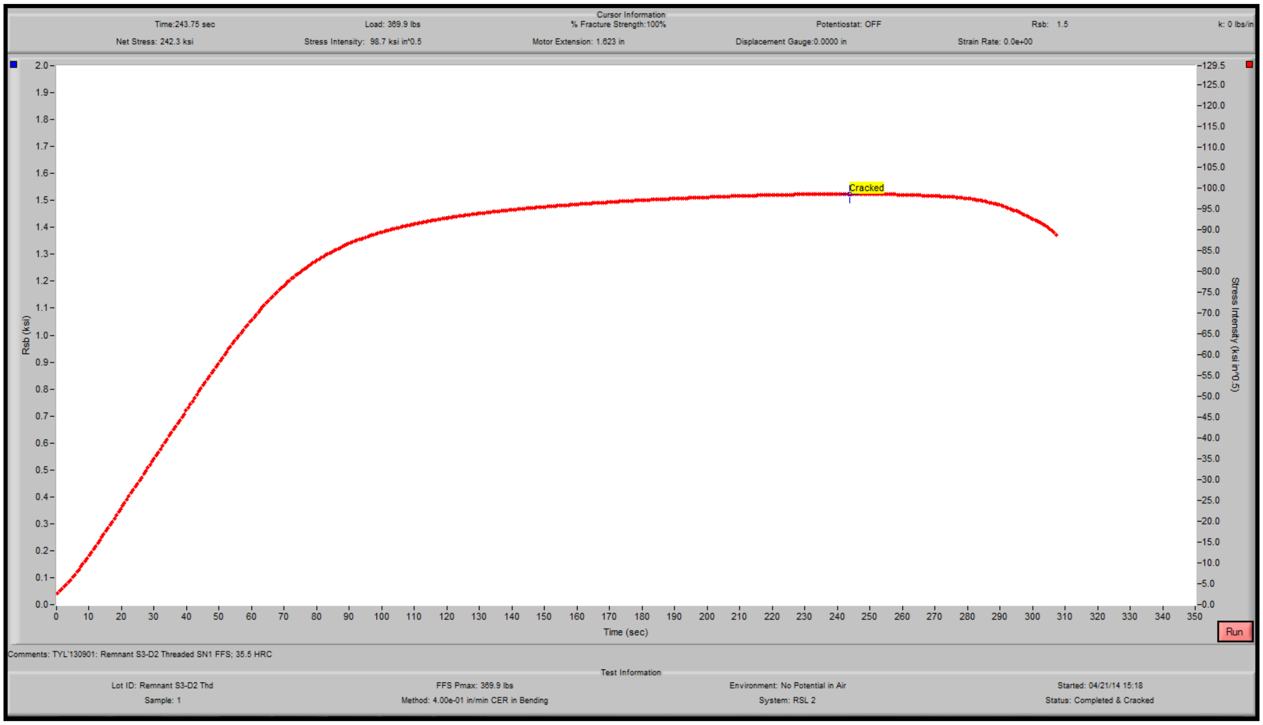


Figure V.4-1: Rod Remnant S3-D2 Thd 1, Graphical FFS Results

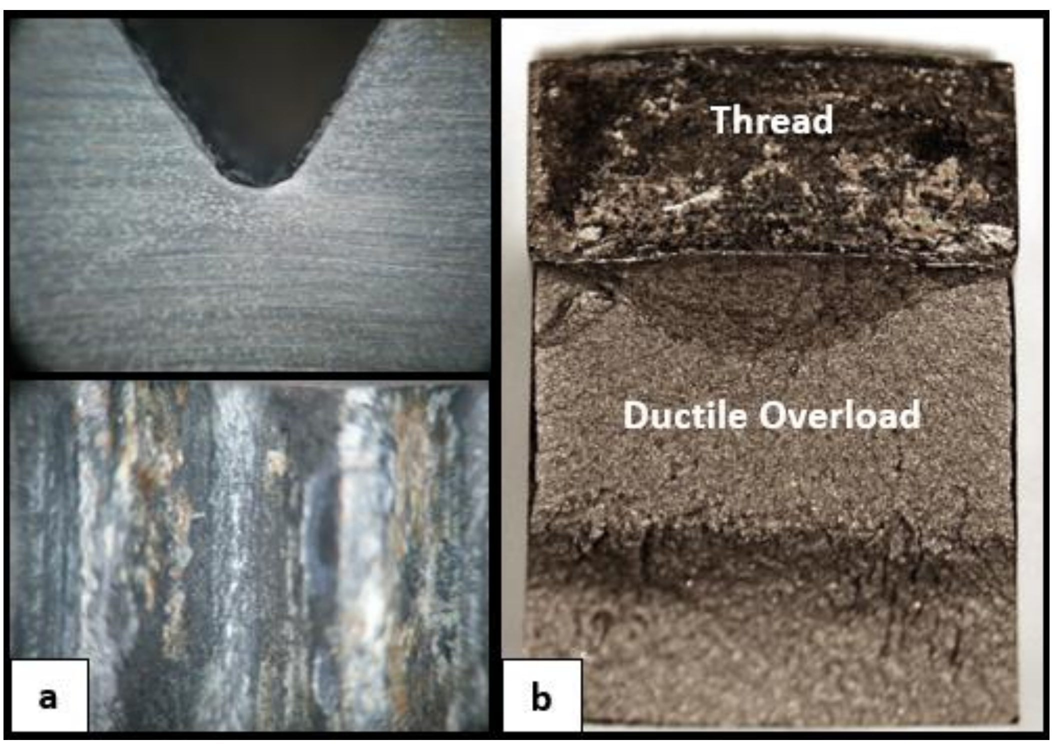


Figure V.4-2: Rod Remnant S3-D2 Thd 1 a) Thread Root from Side and Normal Views Post EHE Test and b) FFS Fracture Face

V.4.2 Thd 3, EHE:

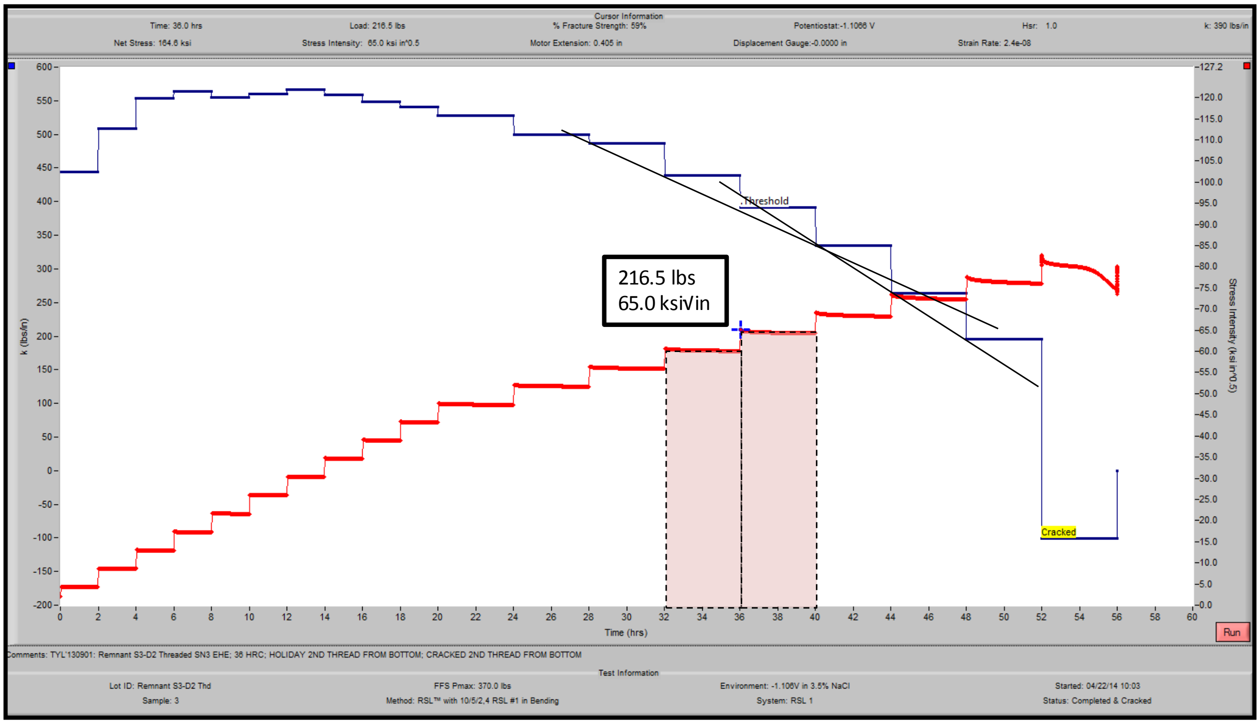


Figure V.4-3: Rod Remnant S3-D2 Thd 3, Graphical EHE Results

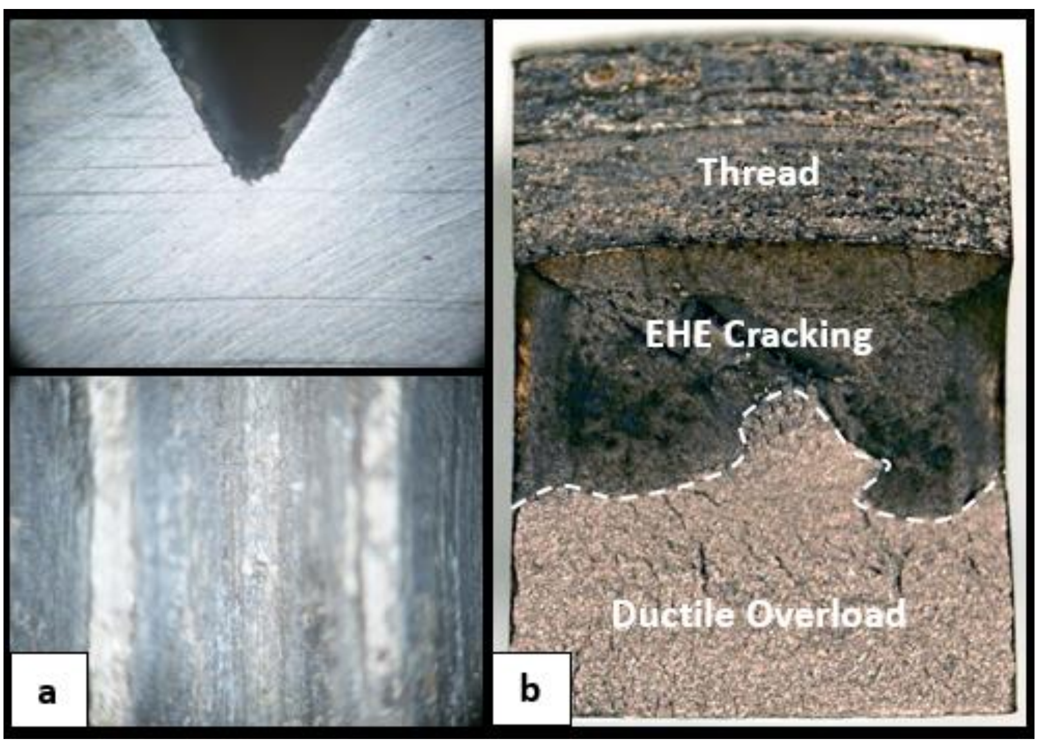


Figure V.4-4: Rod Remnant S3-D2 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

V.4.3 Thd 4, EHE:

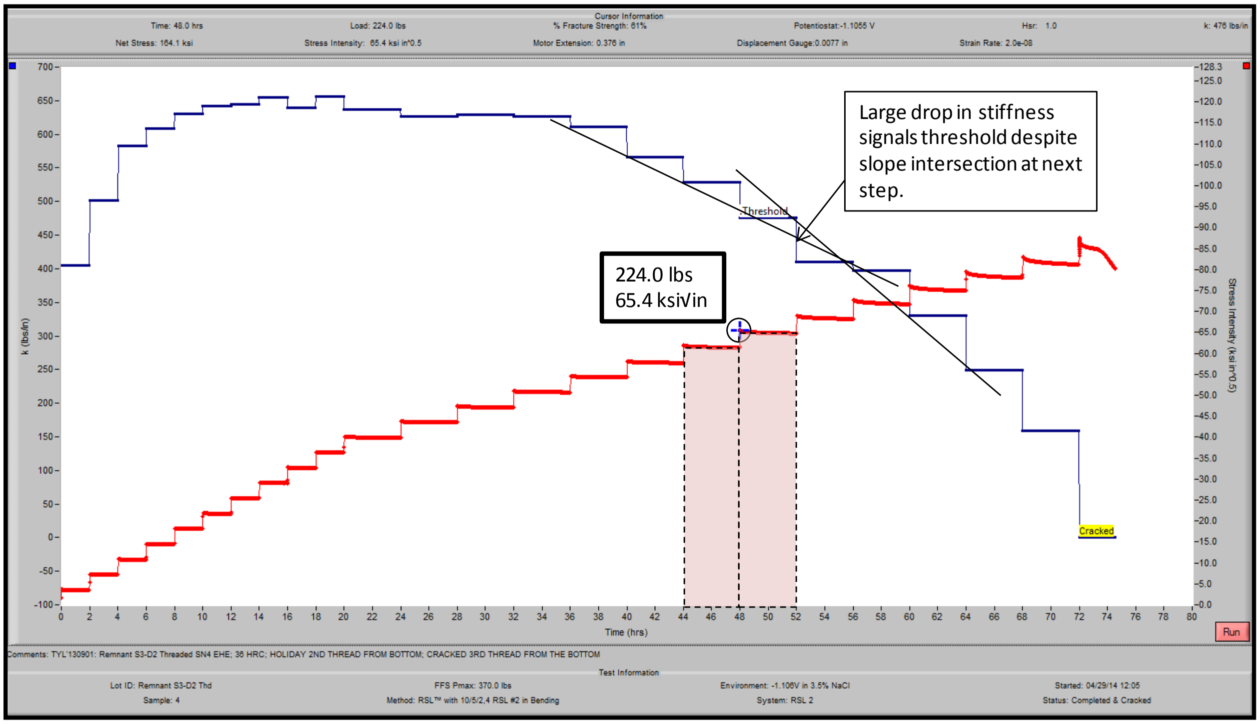


Figure V.4-5: Rod Remnant S3-D2 Thd 4, Graphical EHE Results

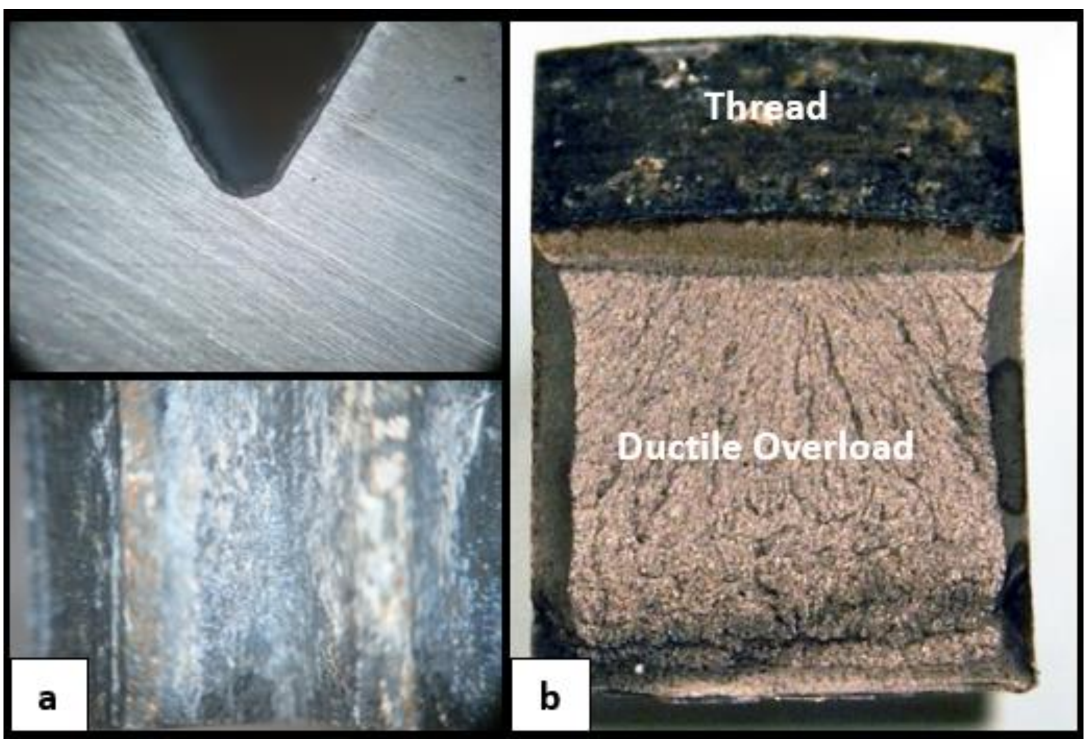


Figure V.4-6: Rod Remnant S3-D2 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

Appendix W: Rod Remnant S4-E2

W.1 Description of Remnants

The Remnant S4-E2 test specimens were taken from the unstressed portion above the nut of the rod tested in Test Rig 4 in Test IV. The specimens were used to specify a design limit at the zinc potential and verify the results of Test IV.

W.2 Open Circuit Potential

The Open Circuit Potential (OCP) was recorded for Rod Remnant S4-E2 and can be seen versus time in **Figure W.2-1**. The final OCP recorded for Rod Remnant S4-E2 was Vsce=-1.009 V.

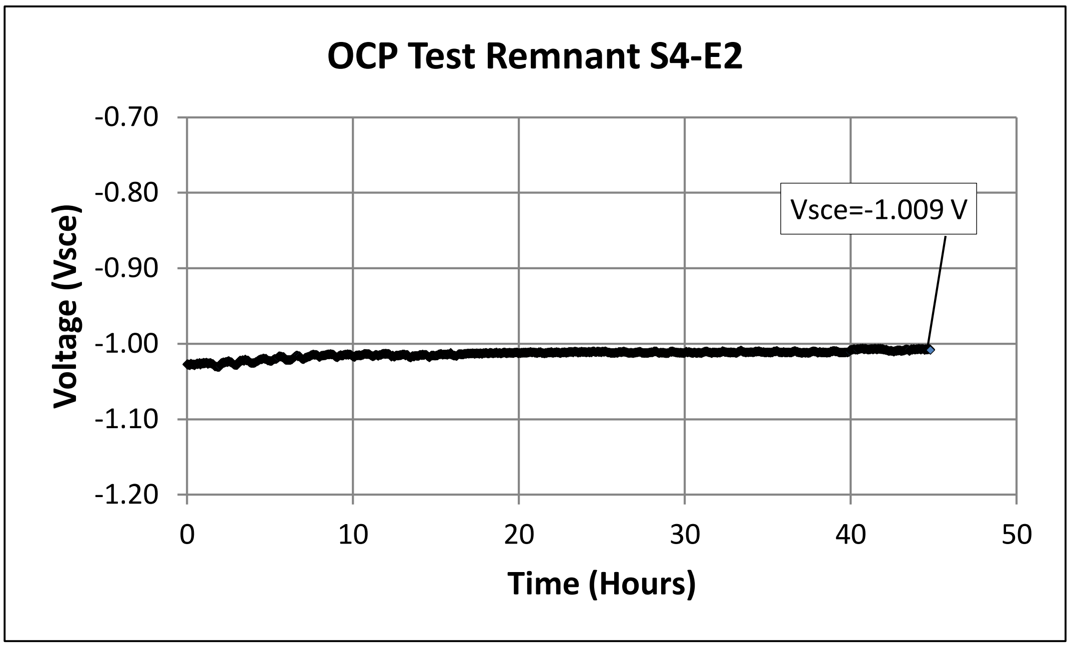


Figure W.2-1: Open Circuit Potential for Rod Remnant S4-E2

W.3 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" table.

W.3.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Remnant ID # S4-E2					
LRA Job No.:	**TYL130901**	**Structural Components:** Pier E2 Shear Key Bolts (Spare) **Comments:** Machined Threads Dead End of Rod from Test Rig #4 in Test IV			
Rod#:	**S4-E2**				
Product Form:	**1e**				
Rod OD:	**3"**				
	Sample #/ID	**HRC**		**P-FFS**	**P-EHE**
Threaded	**Thd 1, FFS**	**35**	Pmax* (lbs)	314.1	
			Fu	1.03	
			Rsb	1.4	
			Strain Rate ($x10^{-8}$ in/in/sec)	2500	
	Thd 3, EHE	**35.5**	Pthreshold* (lbs)		211.9
			Fu		0.70
			Hsr		1.0
			Strain Rate ($x10^{-8}$ in/in/sec)		2.2
	Thd 4, EHE	**34.5**	Pthreshold* (lbs)		218.1
			Fu		0.72
			Hsr		1.0
			Strain Rate ($x10^{-8}$ in/in/sec)		1.9
	Thd 5, EHE	**36**	Pthreshold* (lbs)		214.0
			Fu		0.70
			Hsr		1.0
			Strain Rate ($x10^{-8}$ in/in/sec)		1.0

W.3.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Remnant ID # S4-E2
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**S4-E2**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	Thd 1, FFS	Air	35.0	157	331.3	331.3	331.3	100.0%	91.6	0.58	227.2	1.4	2500	0.4 in/min	314.1	1.03	
	Thd 3, EHE	3.5% NaCl @ -1.106V	35.5	159	273.0	323.2	217.6	67.5%	61.8	0.39	153.4	1.0	2.2	10/5/2,4	211.9	0.70	Cracked in Holiday
	Thd 4, EHE	3.5% NaCl @ -1.106V	34.5	155	240.0	288.5	226.8	69.4%	63.6	0.41	157.9	1.0	1.9	10/5/2,4	218.1	0.72	Cracked in Holiday
	Thd 5, EHE	3.5% NaCl @ -1.106V	36.0	162	240.0	240.4	215.1	68.1%	62.4	0.39	156.3	1.0	1.0	10/5/1,8	214.0	0.70	Cracked in Holiday

W.4 Threaded Specimen Test Results

W.4.1 Thd 1, FFS:

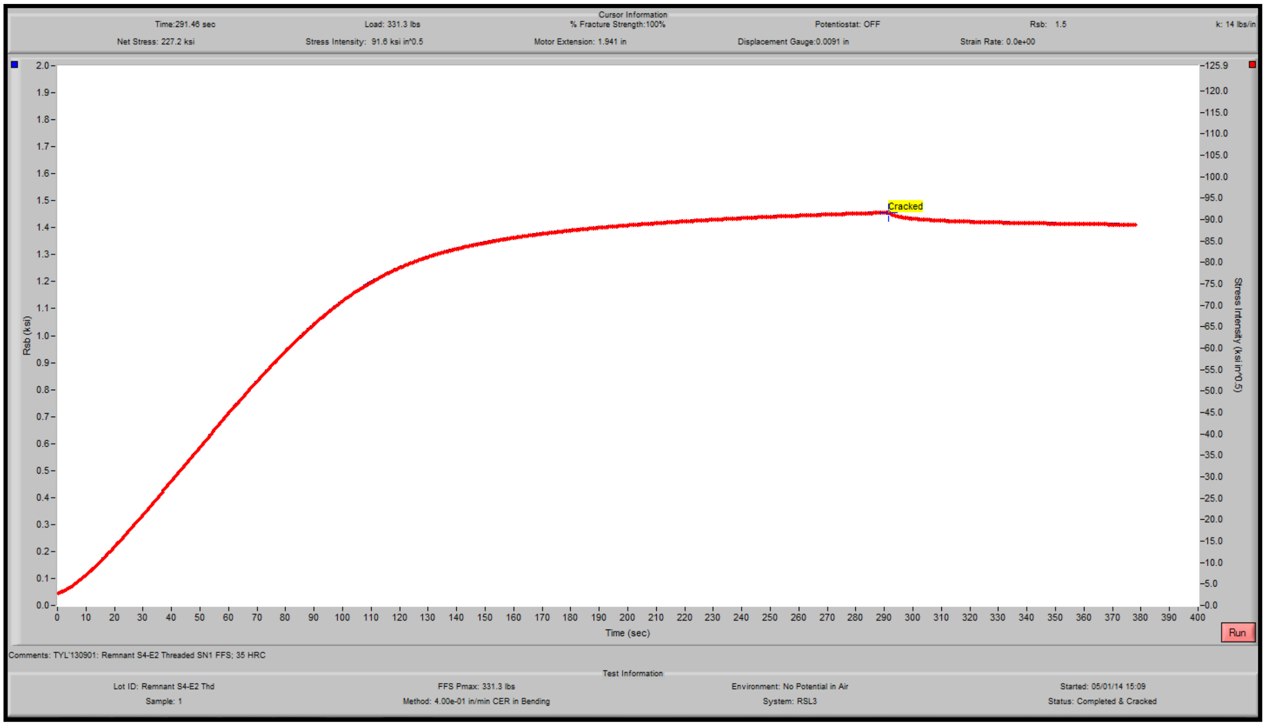


Figure W.4-1: Rod Remnant S4-E2 Thd 1, Graphical FFS Results

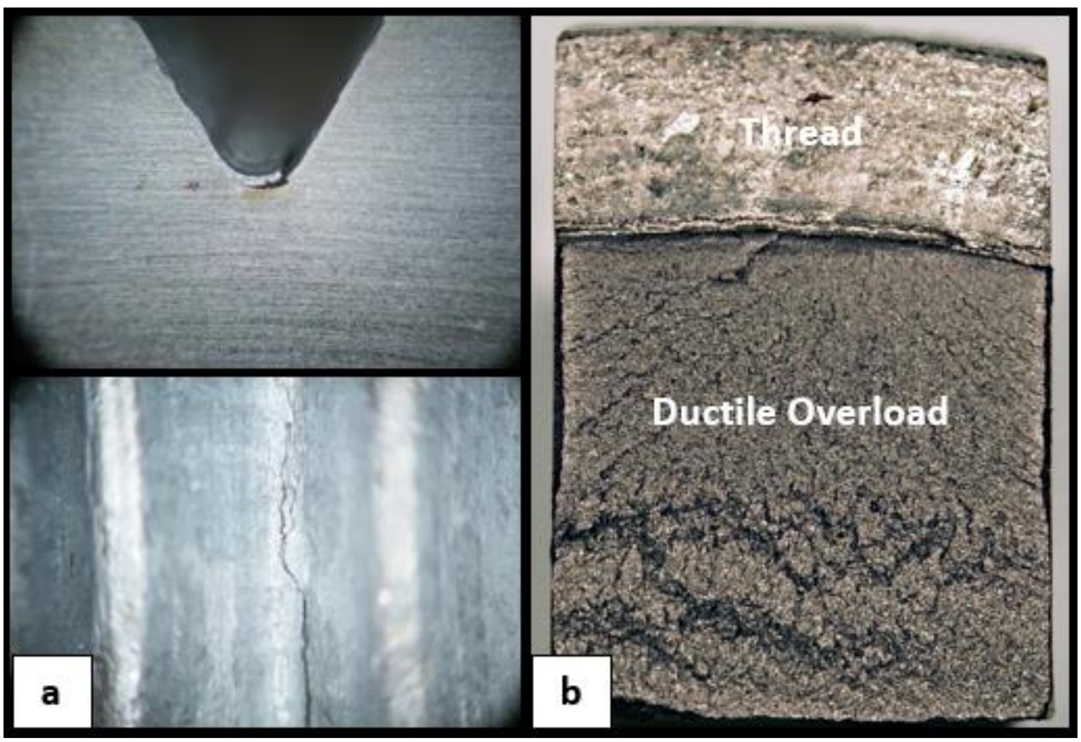


Figure W.4-2: Rod Remnant S4-E2 Thd 1 a) Thread Root from Side and Normal Views Post FFS Test and b) FFS Fracture Face

W.4.2 Thd 3, EHE:

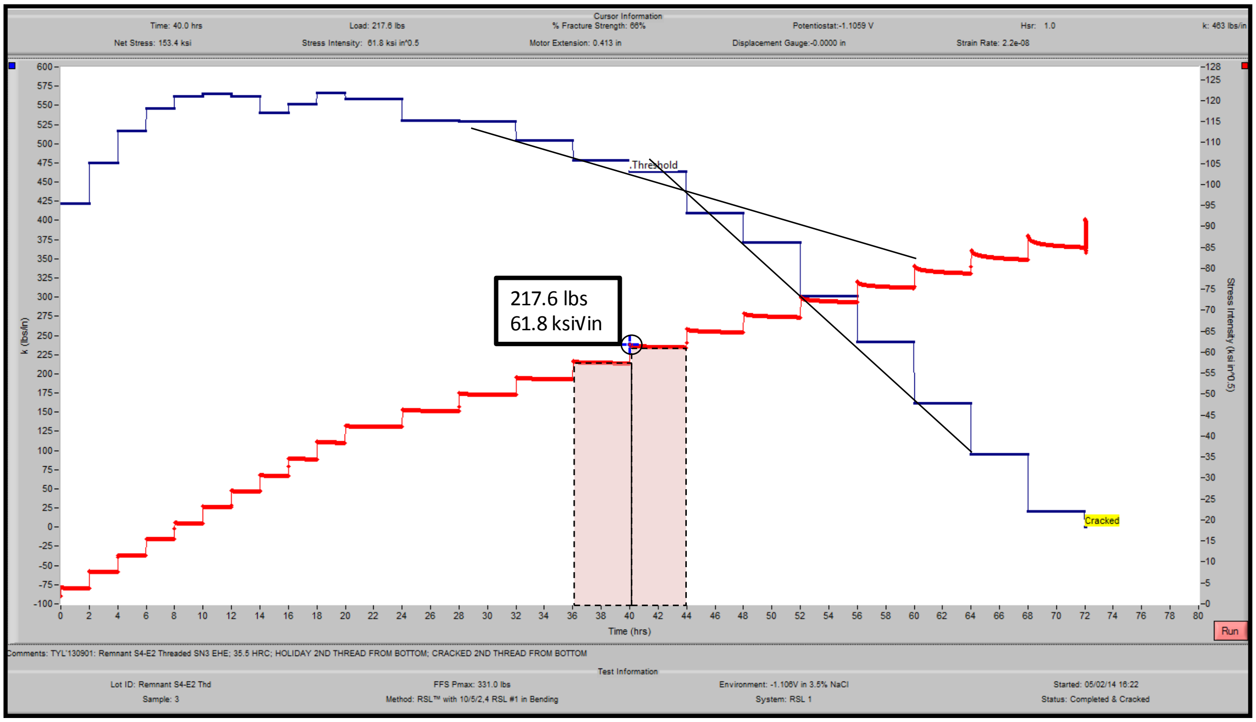


Figure W.4-3: Rod Remnant S4-E2 Thd 3, Graphical EHE Results

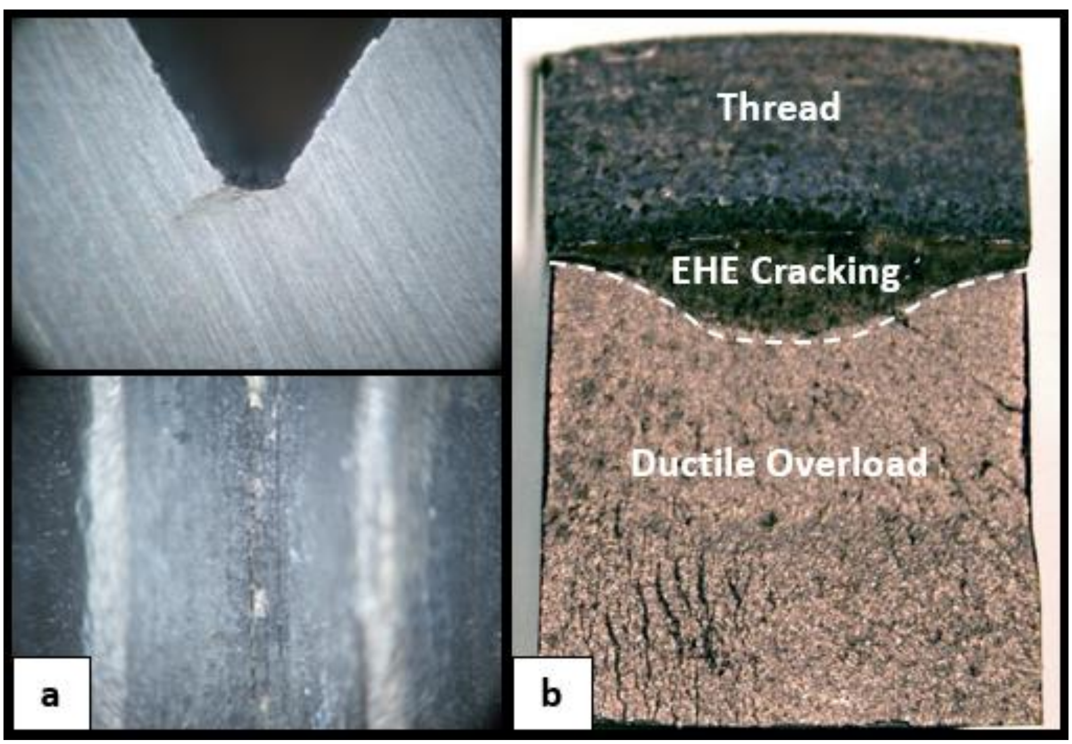


Figure W.4-4: Rod Remnant S4-E2 Thd 3 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

W.4.3 Thd 4, EHE:

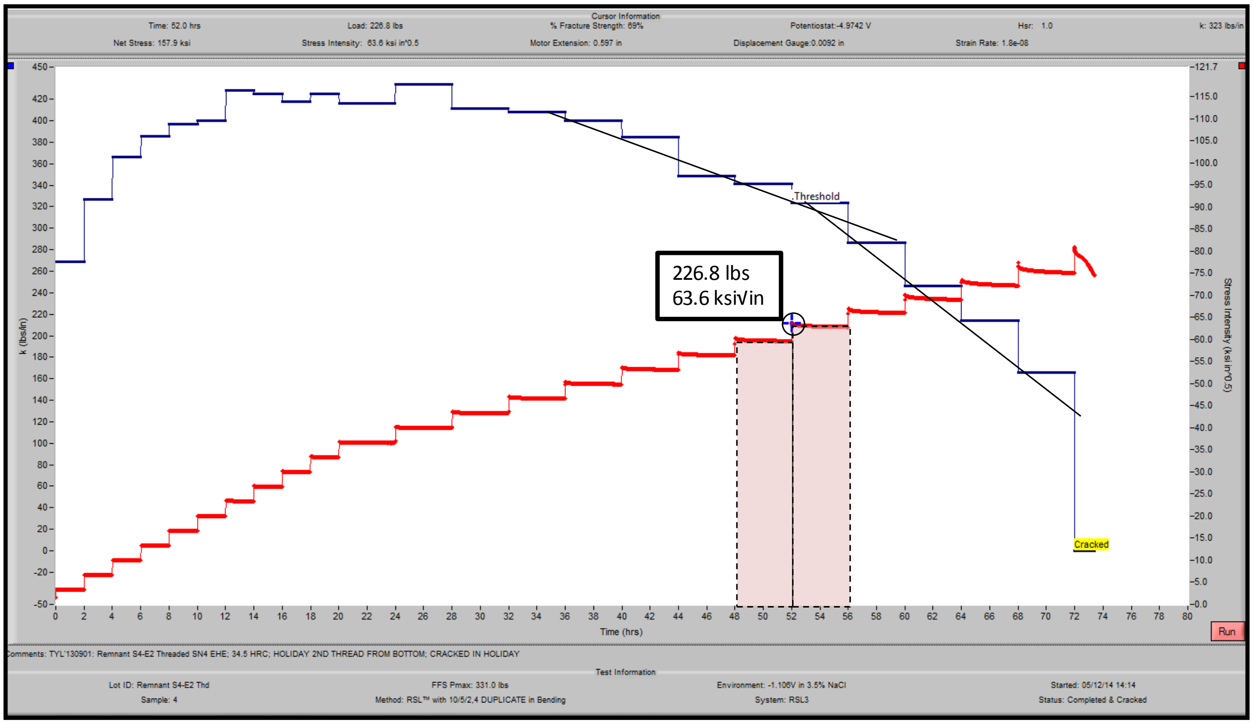


Figure W.4-5: Rod Remnant S4-E2 Thd 4, Graphical EHE Results

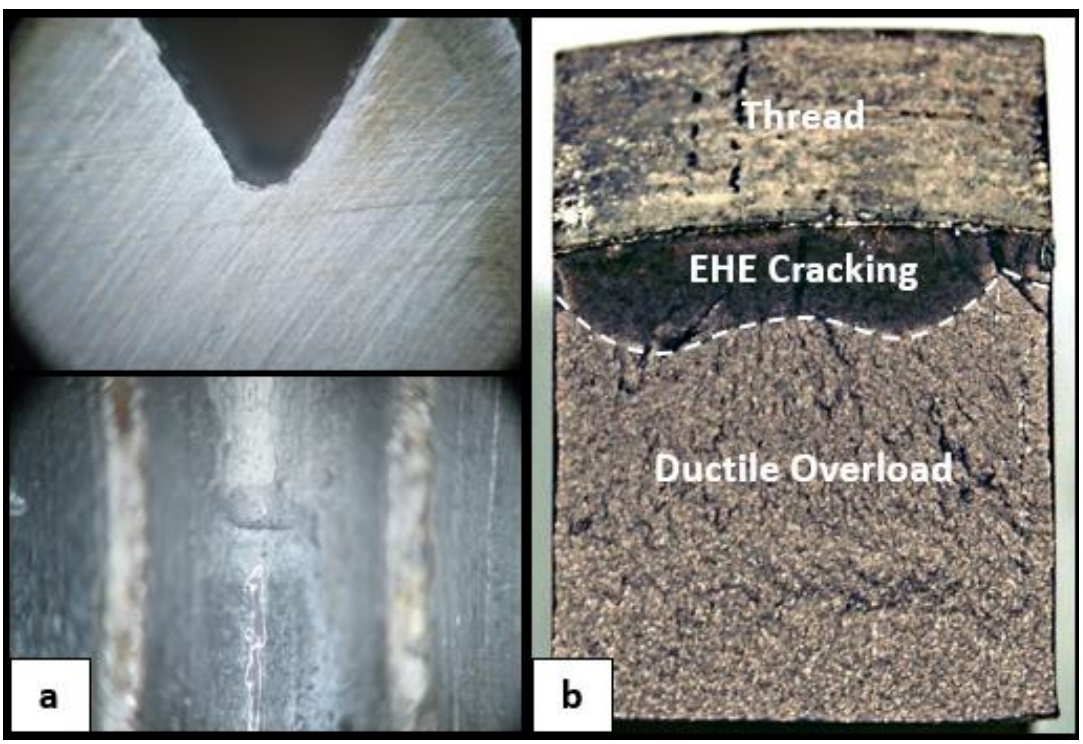


Figure W.4-6: Rod Remnant S4-E2 Thd 4 a) Thread Root from Side and Normal Views Post EHE Test and b) EHE Fracture Face

W.4.4 Thd 5, EHE:

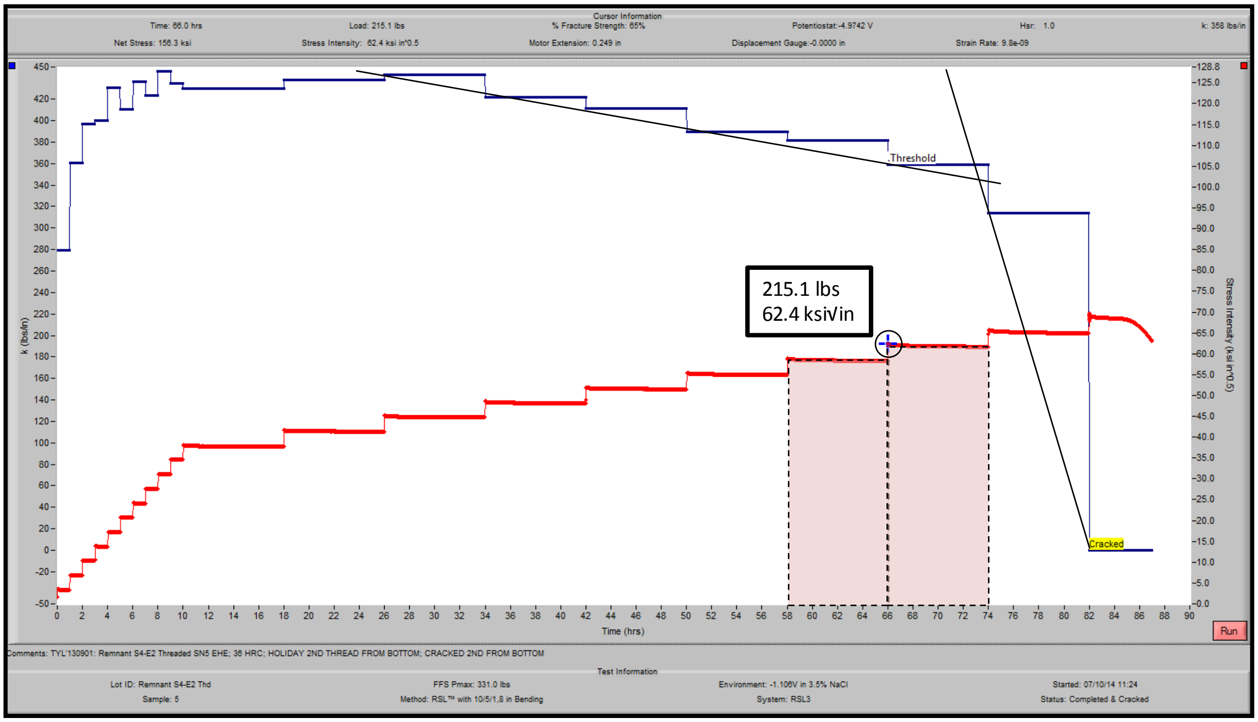


Figure W.4-7: Rod Remnant S4-E2 Thd 5, Graphical EHE Results

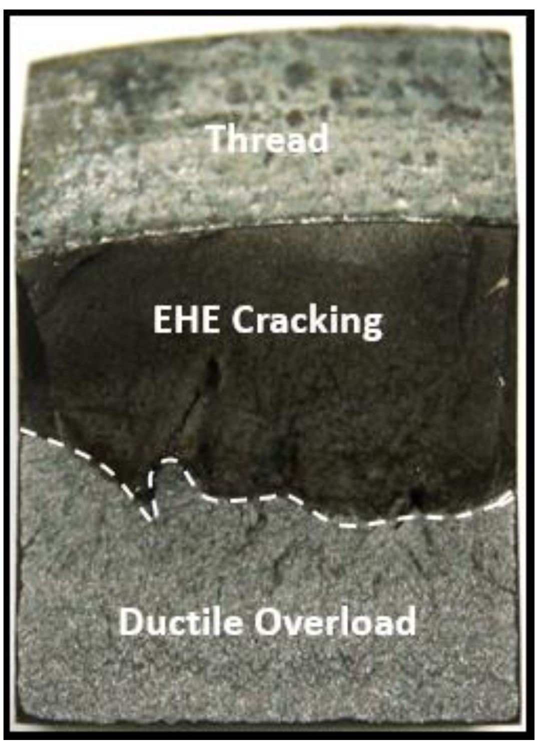


Figure W.4-8: Rod Remnant S4-E2 Thd 5 EHE Fracture Face

Appendix X: Rod Remnant 7-V-TR-9-E

X.1 Description of Remnants

The Remnant 7-V-TR-9-E test specimens were taken from the unstressed portion above the nut of the rod tested in Test Rig 9 in Test IV. The specimens were used to specify a design limit at the zinc potential and verify the results of Test IV.

X.2 Summary

The results from this table are summarized in the following "checker board" table. Detailed data are listed in the following summary table.

X.2.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-TR-9-E						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)				
Rod#:	**7-V-TR-9-E**					
Product Form:	**1e**	**Comments**: 2010 Rolled Threads				
Rod OD:	**3.5"**	Dead End of Rod from Test Rig #9 in Test IV				
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**37.0**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	349.5 1.13 1.5 4400		
	Thd 2, EHE	**36.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			234.2 0.76 1.0 1.1
	Thd 3, EHE	**37.5**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			233.2 0.75 1.0 0.6

X.2.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-TR-9-E
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**7-V-TR-9-E**
Product Form:	**1e**
Rod OD:	**3.5"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	Thd 1, FFS	Air	37.0	167	342.0	342.0	342.0	100.0%	101.9	0.61	254.8	1.5	4400	0.4 in/min	349.5	1.13	
	Thd 2, EHE	3.5% NaCl @ -1.106V	36.5	164	268.0	254.8	239.3	67.0%	68.3	0.42	169.6	1.0	1.1	10/5/1,8	234.2	0.76	Did Crack In Holiday
	Thd 3, EHE	3.5% NaCl @ -1.106V	37.5	169	268.0	254.9	239.5	66.7%	68.0	0.40	167.9	1.0	0.55	10/5/1,16	233.2	0.75	Did Not Crack In Holiday

X.3 Threaded Specimen Test Results

X.3.1 Thd 1, FFS:

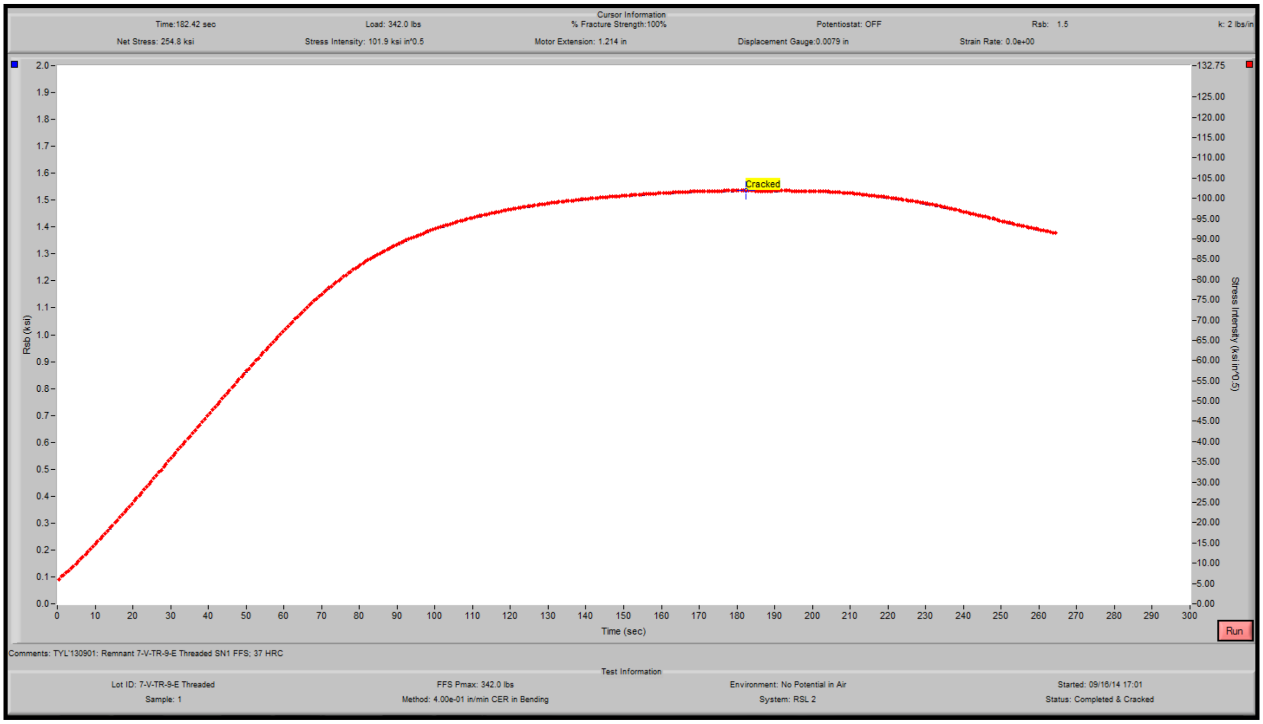


Figure X.3-1: Rod Remnant 7-V-TR-9-E Thd 1, Graphical FFS Results

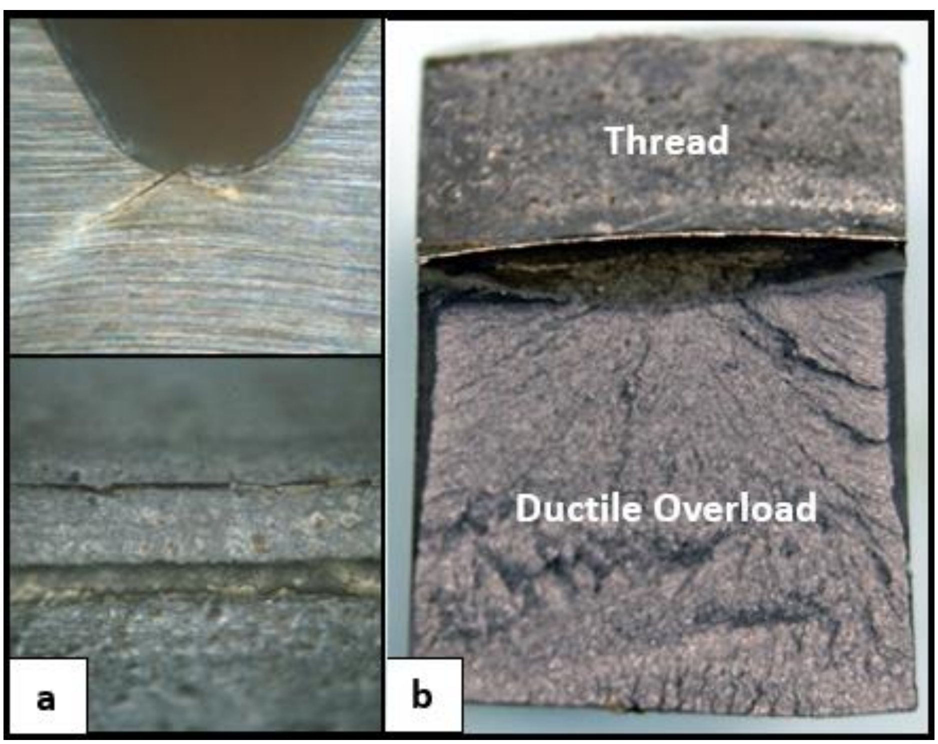


Figure X.3-2: Rod Remnant 7-V-TR-9-E Thd 1 a) Thread Root Post FFS Test V and Pre-Charpy Impact and b) FFS Fracture Face

X.3.2 Thd 2, EHE:

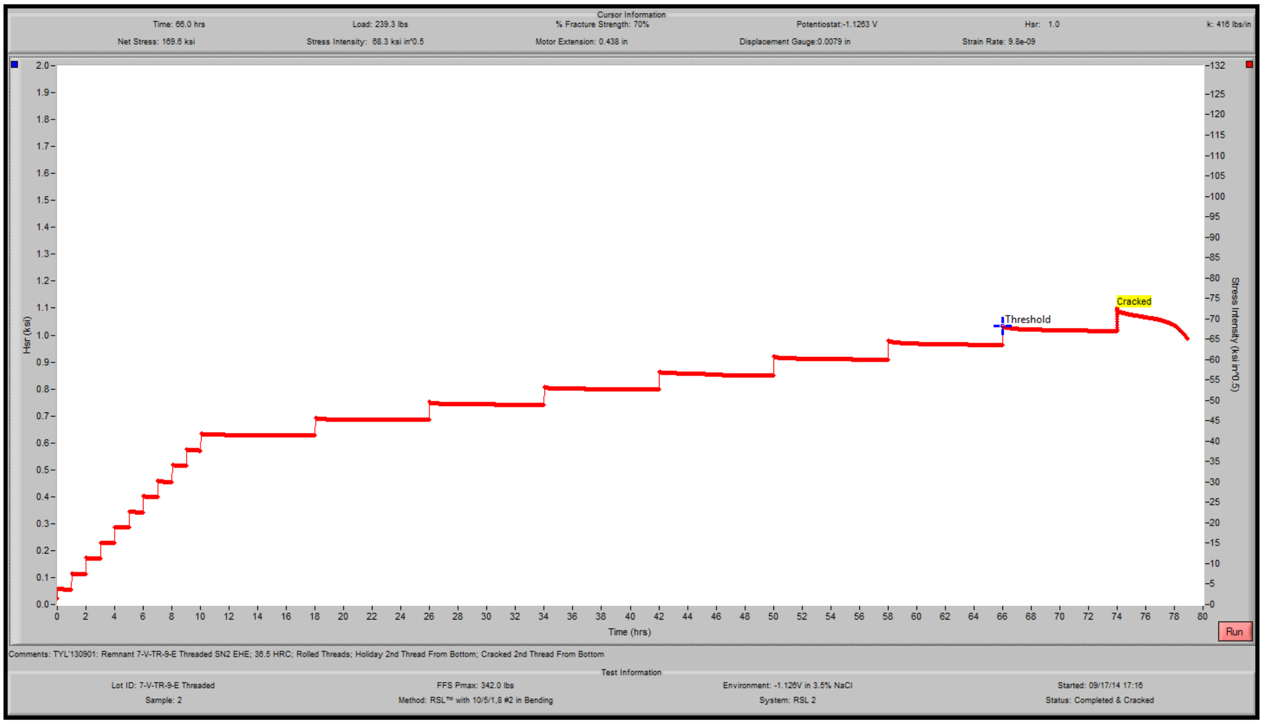


Figure X.3-3: Rod Remnant 7-V-TR-9-E Thd 2, Graphical EHE Results

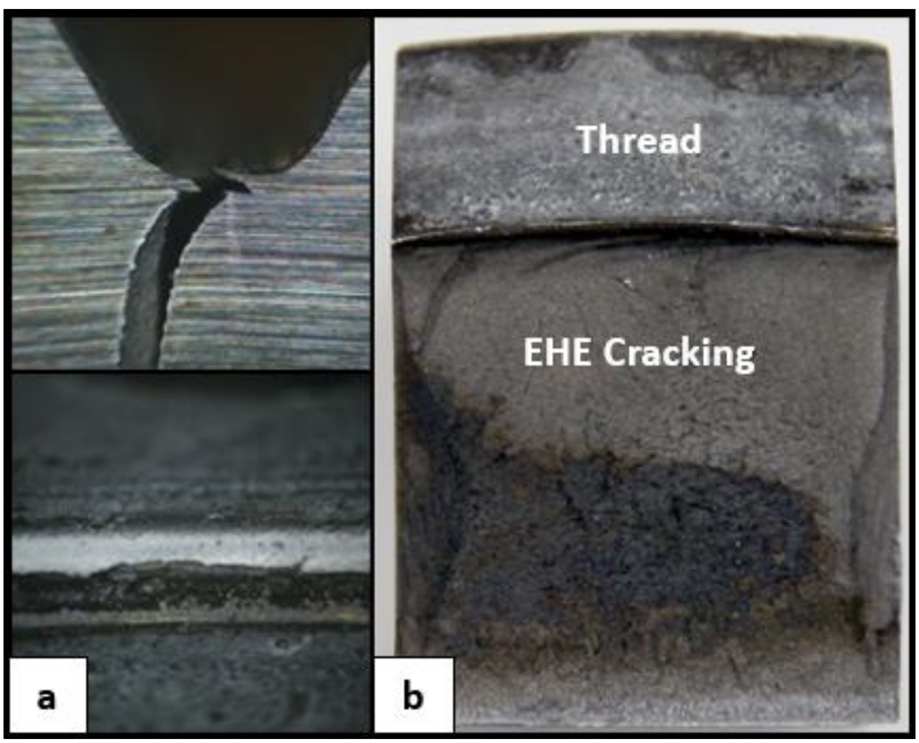


Figure X.3-4: Rod Remnant 7-V-TR-9-E Thd 2 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

X.3.3 Thd 3, EHE:

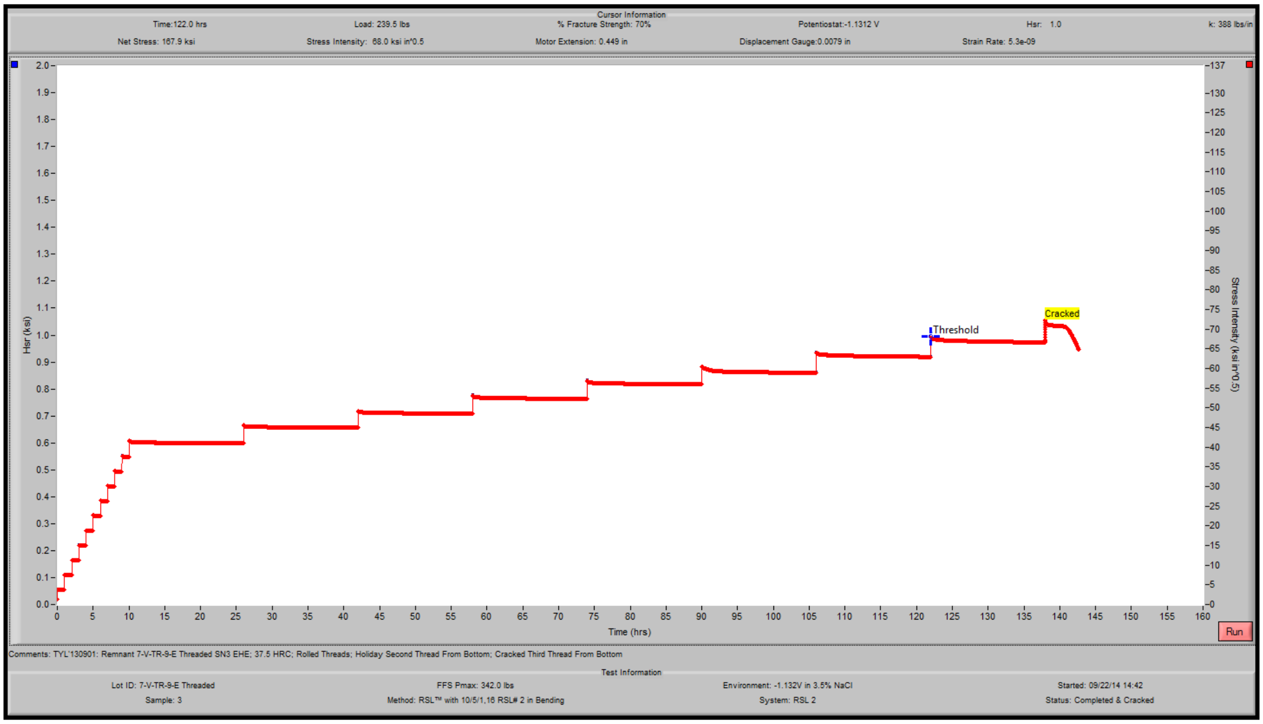


Figure X.3-5: Rod Remnant 7-V-TR-9-E Thd 3, Graphical EHE Results

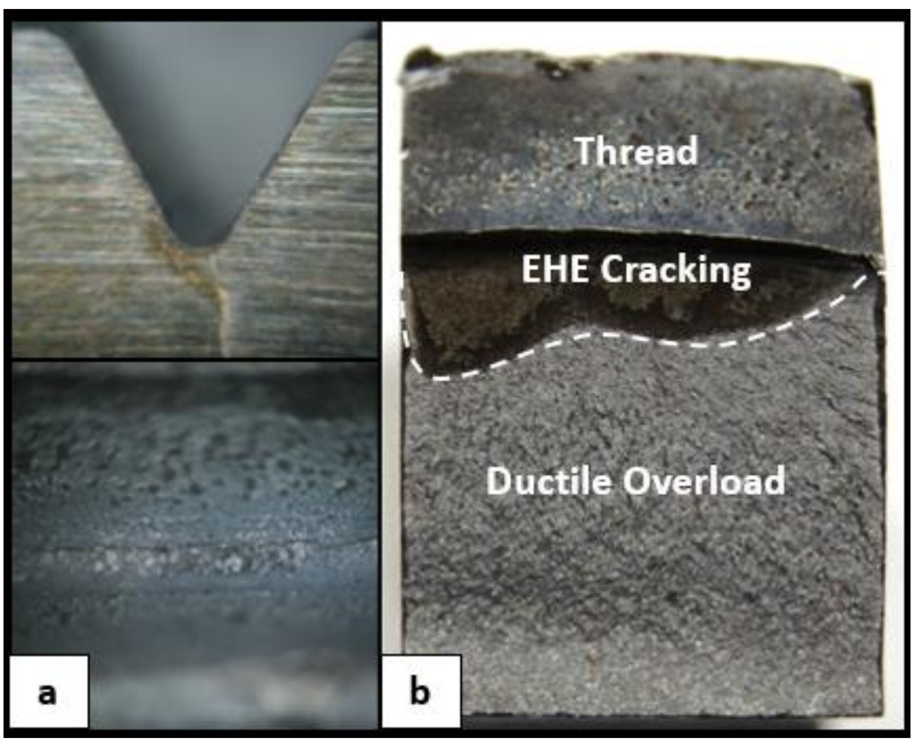


Figure X.3-6: Rod Remnant 7-V-TR-9-E Thd 3 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Appendix Y: Rod Remnant 7-V-TR-10-G

Y.1 Description of Remnants

The Remnant 7-V-TR-10-G test specimens were taken from the unstressed portion above the nut of the rod tested in Test Rig 10 in Test IV. The specimens were used to specify a design limit at the zinc potential and verify the results of Test IV.

Y.2 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" table.

Y.2.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results Threaded Rod ID # 7-V-TR-10-G						
LRA Job No.:	**TYL130901**	**Structural Component:** PWS Strand Anchor Rods (Main Cable)				
Rod#:	**7-V-TR-10-G**					
Product Form:	**1e**	**Comments**: 2010 Machined Threads				
Rod OD:	**3.5"**	Dead End of Rod from Test Rig #10 in Test IV				
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Threaded	**Thd 1, FFS**	**35.5**	Pmax* (lbs) Fu Rsb Strain Rate ($x10^{-8}$ in/in/sec)	343.0 1.11 1.6 4100		
	Thd 2, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			208.5 0.67 0.9 1.1
	Thd 3, EHE	**36.0**	$P_{threshold}$* (lbs) Fu Hsr Strain Rate ($x10^{-8}$ in/in/sec)			195.5 0.63 0.9 0.5

Y.2.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Threaded Rod ID # 7-V-TR-10-G
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Rod #:	**7-V-TR-10-G**
Product Form:	**1e**
Rod OD:	**3.5"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{I\rho\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	Thd 1, FFS	Air	35.5	159	343.9	343.9	343.9	100.0%	100.0	0.63	249.5	1.6	4100	0.4 in/min	343.0	1.11	
	Thd 2, EHE	3.5% NaCl @ -1.106V	36.0	162	264.0	250.8	210.0	60.8%	60.8	0.38	151.8	0.9	1.1	10/5/1,8	208.5	0.67	Did Not Crack In Holiday
	Thd 3, EHE	3.5% NaCl @ -1.106V	36.0	162	264.0	290.5	197.2	57.0%	57.0	0.35	142.2	0.9	0.53	10/5/1,16	195.5	0.63	Did Not Crack In Holiday

Y.3 Threaded Specimen Test Results

Y.3.1 Thd 1, FFS:

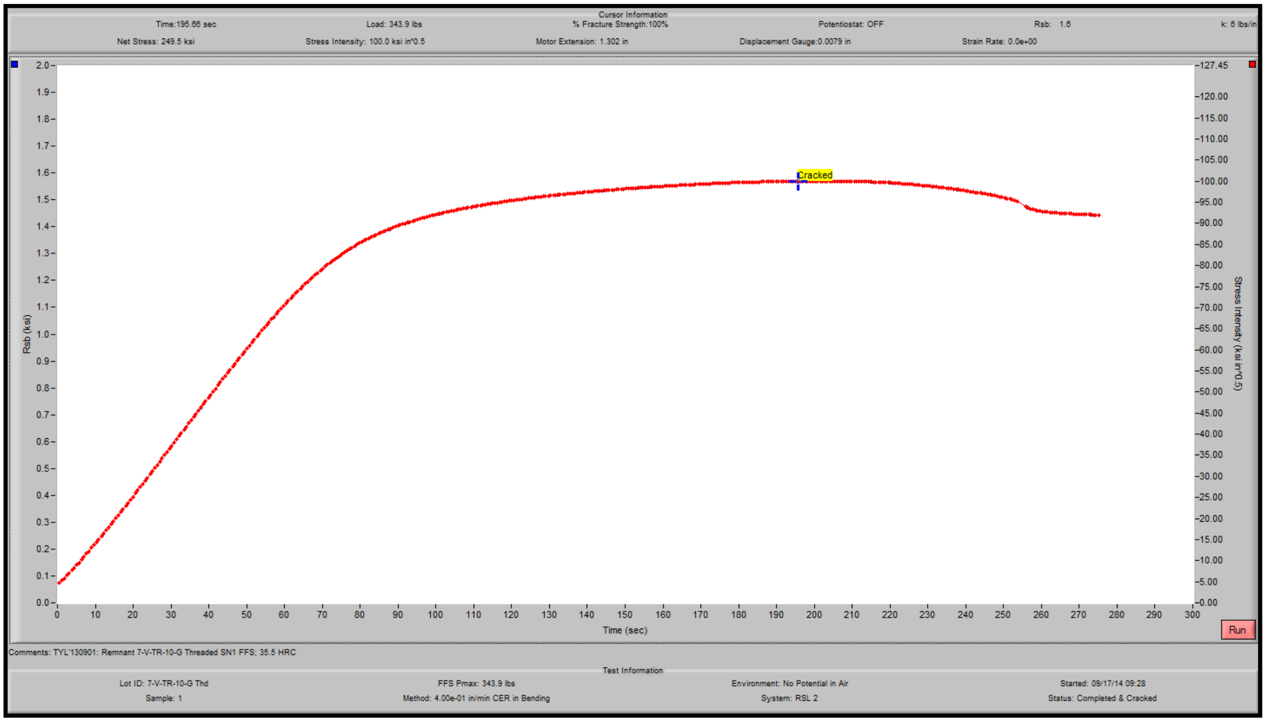


Figure Y.3-1: Rod Remnant 7-V-TR-10-G Thd 1, Graphical FFS Results

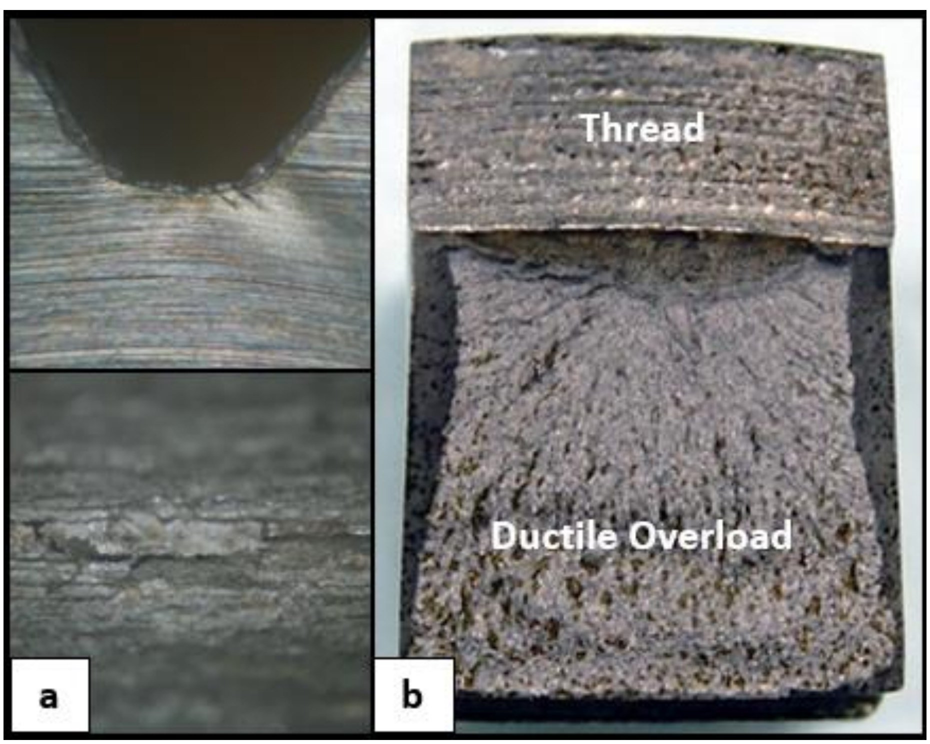


Figure Y.3-2: Rod Remnant 7-V-TR-10-G Thd 1 a) Thread Root Post FFS Test V and Pre-Charpy Impact and b) FFS Fracture Face

Y.3.2 Thd 2, EHE:

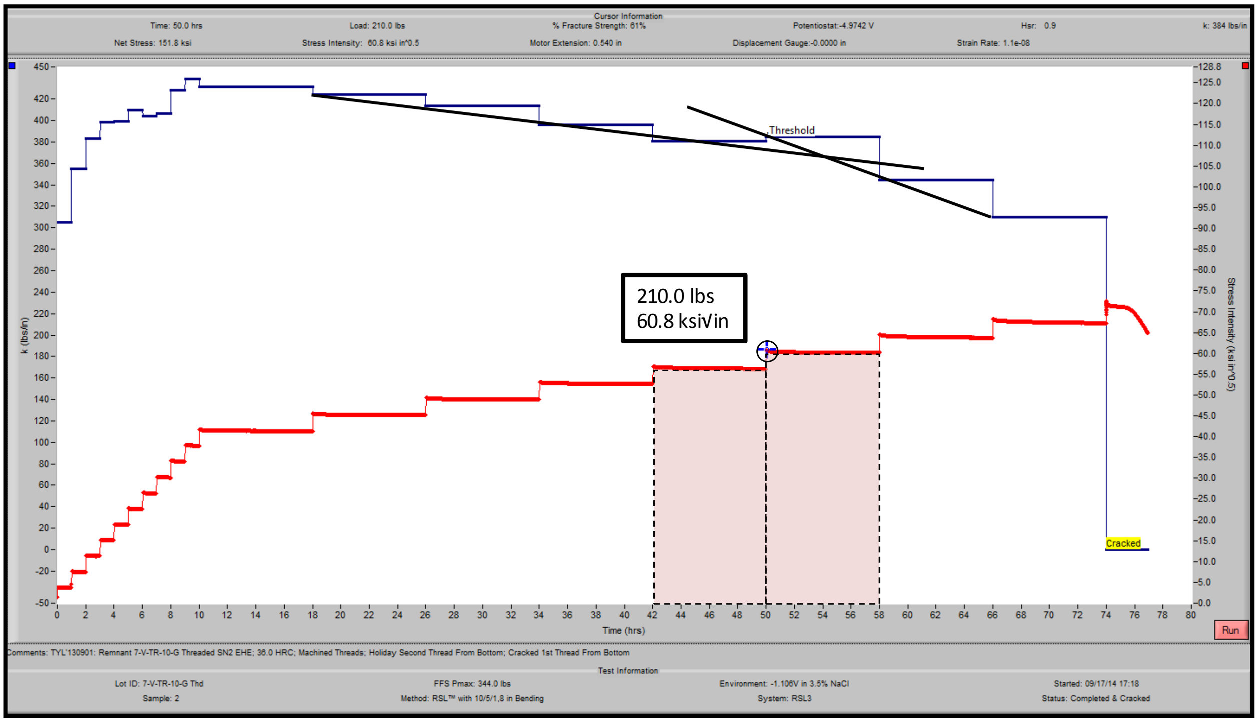


Figure Y.3-3: Rod Remnant 7-V-TR-10-G Thd 2, Graphical EHE Results

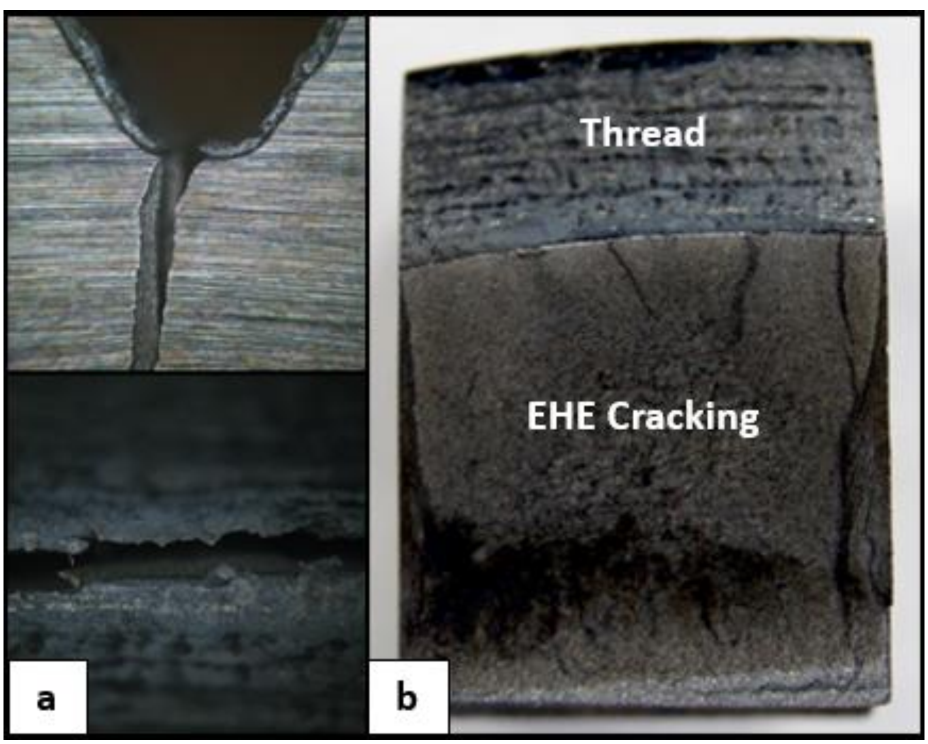


Figure Y.3-4: Rod Remnant 7-V-TR-10-G Thd 2 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Y.3.3 Thd 3, EHE:

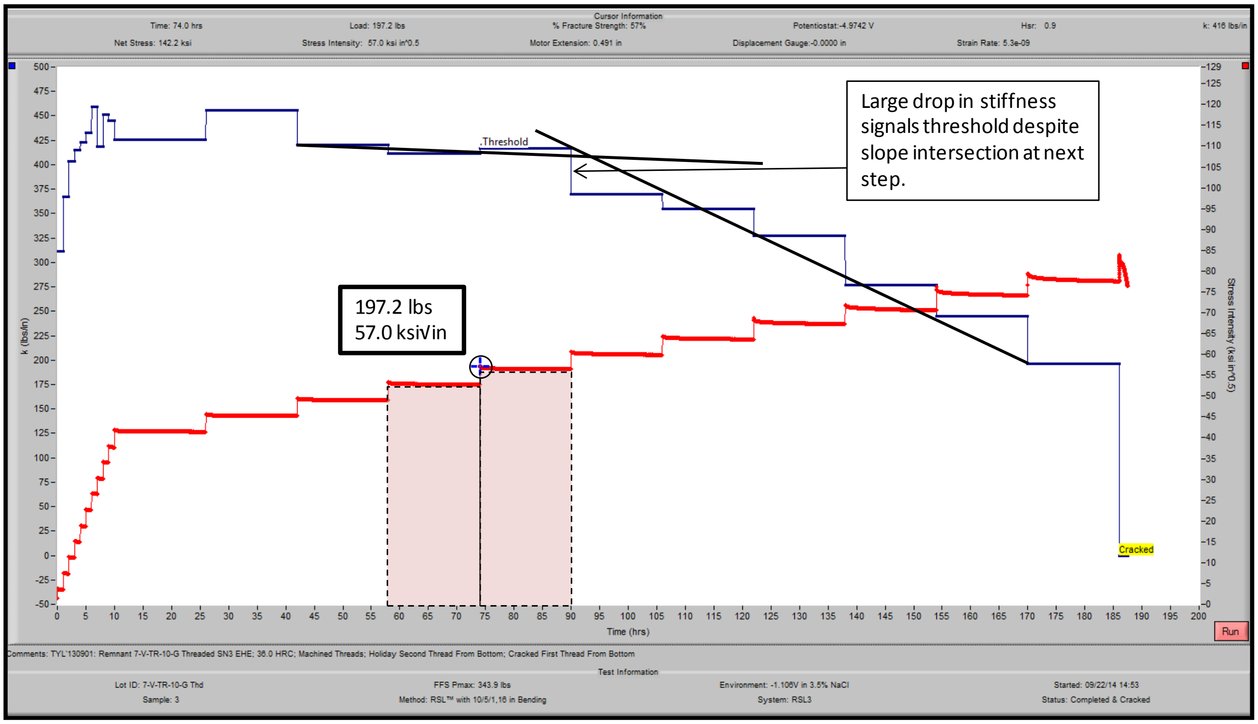


Figure Y.3-5: Rod Remnant 7-V-TR-10-G Thd 3, Graphical EHE Results

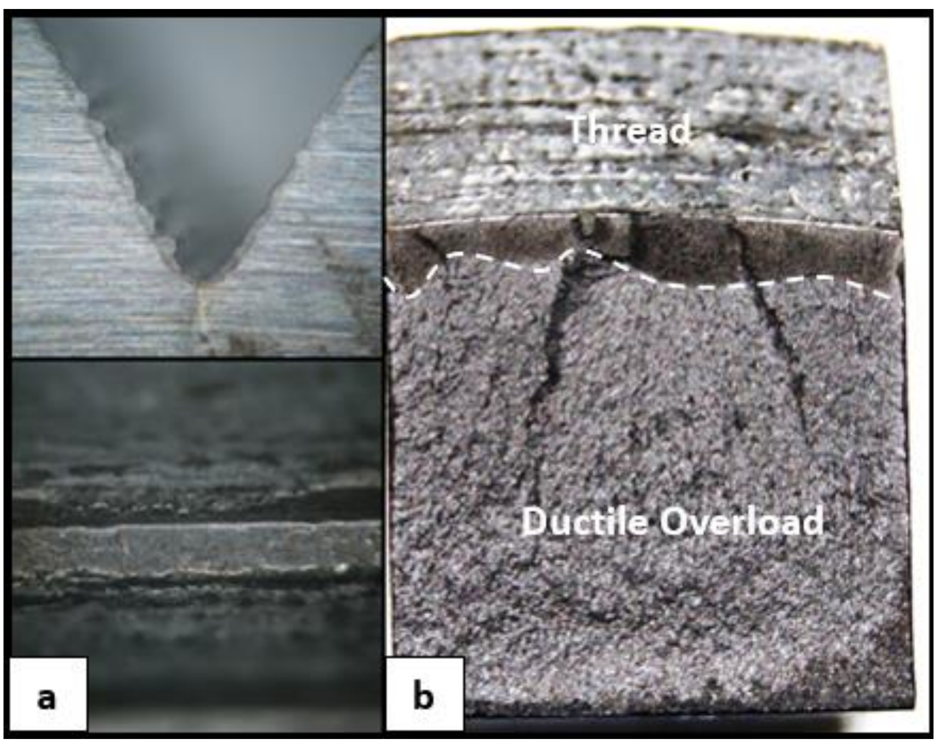


Figure Y.3-6: Rod Remnant 7-V-TR-10-G Thd 3 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

Appendix Z: Zinc Cracking

Z.1 Description of Sample

Rod samples were received at LRA and visually examined for general condition and major defects. Samples varied in length from 6 inches to 24 inches.

Specimens from Rod 7-V-E012 were selected to machine 0.4B threaded specimens to determine when cracking initiated under acoustic emission. Determining crack initiation on specimens with and without galvanizing allowed LRA to distinguish if the galvanizing on the specimens acted as a stress riser at the root of the thread. Short dwell time tests, one minute or less between loading increments, were performed on galvanized and non-galvanized threaded specimens to determine the magnitude of the stress intensity factor at crack initiation.

Additionally, Rod 3-V-10 Threaded SN6 was used to verify that the environmental threshold was equivalent with and without the galvanizing on the specimen.

This specimen had the zinc removed in dilute HCl, was baked at 375^{o}F for 24 hours, visually examined thread root area to verify absence of galvanizing, and RSL tested at parameters identical to Rod 3-V-10 Threaded SN3 (10/5/2,4 with strain rate = 2E-10).

The results determined that the stress intensity factor at crack initiation was similar for both the galvanized and non-galvanized specimens. Hence, the galvanizing on the rod does not act as a stress riser.

Further information on the rods selected for these tests can be found in the previous corresponding rod Appendix G Rod 3-V-10 and Appendix N Rod 7-V-E012.

Z.1.1 Rod 7-V-E012 Thd 5 (Without Galvanizing), Rapid RSL:

Specimens from Rod 7-V-E012 are shown at the end of this appendix but explained in special projects, Section 4.5.4.

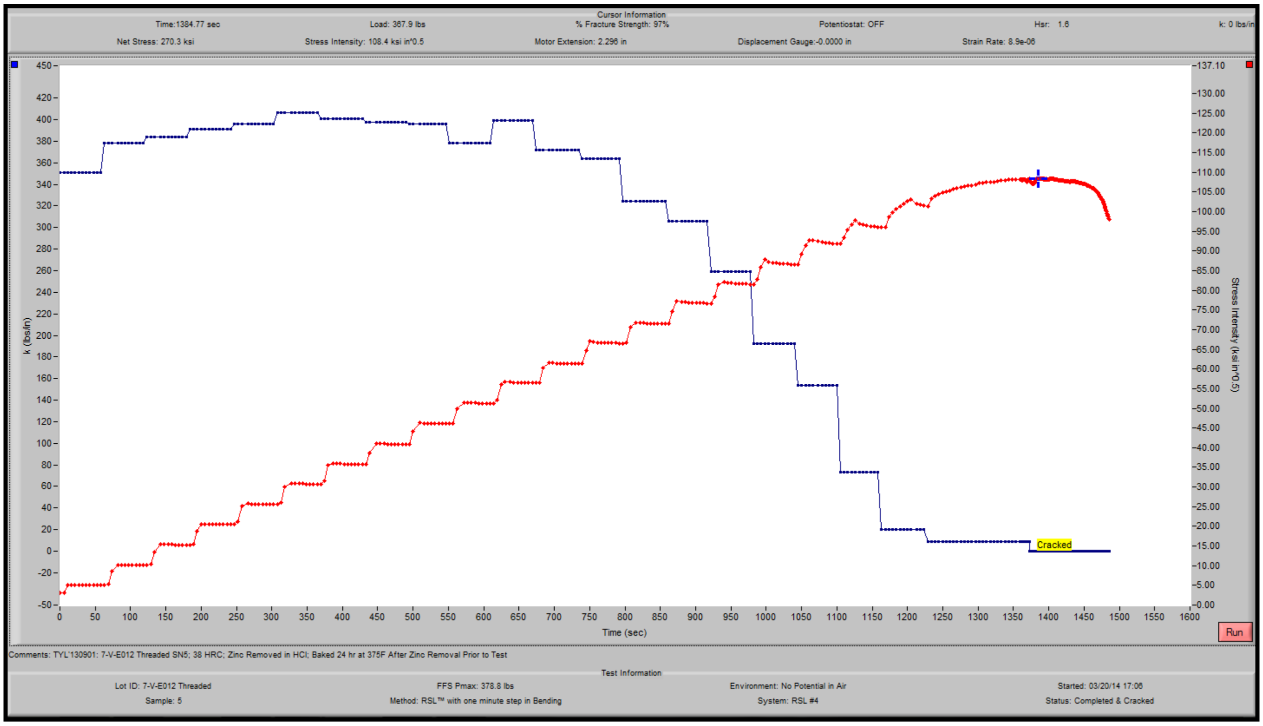


Figure Z.1-1: Rod 7-V-E012 Thd 5 (Without Galvanizing), Graphical Rapid RSL Results

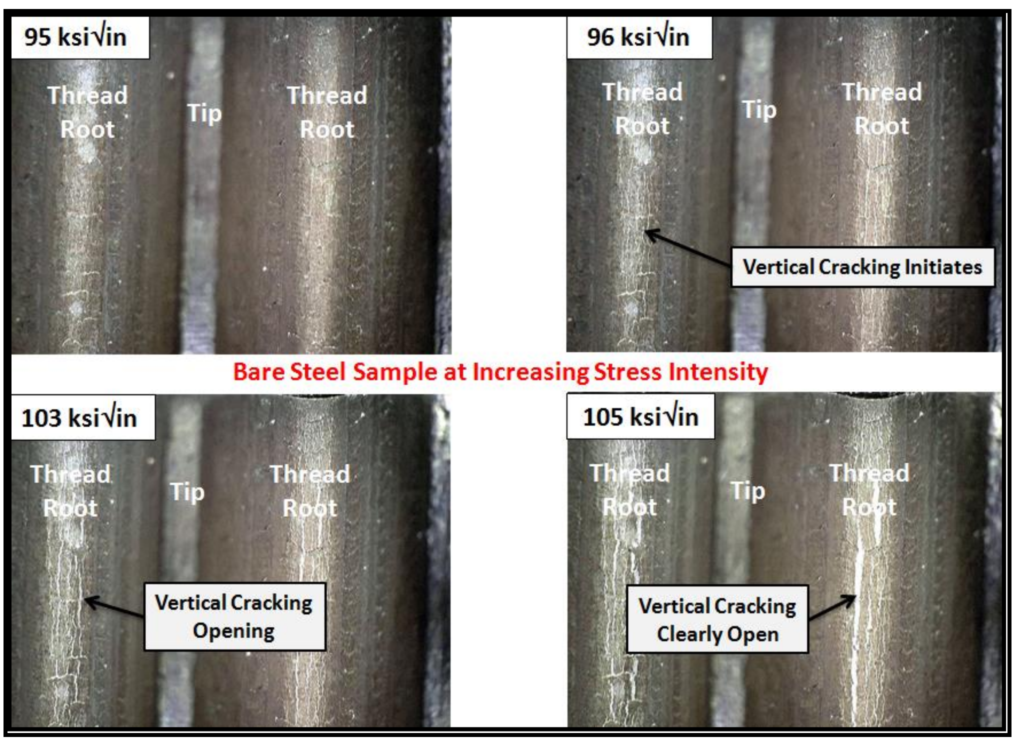


Figure Z.1-2: Rod 7-V-E012 Thd 5 (Without Galvanizing) Thread Root During Test

Z.1.2 Rod 7-V-E012 Thd 6 (With Galvanizing), Rapid RSL:

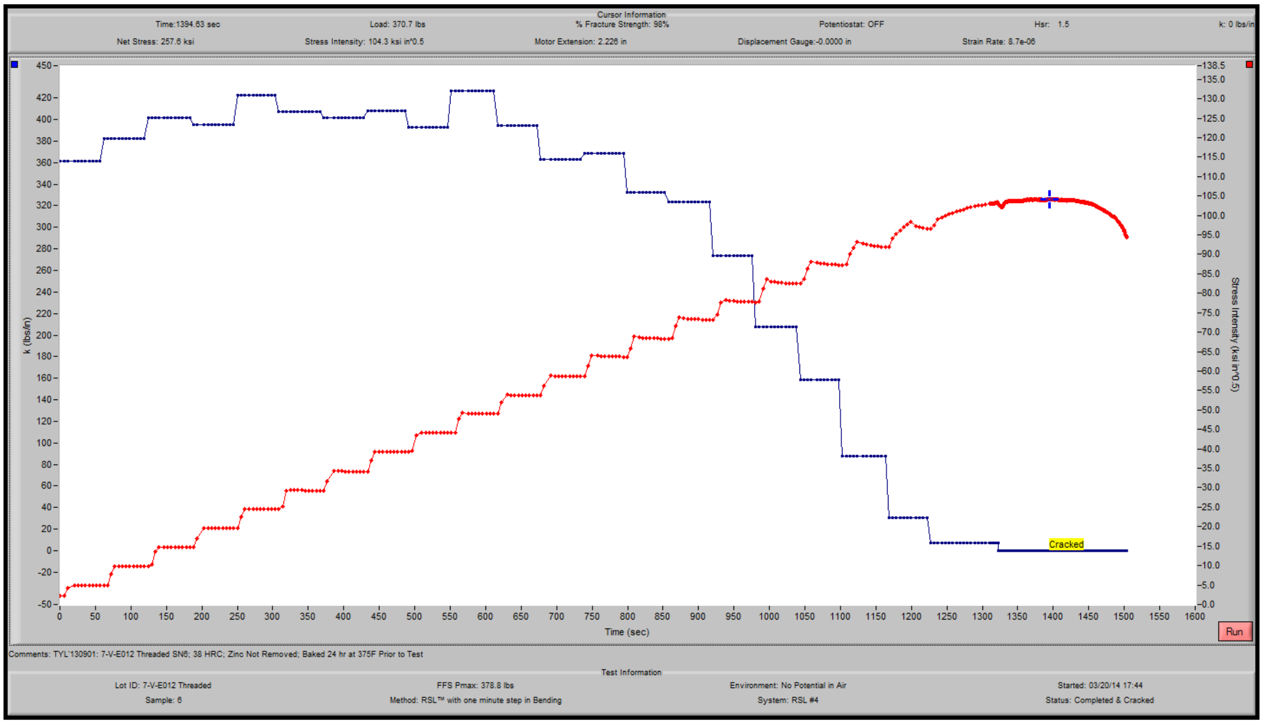


Figure Z.1-3: Rod 7-V-E012 Thd 6 (With Galvanizing), Graphical Rapid RSL Results

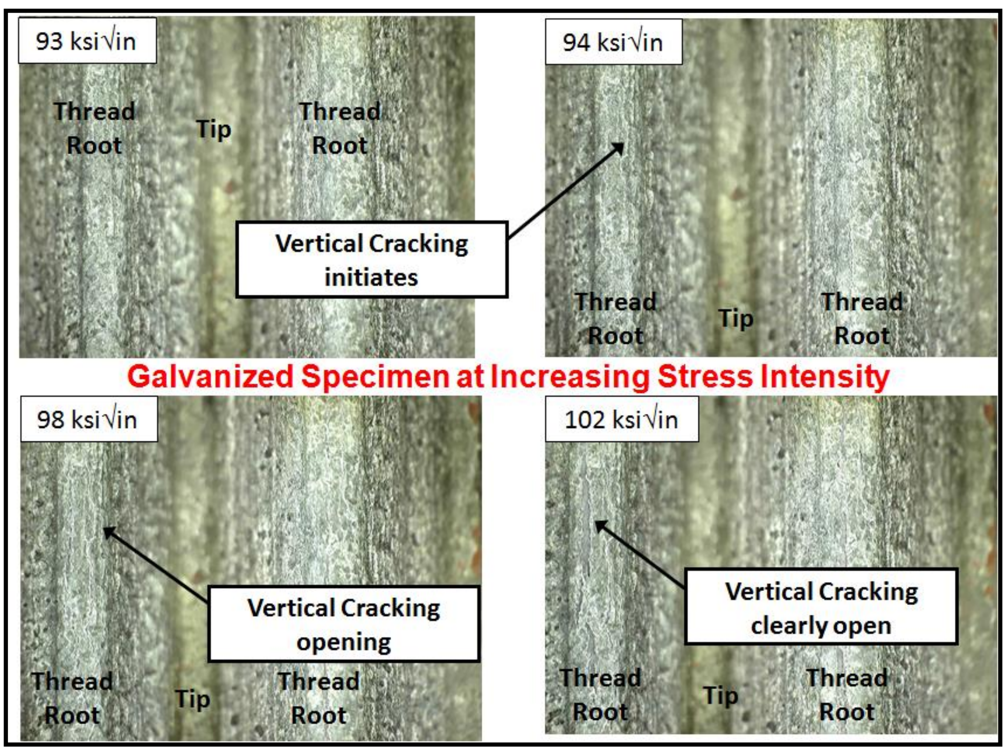


Figure Z.1-4: Rod 7-V-E012 Thd 6 (With Galvanizing) Thread Root During Test

Z.2 Summary

The results for the threaded galvanized and bare EHE specimens from Rod 3-V-10 are summarized in the following "checker board" table and summary table. Detailed data and photos for the threaded galvanized specimens from Rod 3-V-10 are in Appendix G Rod 3-V-10.

Z.2.1 Threaded Results for Rod 3-V-10:

Test V ASTM F1624 Bolt Specimen Results Special Project: Zinc Cracking						
LRA Job No.:	**TYL130901**					
Special Project:	**Zinc Cracking**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**	**Galvanized**	**Environment**		**P-EHE**
Threaded	**3-V-10 Thd 3, EHE**	**35.0**	**Yes**	**3.5% NaCl @ -1.106V**	$P_{threshold}$* (lbs)	227.4
					Fu	0.75
					Hsr	1.0
					Strain Rate ($x10^{-8}$ in/in/sec)	2
	3-V-10 Thd 4, EHE	**36.0**	**Yes**	**3.5% NaCl @ -1.106V**	$P_{threshold}$* (lbs)	235.3
					Fu	0.78
					Hsr	1.0
					Strain Rate ($x10^{-8}$ in/in/sec)	1.4
	3-V-10 Thd 6, EHE	**35.5**	**No**	**3.5% NaCl @ -1.106V**	$P_{threshold}$* (lbs)	231.8
					Fu	0.76
					Hsr	1.0
					Strain Rate ($x10^{-8}$ in/in/sec)	2

Z.2.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Special Project: Zinc Cracking
RSL™ (B) 4-pt Bend Test

LRA Job No.:	TYL130901
Special Project:	Zinc Cracking
Rod OD:	3"

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, Pth (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (V/in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	3-V-10 Thd 3, EHE	3.5% NaCl @ -1.106V	35.0	157	256.6	335.2	242.7	67.0%	66.3	0.42	162.7	1.0	2.0	10/5/2,4	227.4	0.75	Cracked in Holiday
	3-V-10 Thd 4, EHE	3.5% NaCl @ -1.106V	36.0	162	180.0	324.1	241.8	69.4%	68.6	0.42	169.0	1.0	1.4	10/5/1,4	235.3	0.78	Did Not Crack In Holiday
	3-V-10 Thd 6, EHE	3.5% NaCl @ -1.106V	35.5	159	256.6	343.8	242.5	68.4%	67.6	0.42	166.7	1.0	2.0	10/5/2,4	231.8	0.76	Did Not Crack In Holiday

Z.3 Threaded Specimen Test Results

Z.3.1 Rod 3-V-10 Thd 6, EHE:

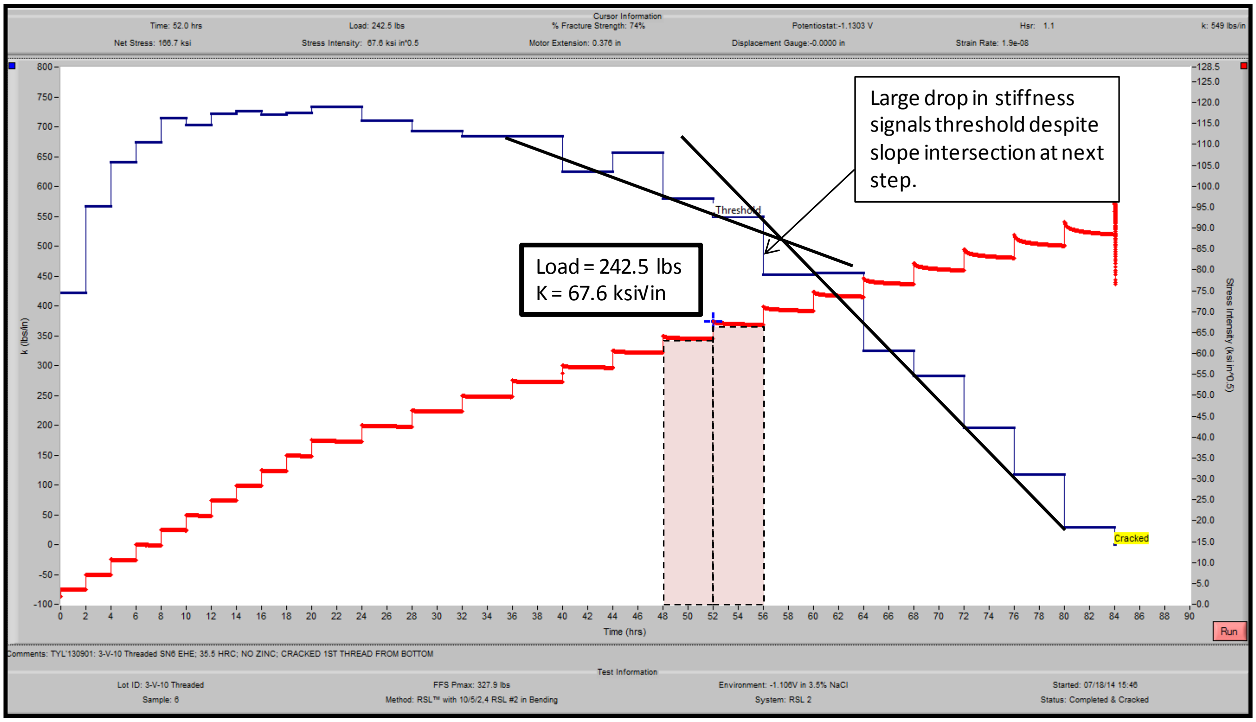


Figure Z.3-1: Rod 3-V-10 Thd 6, Graphical EHE Results

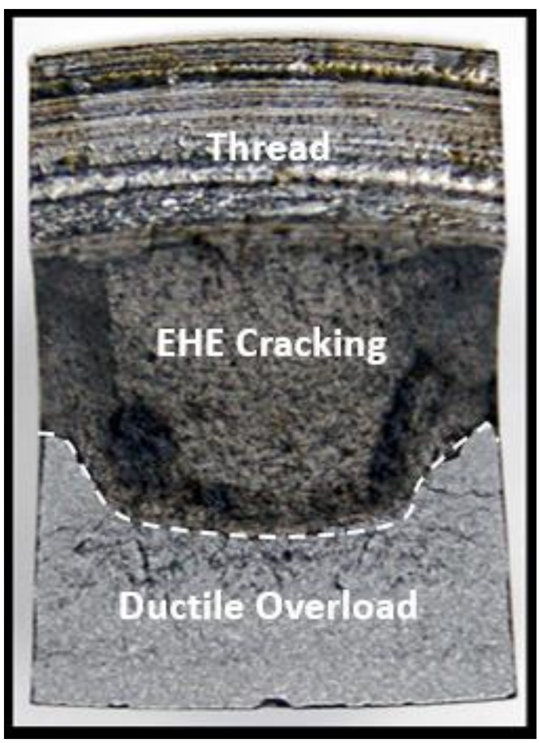


Figure Z.3-2: Rod 3-V-10 Thd 6 EHE Fracture Face

Appendix AA: Plane Strain and Hardened Specimens

AA.1 Description of Sample

Rod samples were received at LRA and visually examined for general condition and major defects. Samples varied in length from 6 to 24 inches. Rod 3-V-12 was selected to machine 1.0B plane strain threaded specimens. The Exemplar Rod from Group ID #16, was selected to machine 0.4B threaded specimens and heat treat said specimens to hardnesses close to 40, 45 and 50 HRC.

AA.2 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" table. Heat treated specimens are seen by HT, and AR for as received.

AA.2.1 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results
Special Project: Plane Strain and Hardened Specimens

LRA Job No.:	**TYL130901**					
Special Project:	**Plane Strain and Hardened Specimens**					
Rod OD:	**3"**					
	Sample #/ID	**HRC**		**P-FFS**	**P-IHE**	**P-EHE**
Plane Strain, Threaded	**Rod 3-V-12, 1.0B Thd 1, FFS**	**35.5**	Pmax* (lbs)	326.5		
			Fu	1.08		
			Rsb	1.5		
			Strain Rate ($x10^{-8}$ in/in/sec)	3900		
	Rod 3-V-12, 1.0B Thd 2, IHE	**36.5**	$P_{threshold}$* (lbs)		311.1	
			Fu		1.02	
			Hsr		1.4	
			Strain Rate ($x10^{-8}$ in/in/sec)		2.1	
	Rod 3-V-12, 1.0B Thd 3, EHE	**35.5**	$P_{threshold}$* (lbs)			216.4
			Fu			0.71
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			2.2
	Rod 3-V-12, 1.0B Thd 4, EHE	**35.5**	$P_{threshold}$* (lbs)			213.0
			Fu			0.70
			Hsr			1.0
			Strain Rate ($x10^{-8}$ in/in/sec)			1.9
Hardened, Threaded	**Rod 16, HT 1000 Thd 1, EHE**	**39.0**	$P_{threshold}$* (lbs)			263.4
			Fu			0.87
			Hsr			1.1
			Strain Rate ($x10^{-8}$ in/in/sec)			1.8
	Rod 16, HT 800 Thd 1, EHE	**45.5**	$P_{threshold}$* (lbs)			220.2
			Fu			0.73
			Hsr			0.7
			Strain Rate ($x10^{-8}$ in/in/sec)			2.1
	Rod 16, AR Thd 1, EHE	**52.0**	$P_{threshold}$* (lbs)			139.9
			Fu			0.46
			Hsr			0.4
			Strain Rate ($x10^{-8}$ in/in/sec)			1.4

AA.2.2 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Special Project: Plane Strain and Hardened Specimens
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Special Project:	**Plane Strain and Hardened Specimens**
Rod OD:	**3"**

		S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, $K_{Ip\text{-}EHE}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	$\delta\varepsilon/\delta t$ ($10^{-8}s^{-1}$)	Step Load Profile	P* (lbs)	Fu	Comments
Threaded	1.0B	Rod 3-V-12, 1.0B Thd 1, FFS	Air	35.5	159	860.8	860.8	860.8	100.0%	95.2	0.60	233.8	1.5	3900	0.4 in/min	326.5	1.08	No Holiday
Threaded	1.0B	Rod 3-V-12, 1.0B Thd 2, IHE	Air	36.5	164	701.0	797.1	797.1	95.3%	90.7	0.55	222.8	1.4	2.1	10/5/2,4	311.1	1.02	No Holiday
Threaded	1.0B	Rod 3-V-12, 1.0B Thd 3, EHE	3.5% NaCl @ -1.106V	35.5	159	702.5	619.9	561.9	66.3%	63.1	0.40	155.1	1.0	2.2	10/5/2,4	216.4	0.71	Did Not Crack In Holiday
Threaded	1.0B	Rod 3-V-12, 1.0B Thd 4, EHE	3.5% NaCl @ -1.106V	35.5	159	618.0	587.1	553.8	65.2%	62.1	0.39	152.6	1.0	1.9	10/5/2,4	213.0	0.70	Did Not Crack In Holiday
Threaded	Hardened	Rod 16, HT 1000 Thd 1, EHE	3.5% NaCl @ -1.106V	39.0	177	240.0	300.4	285.9	59.6%	76.8	0.43	188.1	1.1	1.8	10/5/2,4	263.4	0.87	Cracked Outside Threads
Threaded	Hardened	Rod 16, HT 800 Thd 1, EHE	3.5% NaCl @ -1.106V	45.5	218	280.0	252.0	237.5	42.4%	64.2	0.29	157.7	0.7	2.1	10/5/2,4	220.2	0.73	No Holiday
Threaded	Hardened	Rod 16, AR Thd 1, EHE	3.5% NaCl @ -1.106V	52.0	273	180.0	162.0	152.8	21.1%	40.8	0.15	99.9	0.4	1.4	10/5/2,4	139.9	0.46	No Holiday

AA.3 Threaded Specimen Test Results

AA.3.1 Rod 3-V-12, 1.0B Thd 1, FFS:

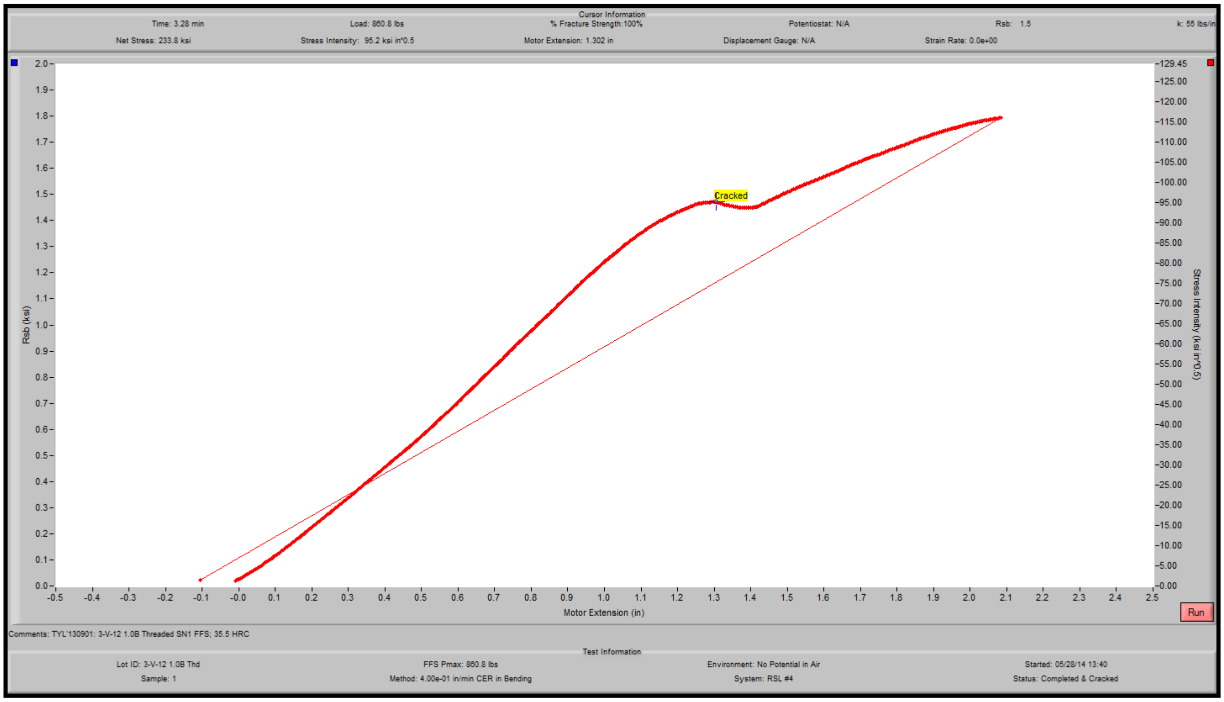


Figure AA.3-1: Rod 3-V-12, 1.0B Thd 1, Graphical FFS Results

AA.3.2 Rod 3-V-12, 1.0B Thd 2, IHE:

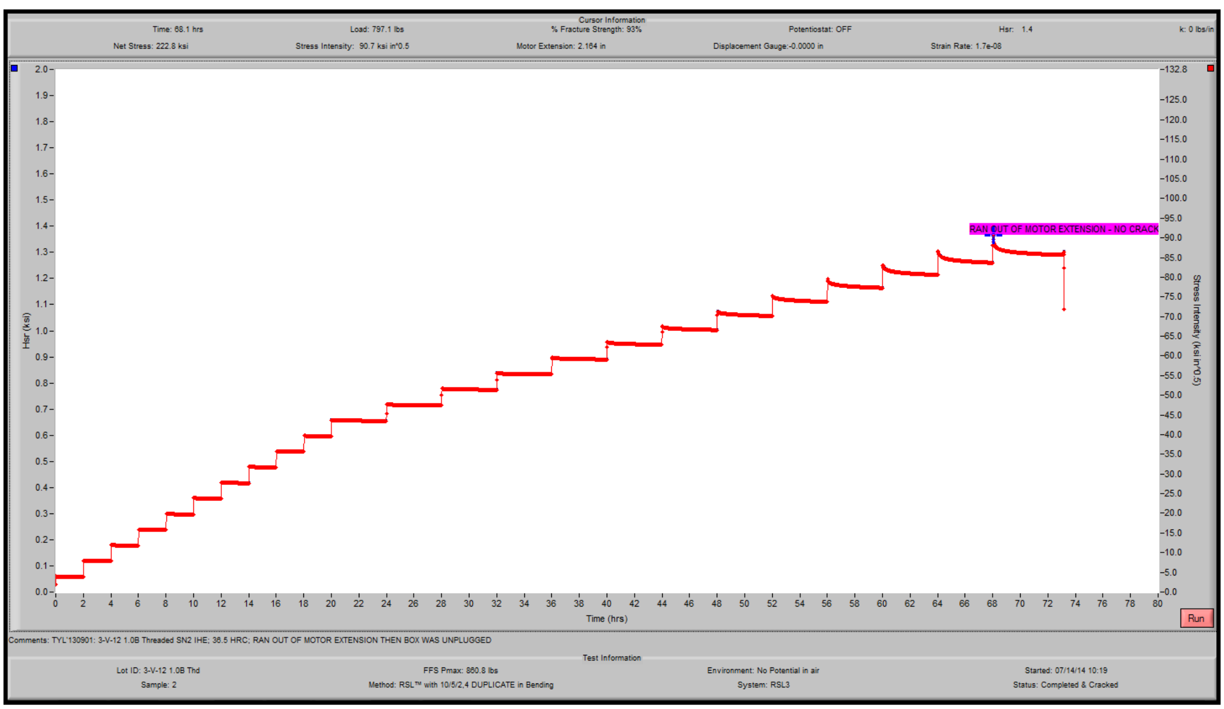


Figure AA.3-2: Rod 3-V-12, 1.0B Thd 2, Graphical IHE Results

AA.3.3 Rod 3-V-12, 1.0B Thd 3, EHE:

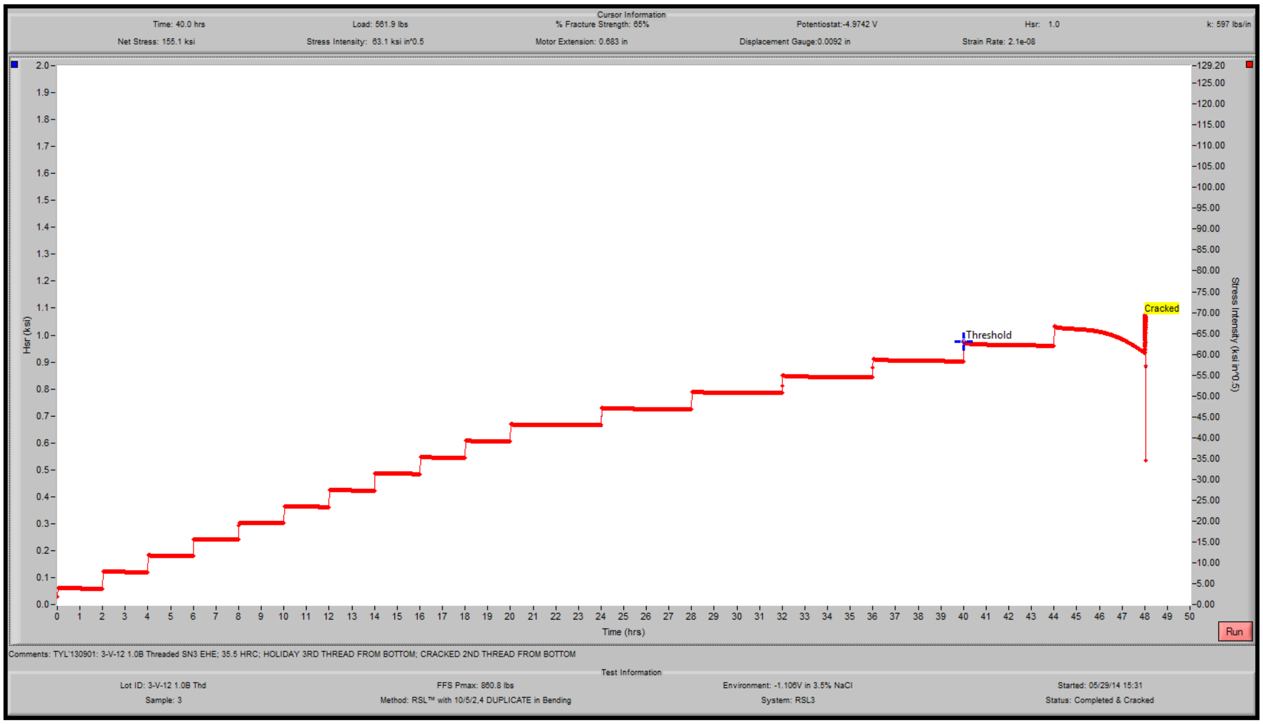


Figure AA.3-3: Rod 3-V-12, 1.0B Thd 3, Graphical EHE Results

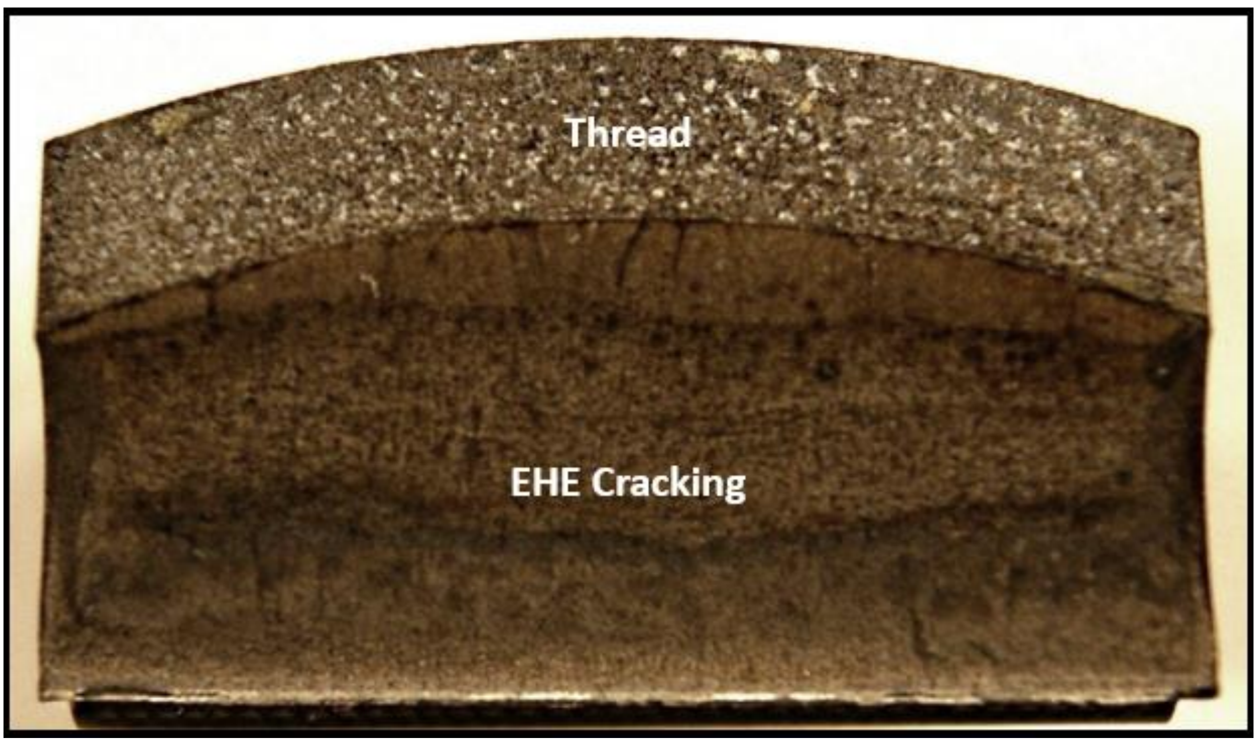


Figure AA.3-4: Rod 3-V-12, 1.0B Thd 3 EHE Fracture Face

AA.3.4 Rod 3-V-12, 1.0B Thd 4, EHE:

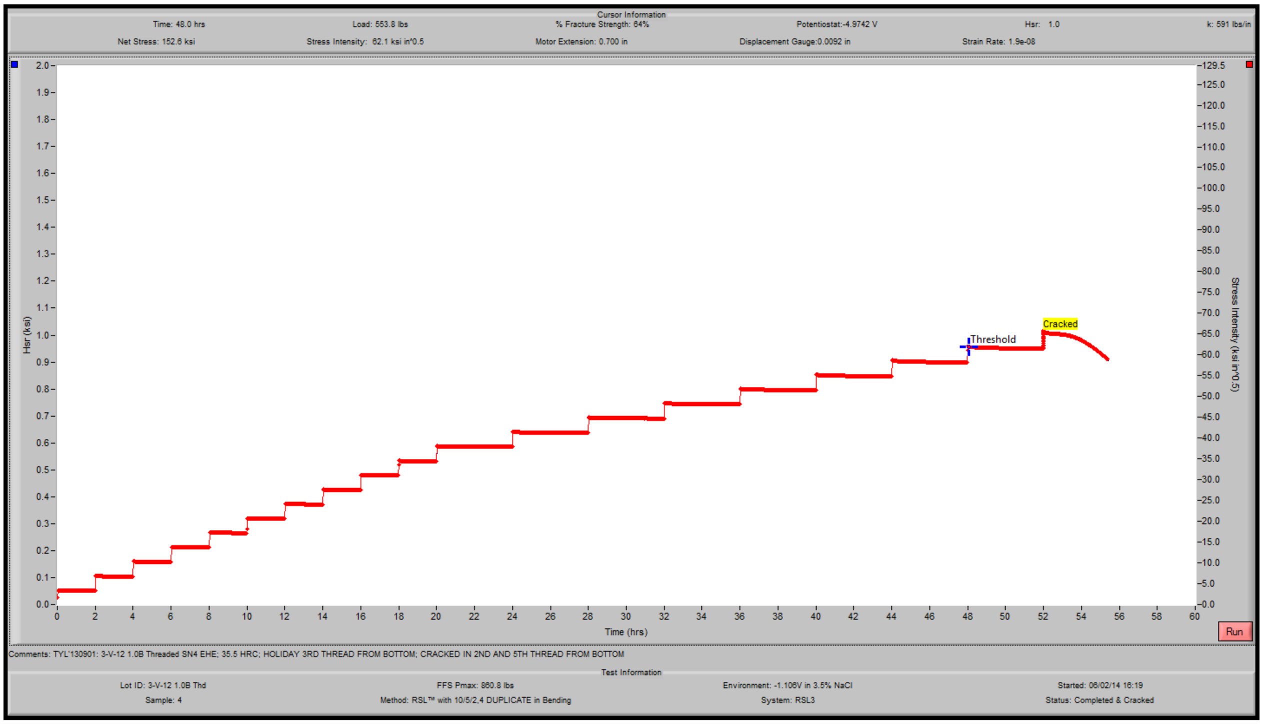


Figure AA.3-5: Rod 3-V-12, 1.0B Thd 4, Graphical EHE Results

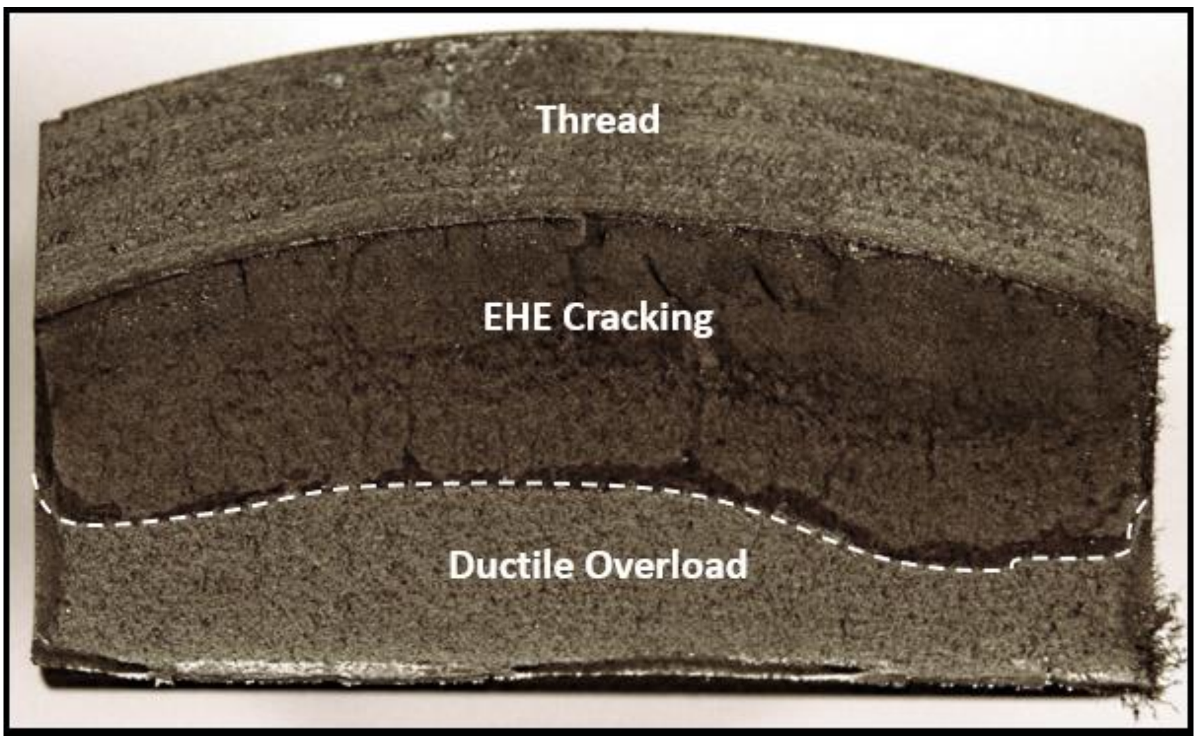


Figure AA.3-6: Rod 3-V-12, 1.0B Thd 4 EHE Fracture Face

AA.3.5 Rod 16, HT 1000 Thd 1, EHE:

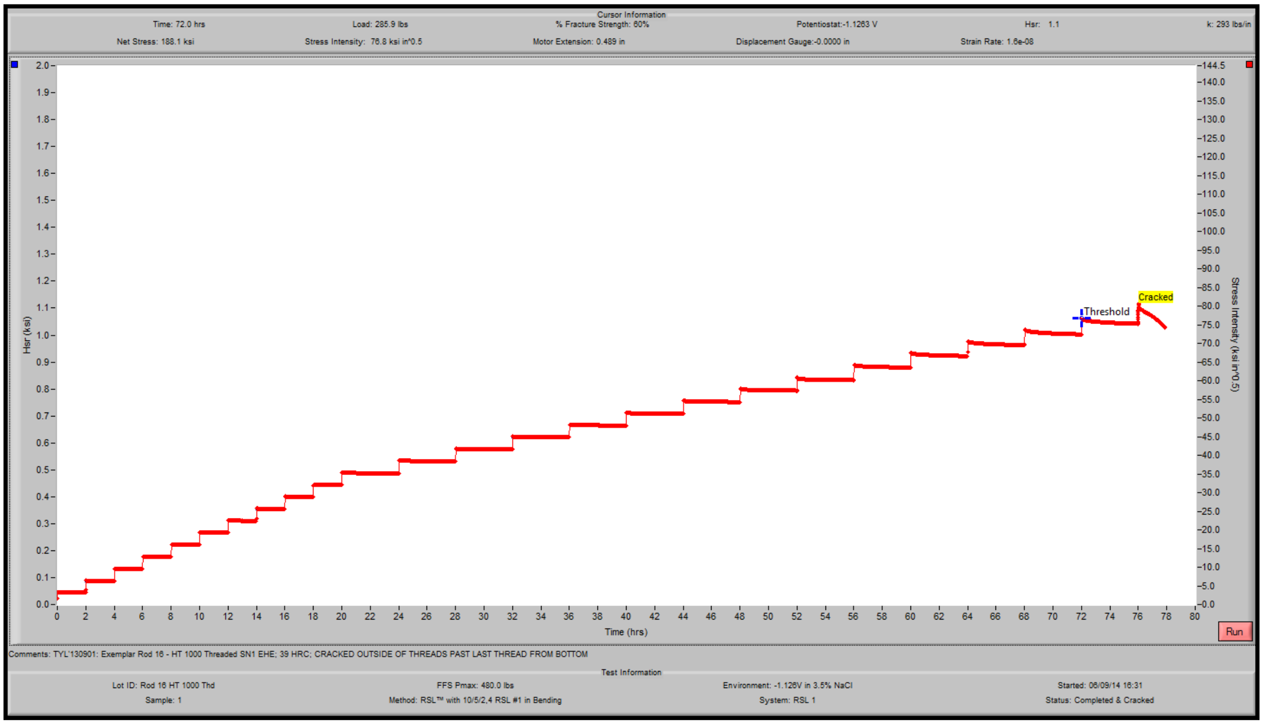


Figure AA.3-7: Rod 16, HT 1000 Thd 1, Graphical EHE Results

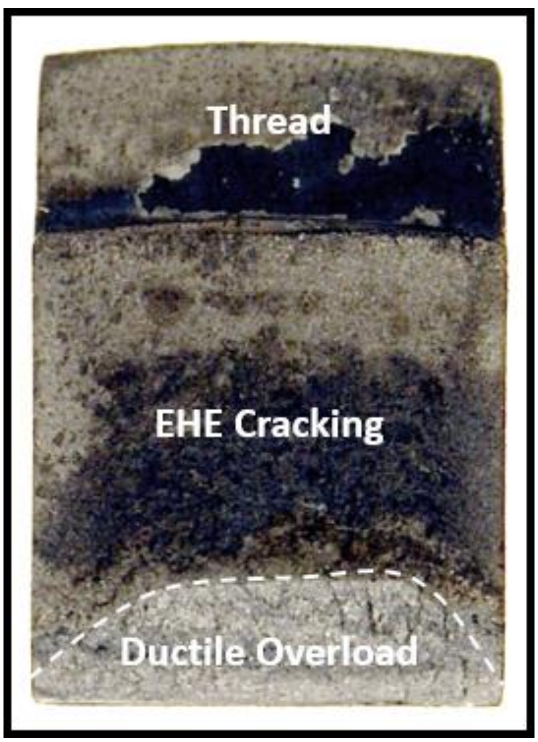


Figure AA.3-8: Rod 16, HT 1000 Thd 1 EHE Fracture Face

AA.3.6 Rod 16, HT 800 Thd 1, EHE:

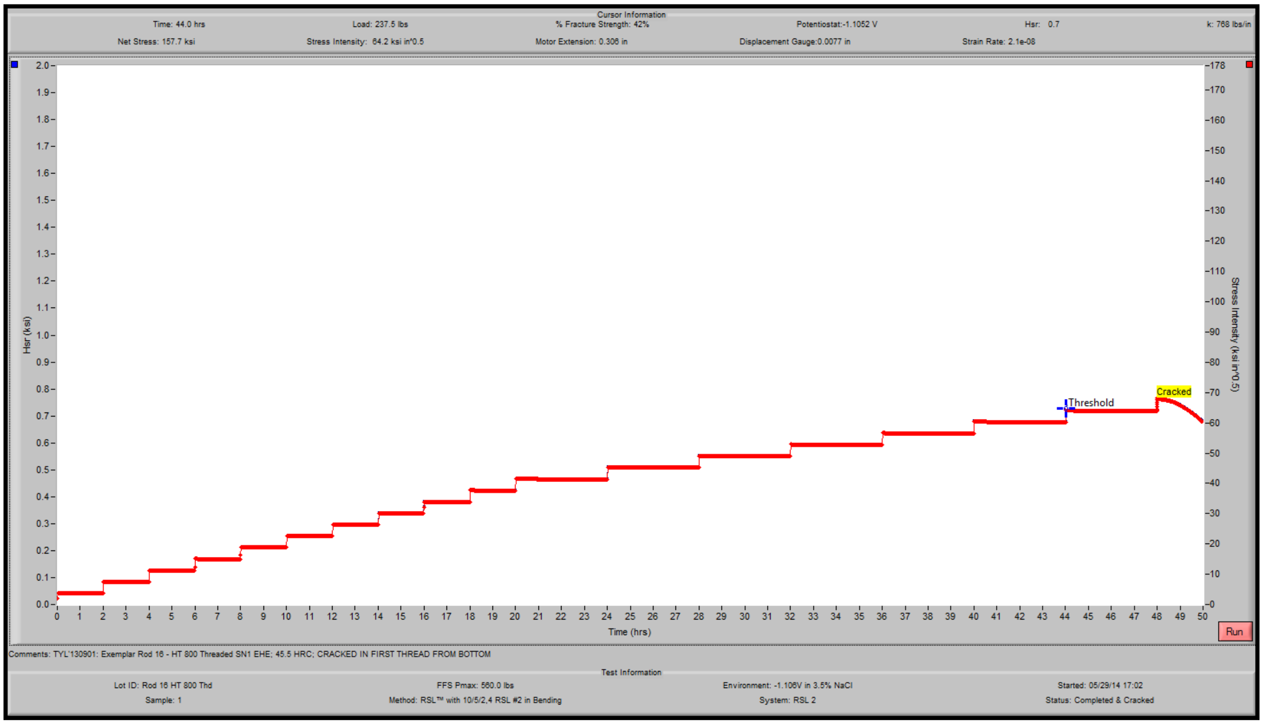


Figure AA.3-9: Rod 16, HT 800 Thd 1, Graphical EHE Results

Figure AA.3-10: Rod 16, HT 800 Thd 1 EHE Fracture Face

AA.3.7 Rod 16, AR Thd 1, EHE:

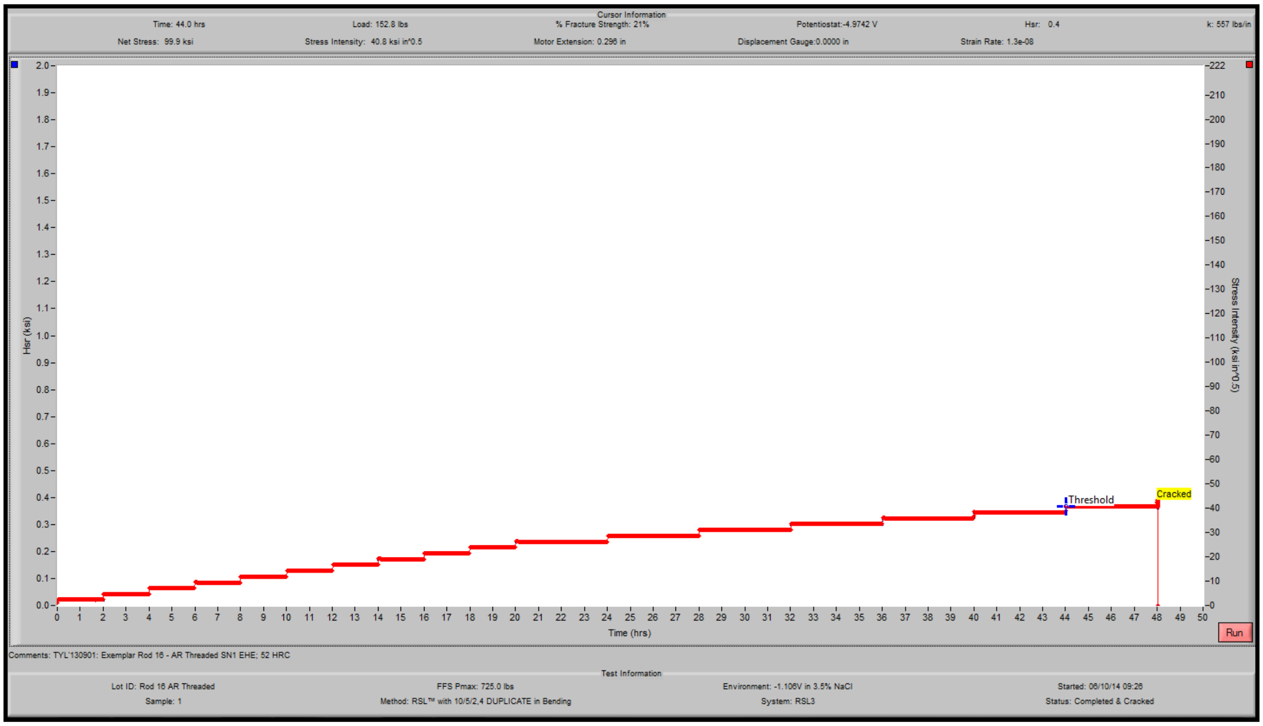


Figure AA.3-11: Rod 16, AR Thd 1, Graphical EHE Results

Figure AA.3-12: Rod 16, AR Thd 1 EHE Fracture Face

Appendix BB: Imposed Potentials

BB.1 Description of Sample

Rod samples were received at LRA and visually examined for general condition and major defects. Samples varied in length from 6 to 24 inches. All specimens used in this appendix had potentials imposed other than the -1.106Vsce used throughout Test V. These specimens were machined from rods selected from Rod 1-V-S2-A2-D and Group ID #3 (Rod 3-V-9, Rod 3-V-10, Rod 3-V-11, and Rod 3-V-12).

The 0.4B threaded specimens and 0.4B fatigue pre-cracked specimens machined from rods selected from Group ID #3 were tested at different imposed potentials ranging from -0.800 to -1.200 Vsce.

The 0.4B threaded specimens machined from the rod selected from Rod 1-V-S2-A2-D were tested without any imposed potential while immersed in 3.5% NaCl solution. This exposed the specimens to their Open Current Potential (OCP) imposed by the zinc coating. The measured OCP of the rods from Group ID #1 are more positive than the typical imposed Test V potential of -1.106 Vsce. To avoid anodic corrosion, the adapter and bare steel on the specimens were masked off with stop off lacquer.

From these tests it was verified that a more negative applied voltage versus a saturated calomel reference electrode will result in a more conservative threshold stress intensity than a more positively applied voltage. Further information on these rods can be found in Appendix E Rod 1-V-S2-A2-D, Appendix F Rod 3-V-9, Appendix G Rod 3-V-10, Appendix H Rod 3-V-11, and Appendix I Rod 3-V-12.

BB.2 Summary

Detailed data are listed in the following summary table. The results from this table are summarized in the following "checker board" tables. The highlighted cells represent the threshold for each respective potential.

BB.2.1 Fatigue Pre-cracked Results:

Test V ASTM F1624 Bolt Specimen Results Special Project: Effect of Potential					
LRA Job No.:	**TYL130901**				
Special Project:	**Effect of Potential**				
Product Form:	**1e**				
Rod OD:	**3"**				
	Sample #/ID	**HRC**	**Environment**		**K-EHE**
Fatigue Pre-cracked	**3-V-12 OD 12, EHE**	**36.0**	**3.5% NaCl @ -0.800 V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	57.0 0.35 0.64 1.2
	3-V-12 OD 7, EHE	**35.5**	**3.5% NaCl @ -0.900 V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	53.5 0.34 0.60 2.5
	3-V-12 OD 8, EHE	**36.0**	**3.5% NaCl @ -0.900 V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	56.2 0.35 0.63 2.2
	3-V-12 OD 9, EHE	**36.0**	**3.5% NaCl @ -0.975 V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	44.2 0.27 0.50 1.6

Test V ASTM F1624 Bolt Specimen Results Special Project: Effect of Potential					
LRA Job No.:	**TYL130901**				
Special Project:	**Effect of Potential**				
Product Form:	**1e**				
Rod OD:	**3"**				
	Sample #/ID	**HRC**	**Environment**		**K-EHE**
Fatigue Pre-cracked	**3-V-11 OD 10, EHE**	**36.5**	**3.5% NaCl @ -1.060V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	29.5 0.18 0.33 1.9
	3-V-11 OD 11, EHE	**36.0**	**3.5% NaCl @ -1.060V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	31.1 0.19 0.35 2.0
	3-V-11 OD 13, EHE	**35.5**	**3.5% NaCl @ -1.060V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	29.2 0.18 0.33 1.3
	3-V-9 OD 7, EHE	**36.5**	**3.5% NaCl @ -1.200V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	27.5 0.17 0.31 1.4
	3-V-9 OD 8, EHE	**36.0**	**3.5% NaCl @ -1.200V**	$K_{threshold}$ DTI_{th} Fu Strain Rate ($x10^{-8}$ in/in/sec)	20.5 0.13 0.23 0.8

BB.2.2 Threaded Results:

Test V ASTM F1624 Bolt Specimen Results
Special Project: Effect of Potential

LRA Job No.:	**TYL130901**
Special Project:	**Effect of Potential**
Product Form:	**1e**
Rod OD:	**3"**

	Sample #/ID	**HRC**	**Environment**		**P-EHE**
Threaded	**3-V-10 Thd 5, EHE**	**36.5**	**3.5% NaCl @ -0.850V**	$P_{threshold}$* (lbs)	313.1
				Fu	1.03
				Hsr	1.4
				Strain Rate ($x10^{-8}$ in/in/sec)	0.7
	3-V-11 Thd 11	**35.5**	**3.5% NaCl @ -0.950V**	$P_{threshold}$* (lbs)	291.5
				Fu	0.96
				Hsr	1.3
				Strain Rate ($x10^{-8}$ in/in/sec)	1.2
	3-V-9 Thd 4, EHE	**35.0**	**3.5% NaCl @ -1.106V**	$P_{threshold}$* (lbs)	213.7
				Fu	0.70
				Hsr	1.0
				Strain Rate ($x10^{-8}$ in/in/sec)	1.2
	3-V-12 1.0B Thd 5, EHE	**36.0**	**3.5% NaCl @ -1.200V**	$P_{threshold}$* (lbs)	213.7
				Fu	0.70
				Hsr	0.9
				Strain Rate ($x10^{-8}$ in/in/sec)	1.9
	1-V-S2-A2-D Thd 10, EHE	**36.0**	**3.5% NaCl @ OCP**	$P_{threshold}$* (lbs)	253.4
				Fu	0.83
				Hsr	1.1
				Strain Rate ($x10^{-8}$ in/in/sec)	0.8
	1-V-S2-A2-D Thd 11, EHE	**36.0**	**3.5% NaCl @ OCP**	$P_{threshold}$* (lbs)	262.0
				Fu	0.86
				Hsr	1.2
				Strain Rate ($x10^{-8}$ in/in/sec)	0.37

BB.2.3 Summary Table:

Summary Table of Test V ASTM F1624 Bolt Specimen Results
Special Project: Effect of Potential
RSL™ (B) 4-pt Bend Test

LRA Job No.:	**TYL130901**
Special Project:	**Effect of Potential**
Product Form:	**1e**
Rod OD:	**3"**

	S/N	Environment	Hardness (HRC)	UTS (ksi)	P_{target} (lbs)	Pmax (lbs)	Pmax, P_{th} (lbs)	%FS (Pth/Pmax)	K_{max}, KI_{scc}, $KIp_{\text{-EHE}}$ (ksi√in)	DTI (√in)	σ_{net} (ksi)	Rsb, Hsrb	δε/δt ($10^{-8}s^{-1}$)	a (in)	Step Load Profile	P* (lbs)	Fu	Comments
Fatigue Pre-cracked	3-V-12 OD 12, EHE	3.5% NaCl @ -0.800 V	36.0	162	65.0	78.0	61.6	66.8%	57.0	0.35	195.1	1.2	1.2	0.2141	10/5/1,8		0.64	
	3-V-12 OD 7, EHE	3.5% NaCl @ -0.900 V	35.5	159	68.0	71.4	57.8	62.7%	53.5	0.34	183.5	1.2	2.5	0.2157	10/5/2,4		0.60	
	3-V-12 OD 8, EHE	3.5% NaCl @ -0.900 V	36.0	162	60.0	72.1	59.9	65.9%	56.2	0.35	193.9	1.2	2.2	0.2159	10/5/2,4		0.63	
	3-V-12 OD 9, EHE	3.5% NaCl @ -0.975 V	36.0	162	45.0	58.5	49.4	51.8%	44.2	0.27	150.2	0.9	1.6	0.2111	10/5/2,4		0.50	
	3-V-11 OD 10, EHE	3.5% NaCl @ -1.060V	36.5	164	59.5	38.7	32.6	34.2%	29.5	0.18	100.6	0.6	1.9	0.2130	10/5/2,4		0.33	
	3-V-11 OD 11, EHE	3.5% NaCl @ -1.060V	36.0	162	59.5	41.7	32.6	36.1%	31.1	0.19	108.1	0.7	2.0	0.2200	10/5/2,4		0.35	
	3-V-11 OD 13, EHE	3.5% NaCl @ -1.060V	35.5	159	35.0	35.0	31.4	33.9%	29.2	0.18	99.9	0.6	1.3	0.2141	10/5/2,4		0.33	
	3-V-9 OD 7, EHE	3.5% NaCl @ -1.200V	36.5	164	40.0	36.0	29.9	31.8%	27.5	0.17	94.4	0.6	1.4	0.2158	10/5/2,4		0.31	
	3-V-9 OD 8, EHE	3.5% NaCl @ -1.200V	36.0	162	20.0	29.0	22.0	23.7%	20.5	0.13	70.8	0.4	0.8	0.2170	10/5/2,4		0.23	
Threaded	3-V-10 Thd 5, EHE	3.5% NaCl @ -0.850V	36.5	164	180.0	324.0	314.4	92.3%	91.3	0.56	225.4	1.4	0.7	N/A	10/5/1,8	313.1	1.03	Cracked in Holiday
	3-V-11 Thd 11	3.5% NaCl @ -0.950V	35.5	159	362.0	317.1	305.2	85.2%	85.0	0.53	209.6	1.3	1.2	N/A	10/5/1,8	291.5	0.96	Did Not Crack In Holiday
	3-V-9 Thd 4, EHE	3.5% NaCl @ -1.106V	35.0	157	175.0	335.1	243.9	62.4%	62.3	0.40	150.1	1.0	1.2	N/A	10/5/2,4	213.7	0.70	Did Not Crack In Holiday
	3-V-12 1.0B Thd 5, EHE	3.5% NaCl @ -1.200V	36.0	162	618.0	587.2	554.1	62.7%	62.3	0.39	152.9	0.9	1.9	N/A	10/5/2,4	213.7	0.70	Did Not Crack In Holiday
	1-V-S2-A2-D Thd 10, EHE	3.5% NaCl @ OCP	36.0	162	204.0	275.9	262.6	77.7%	73.9	0.46	183.8	1.1	0.8	N/A	10/5/1,8	253.4	0.83	Did Not Crack In Holiday
	1-V-S2-A2-D Thd 11, EHE	3.5% NaCl @ OCP	36.0	162	204.0	295.9	282.6	80.3%	76.4	0.47	189.8	1.2	0.4	N/A	10/5/1,16	262.0	0.86	No Holiday

BB.3 Fatigue Pre-cracked Specimen Test Results

BB.3.1 3-V-12 OD 12, EHE @ -0.800 Vsce:

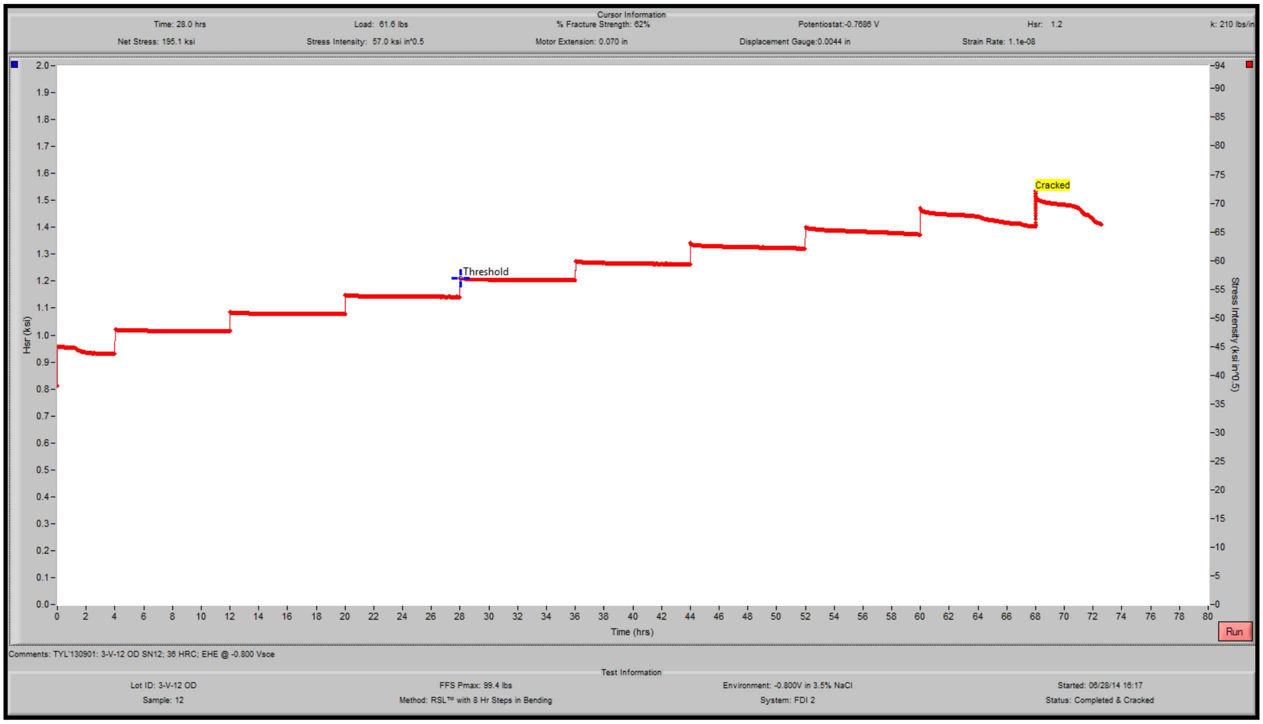


Figure BB.3-1: Rod 3-V-12 OD 12, Graphical EHE Results

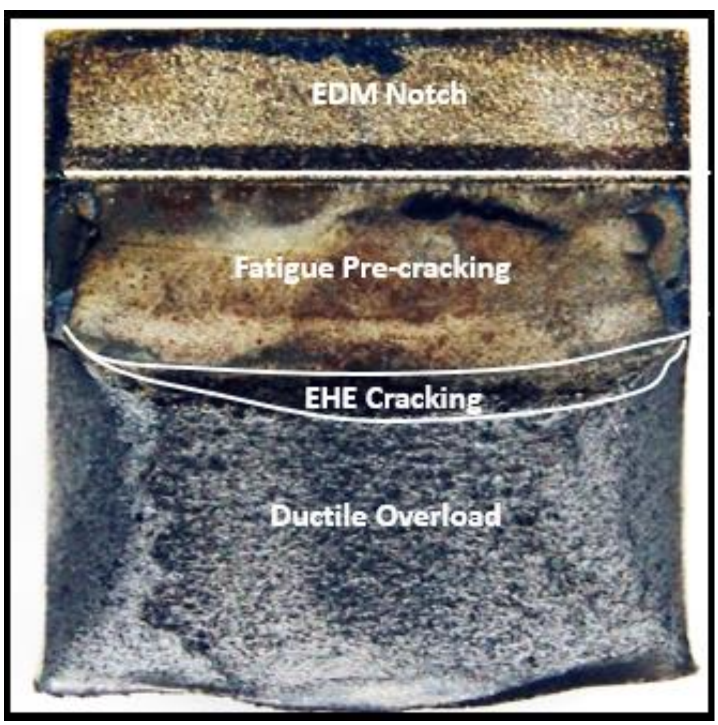


Figure BB.3-2: Fracture Face of Rod 3-V-12 OD 12, EHE

BB.3.2 3-V-12 OD 7, EHE @ -0.900 Vsce:

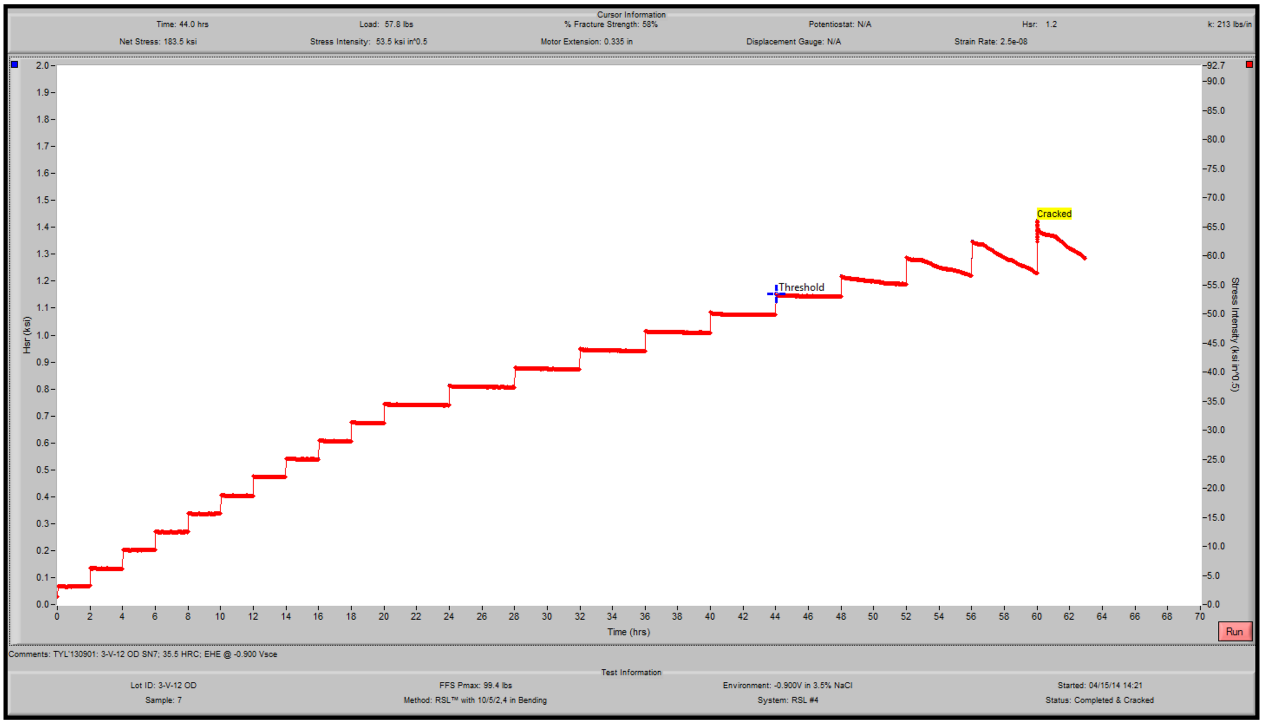


Figure BB.3-3: Rod 3-V-12 OD 7, Graphical EHE Results

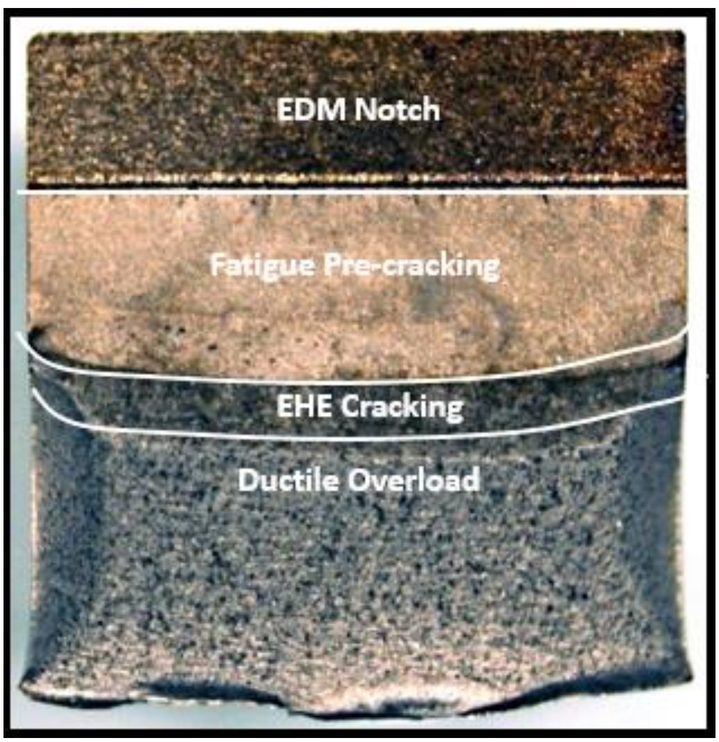


Figure BB.3-4: Fracture Face of Rod 3-V-12 OD 7, EHE

BB.3.3 3-V-12 OD 8, EHE @ -0.900 Vsce:

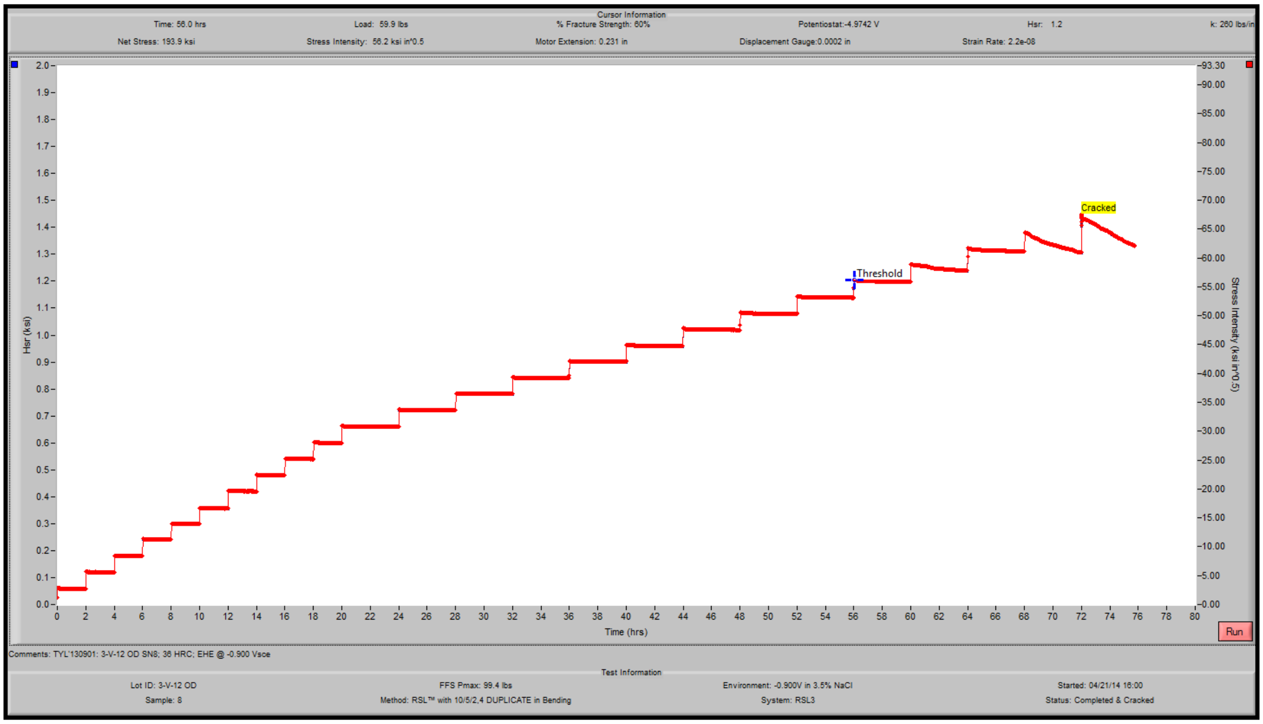


Figure BB.3-5: Rod 3-V-12 OD 8, Graphical EHE Results

Figure BB.3-6: Fracture Face of Rod 3-V-12 OD 8, EHE

BB.3.4 3-V-12 OD 9, EHE @ -0.900 Vsce:

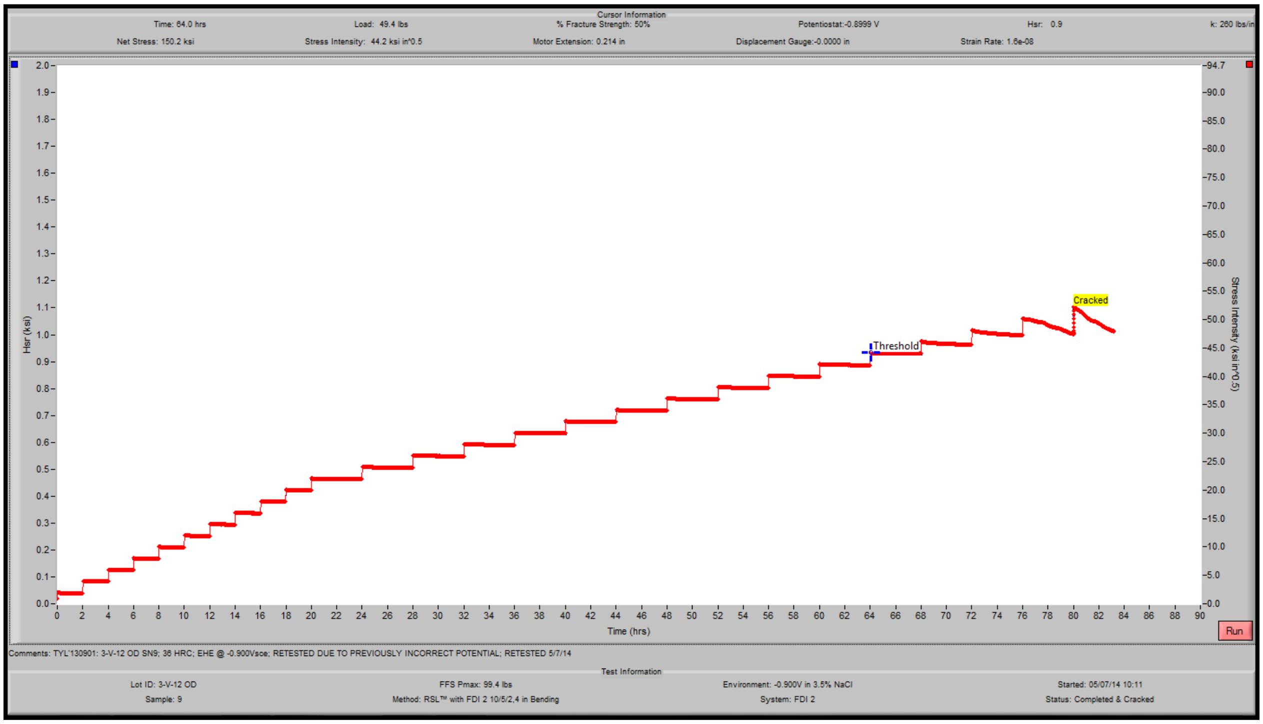


Figure BB.3-7: Rod 3-V-12 OD 9, Graphical EHE Results

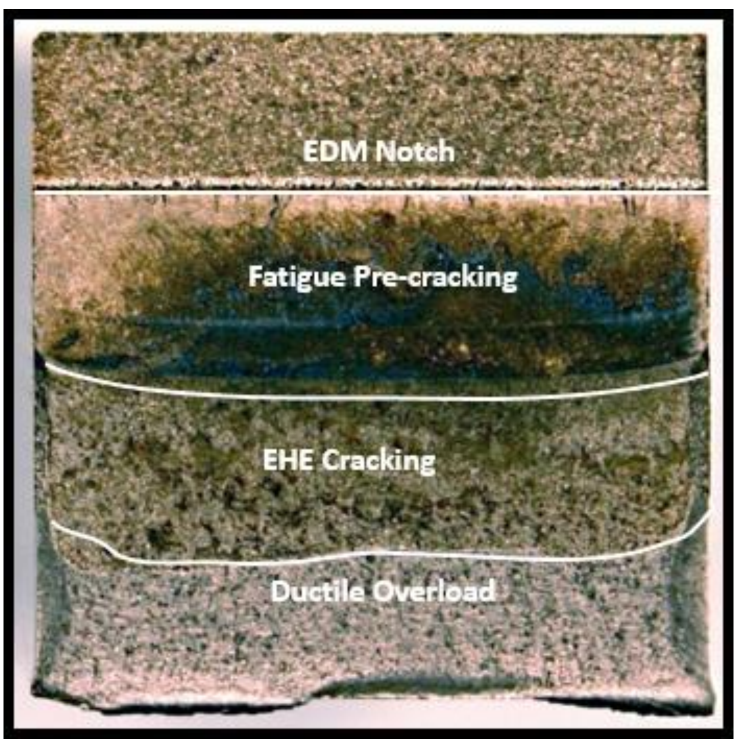


Figure BB.3-8: Fracture Face of Rod 3-V-12 OD 9, EHE

BB.3.5 3-V-11 OD 10, EHE @ -1.060 Vsce:

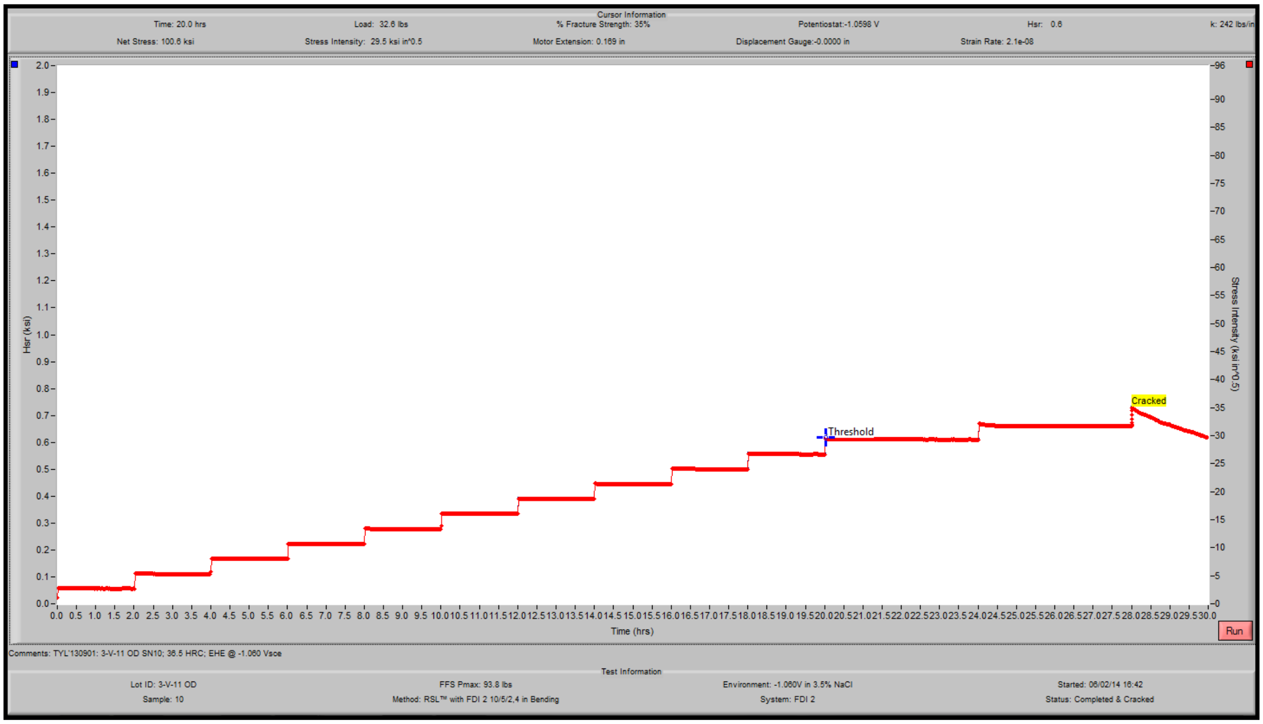


Figure BB.3-9: Rod 3-V-11 OD 10, Graphical EHE Results

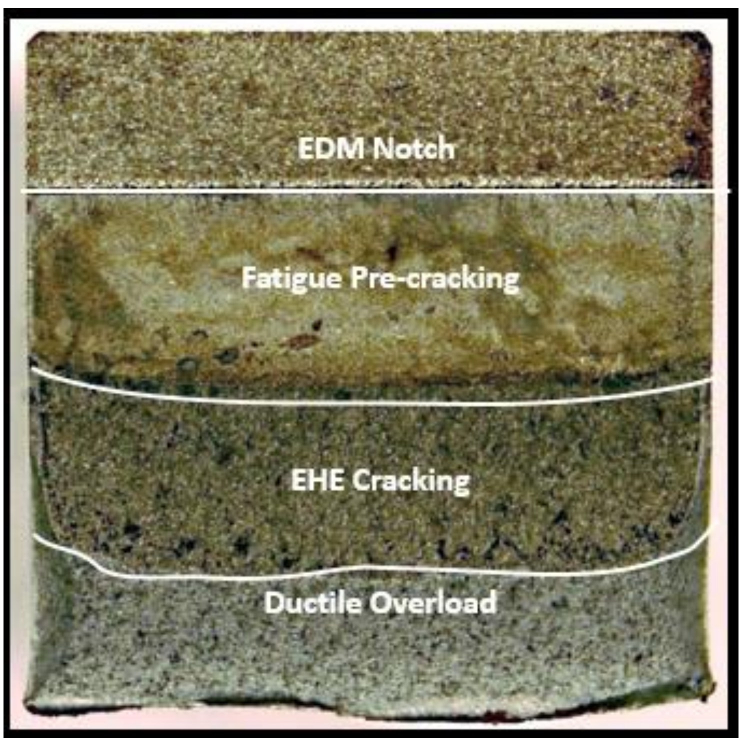


Figure BB.3-10: Fracture Face of Rod 3-V-11 OD 10, EHE

BB.3.6 3-V-11 OD 11, EHE @ -1.060Vsce:

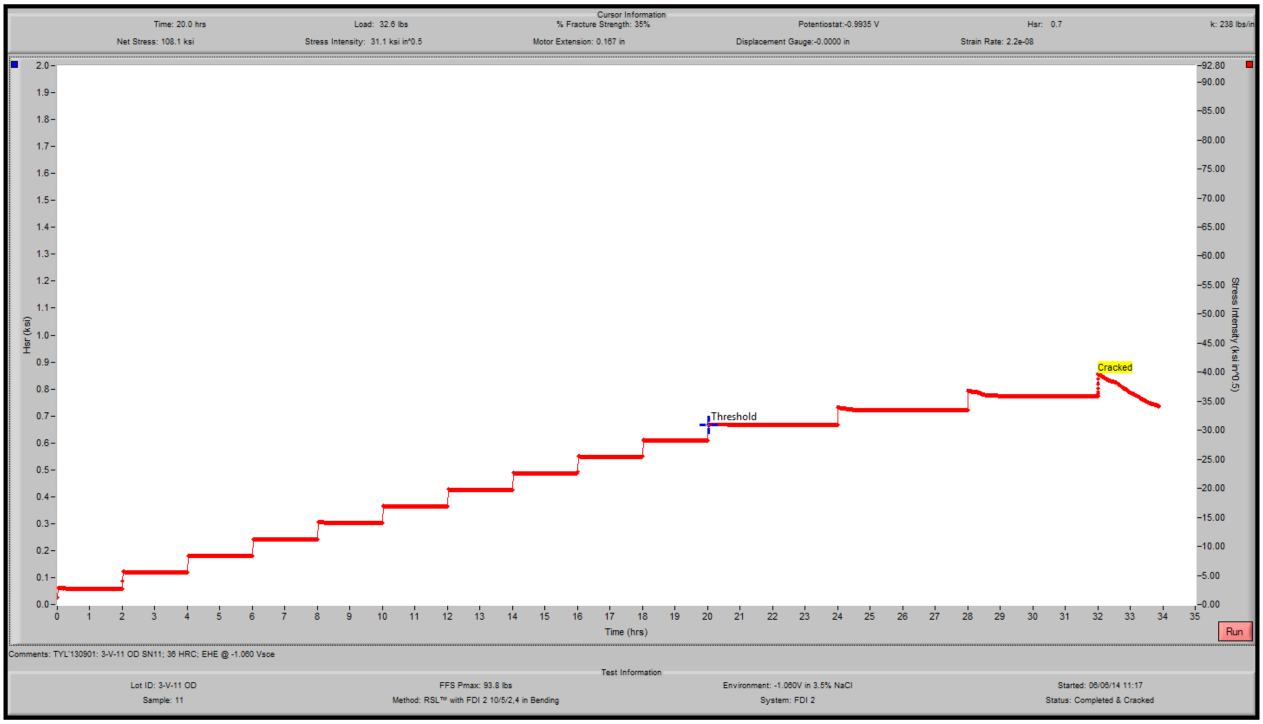


Figure BB.3-11: Rod 3-V-11 OD 11, Graphical EHE Results

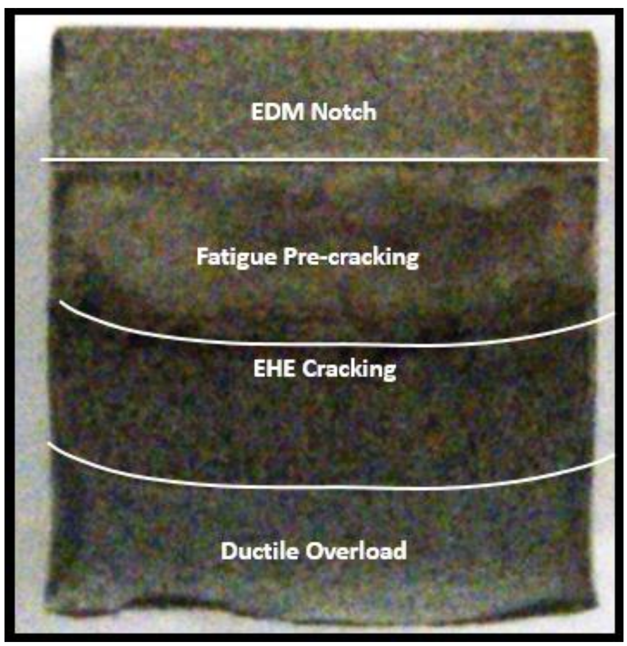


Figure BB.3-12: Fracture Face of Rod 3-V-11 OD 11, EHE

BB.3.7 3-V-11 OD 13, EHE @ -1.060 Vsce:

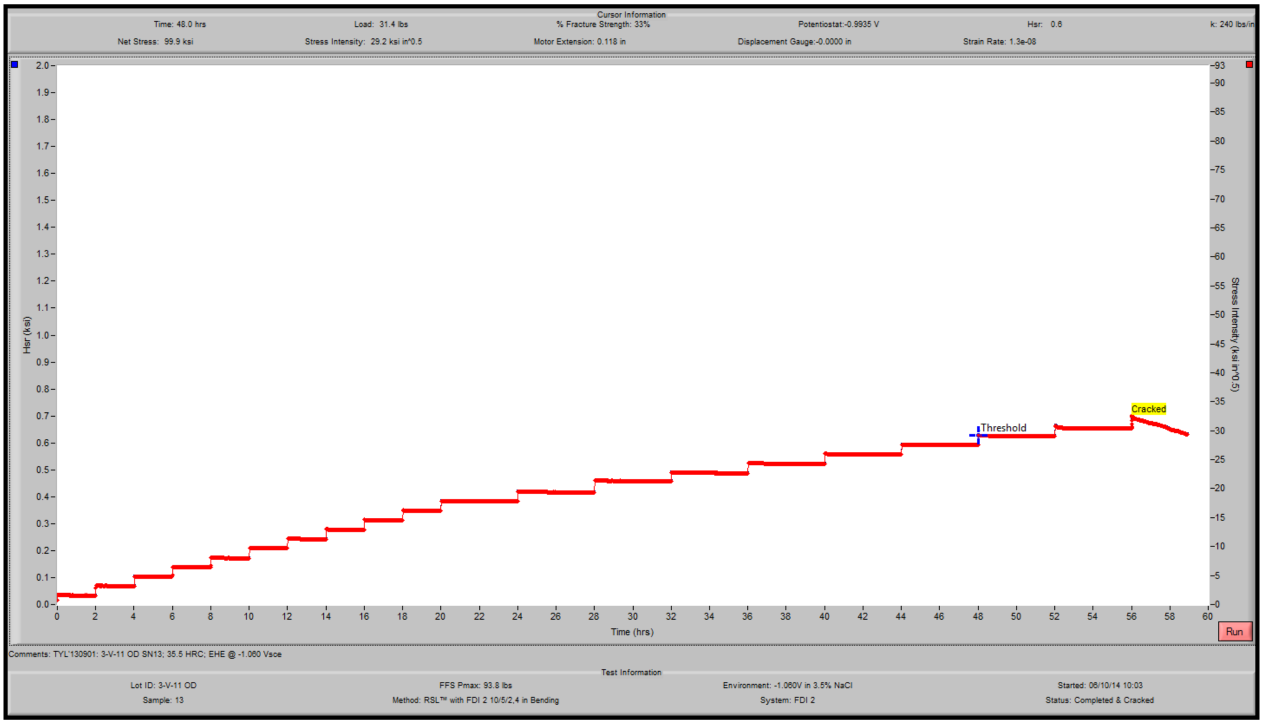


Figure BB.3-13: Rod 3-V-11 OD 13, Graphical EHE Results

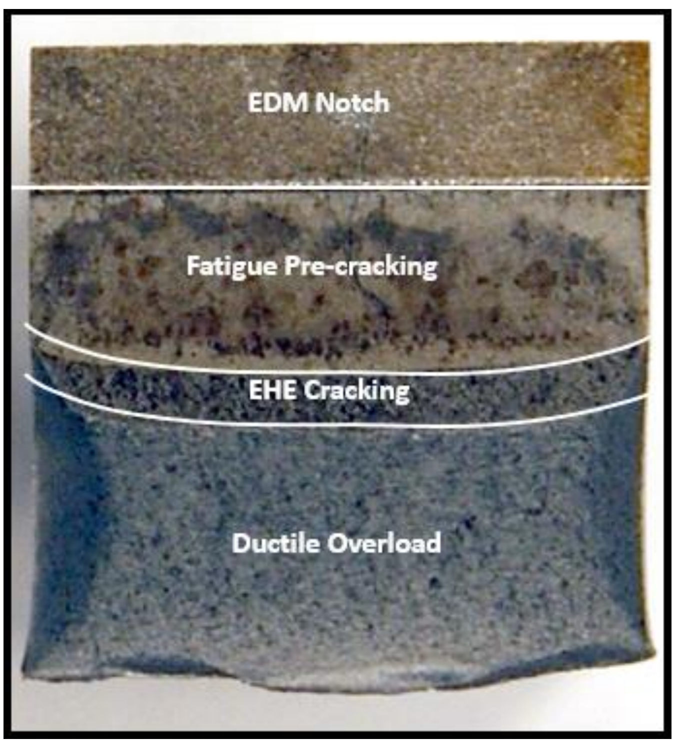


Figure BB.3-14: Fracture Face of Rod 3-V-11 OD 13, EHE

BB.3.8 3-V-9 OD 7, EHE @ -1.200 Vsce:

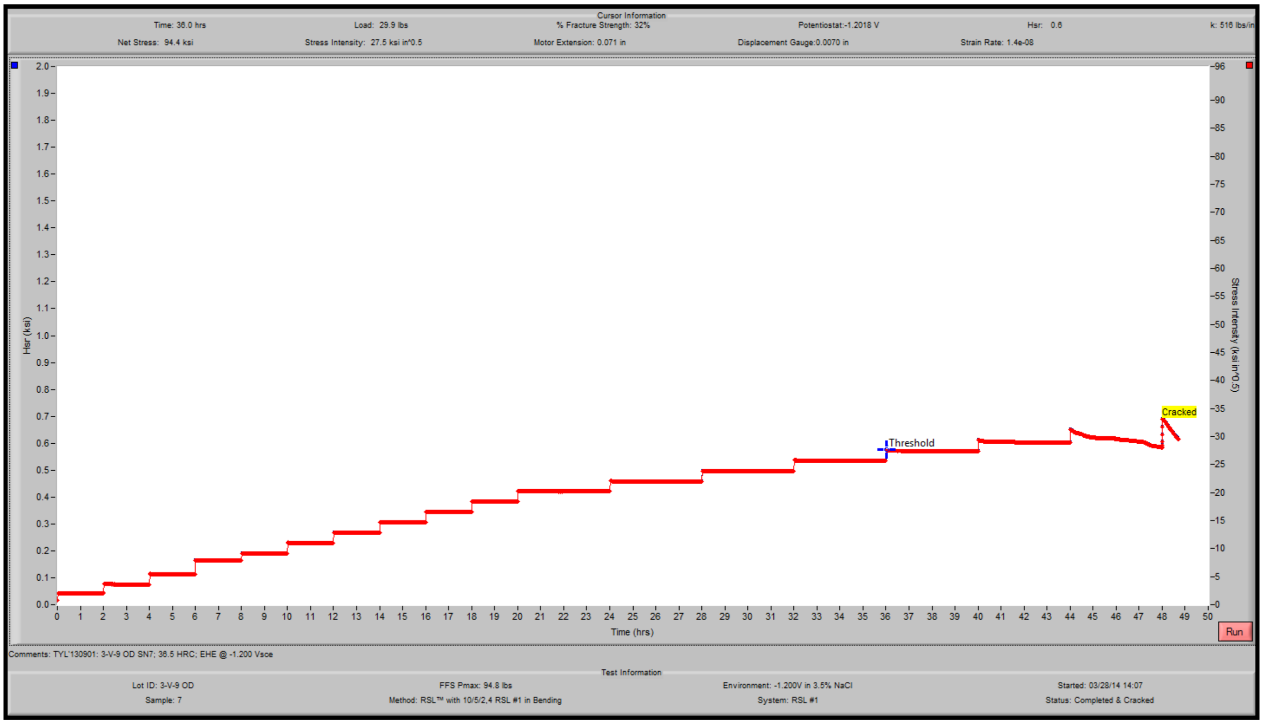


Figure BB.3-15: Rod 3-V-9 OD 7, Graphical EHE Results

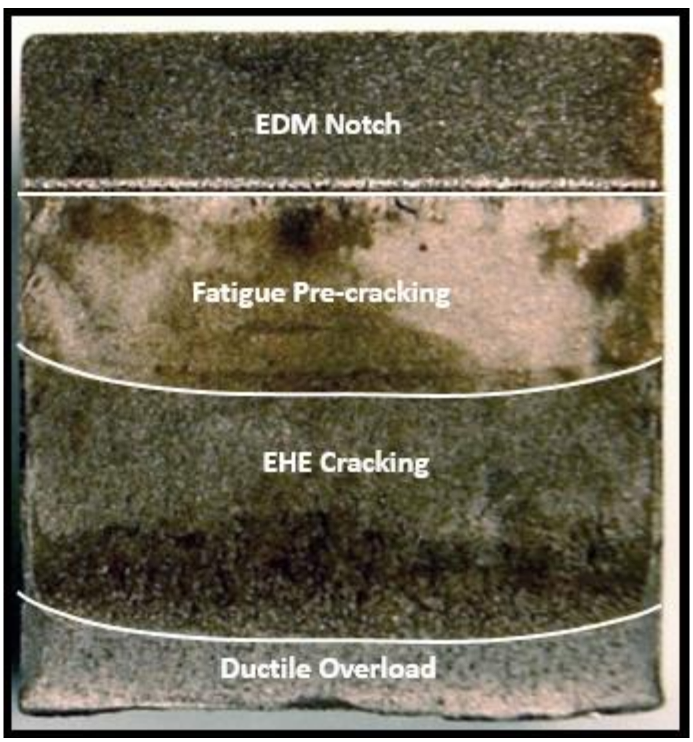


Figure BB.3-16: Fracture Face of Rod 3-V-9 OD 7, EHE

BB.3.9 3-V-9 OD 8, EHE @ -1.200 Vsce:

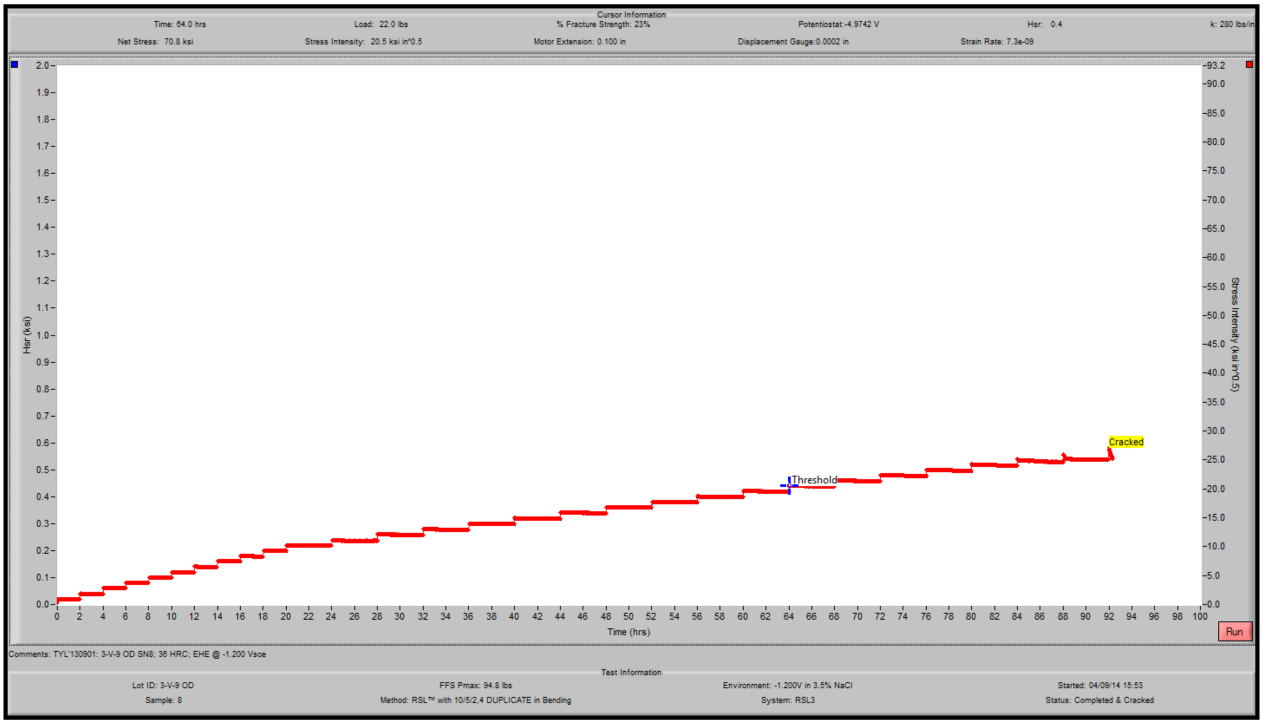


Figure BB.3-17: Rod 3-V-9 OD 8, Graphical EHE Results

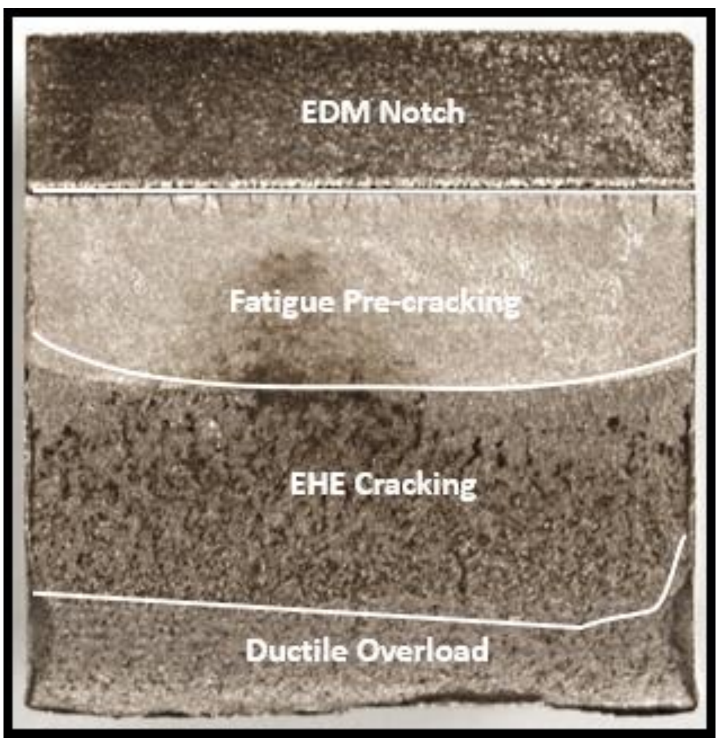


Figure BB.3-18: Fracture Face of Rod 3-V-9 OD 8, EHE

BB.4 Threaded Specimen Test Results

BB.4.1 3-V-10 Thd 5, EHE @ -0.850 Vsce:

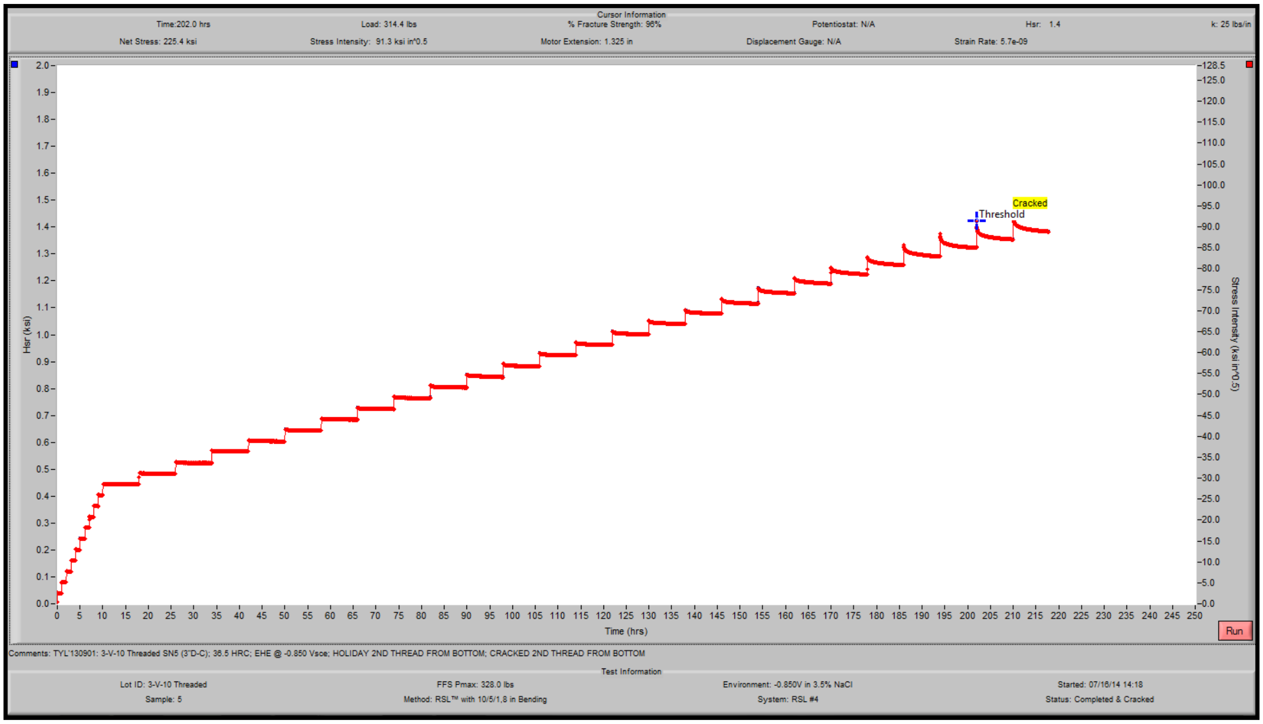


Figure BB.4-1: Rod 3-V-10 Thd 5, Graphical EHE Results

Figure BB.4-2: Rod 3-V-10 Thd 5 EHE Fracture Face

BB.4.2 3-V-11 Thd 11, EHE @ -0.950 Vsce:

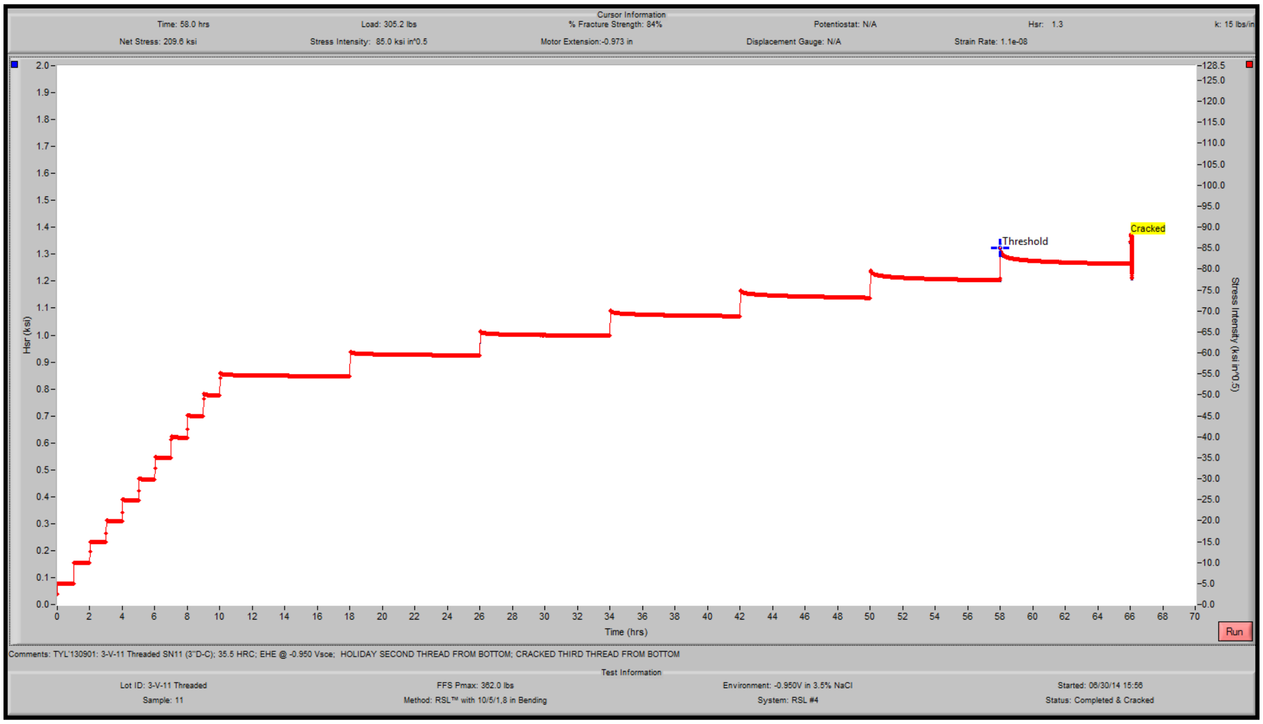


Figure BB.4-3: Rod 3-V-11 Thd 11, Graphical EHE Results

Figure BB.4-4: Rod 3-V-11 Thd 11 EHE Fracture Face

BB.4.3 3-V-9 Thd 4, EHE @ -1.106 Vsce:

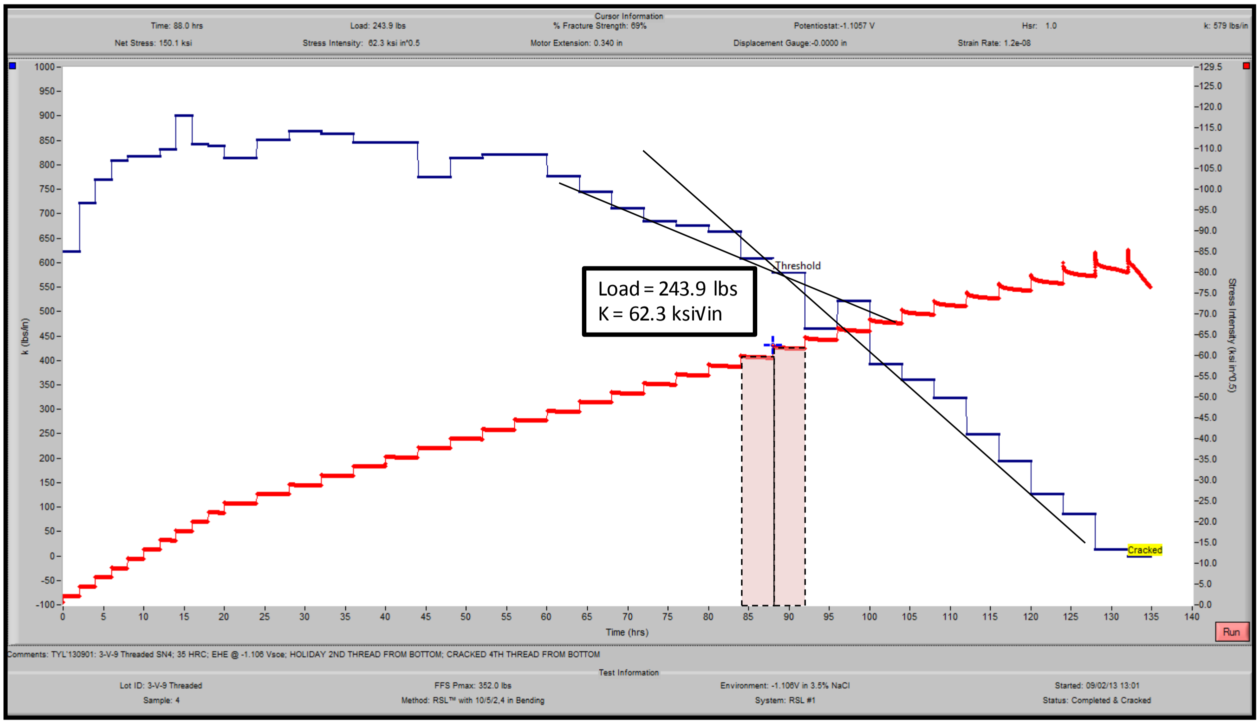


Figure BB.4-5: Rod 3-V-9 Thd 4, Graphical EHE Results

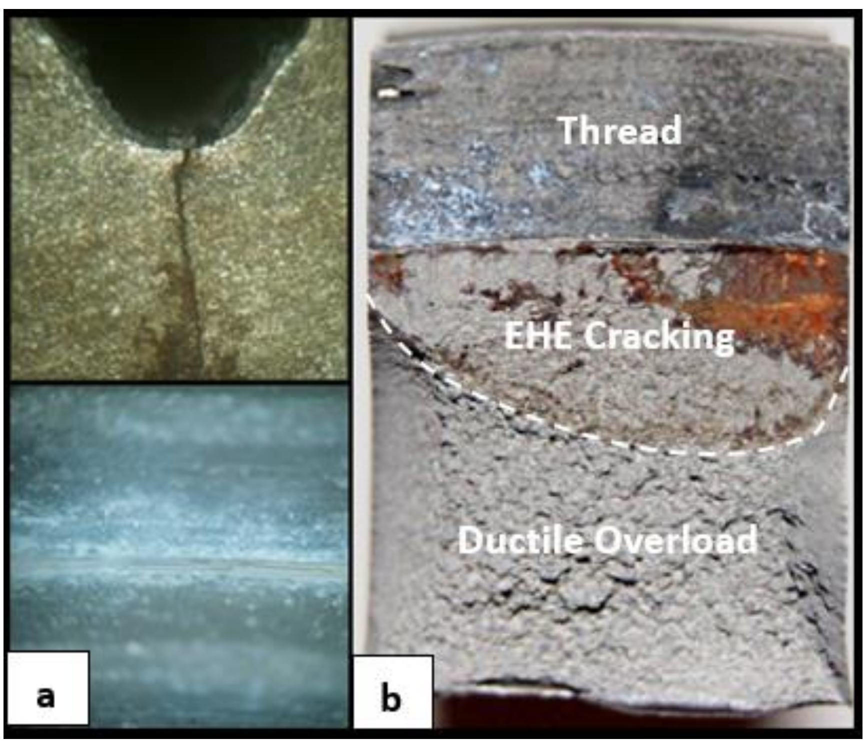


Figure BB.4-6: Rod 3-V-9 Thd 4 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

BB.4.4 3-V-12 1.0B Thd 5, EHE @ -1.200 Vsce:

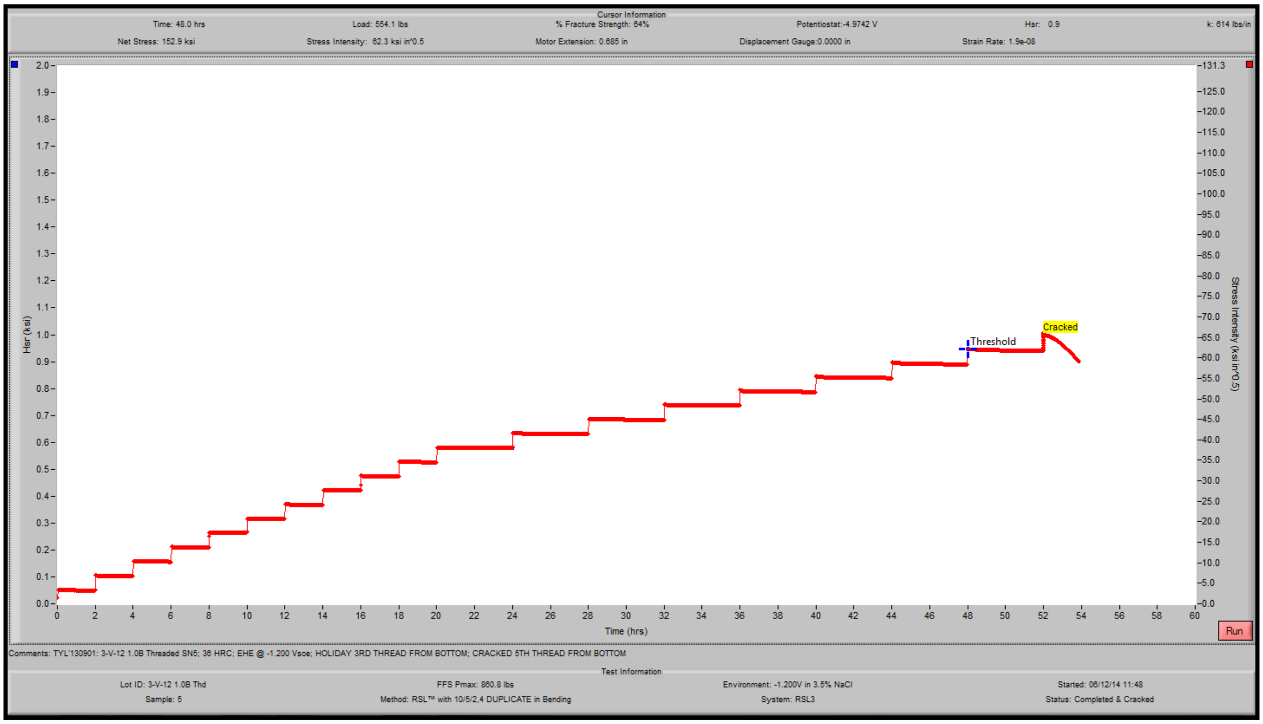


Figure BB.4-7: Rod 3-V-12 1.0B Thd 5, Graphical EHE Results

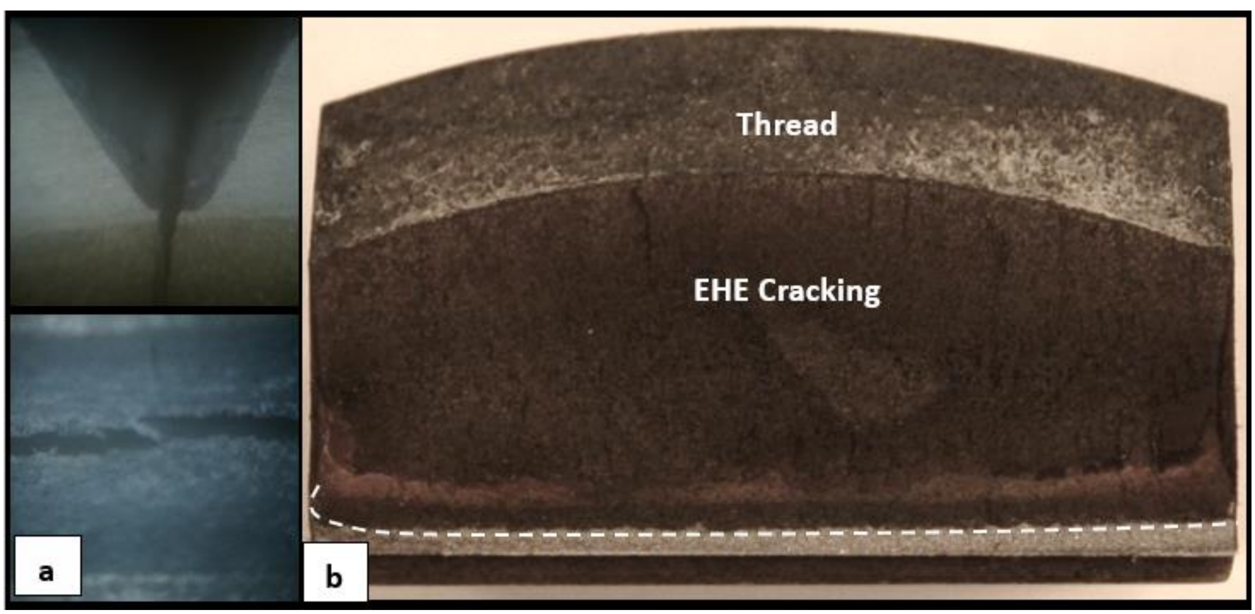


Figure BB.4-8: Rod 3-V-12 1.0B Thd 5 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

BB.4.5 1-V-S2-A2-D Thd 10, EHE @ OCP:

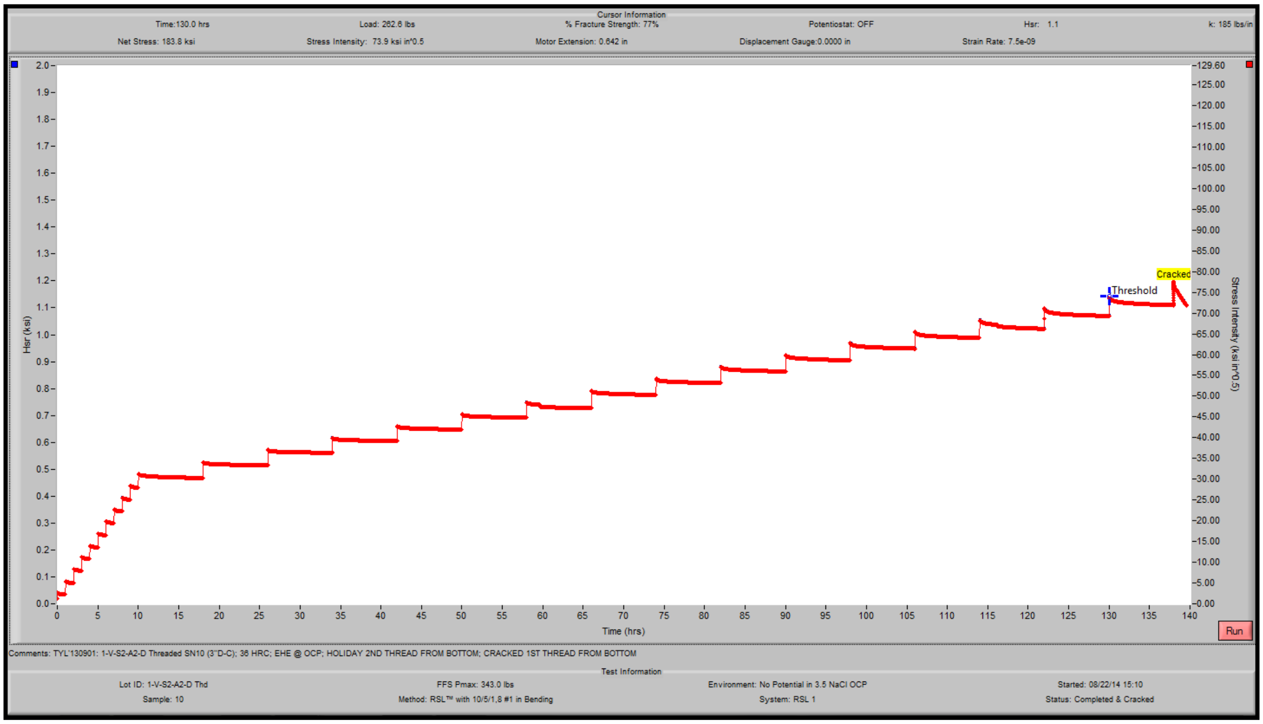


Figure BB.4-9: Rod 1-V-S2-A2-D Thd 10, Graphical EHE Results

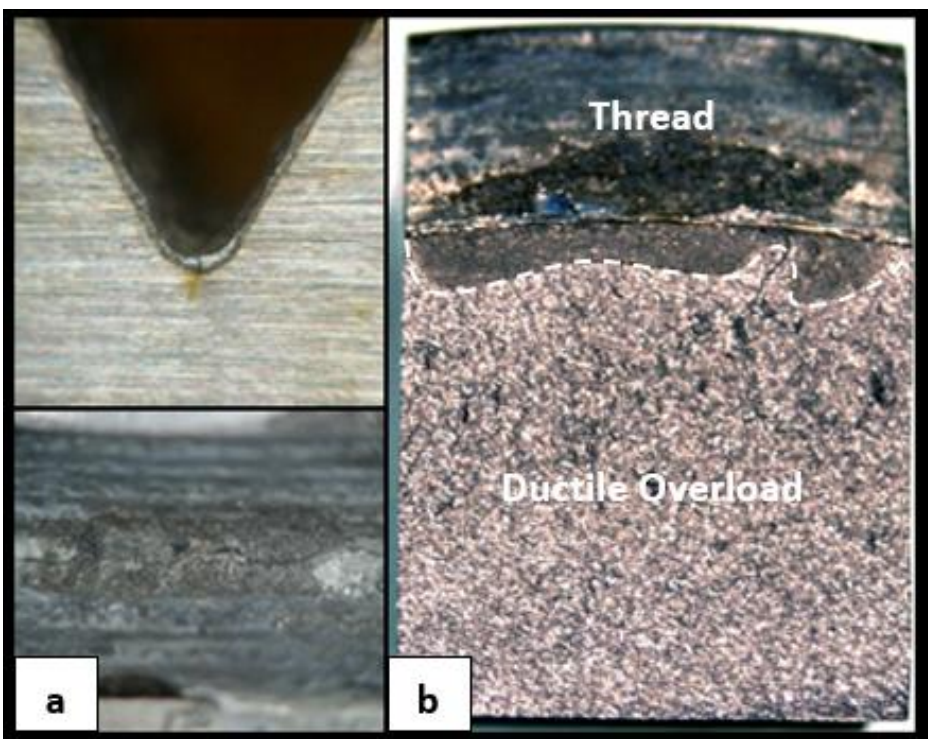


Figure BB.4-10: Rod 1-V-S2-A2-D Thd 10 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face

BB.4.6 1-V-S2-A2-D Thd 11, EHE @ OCP:

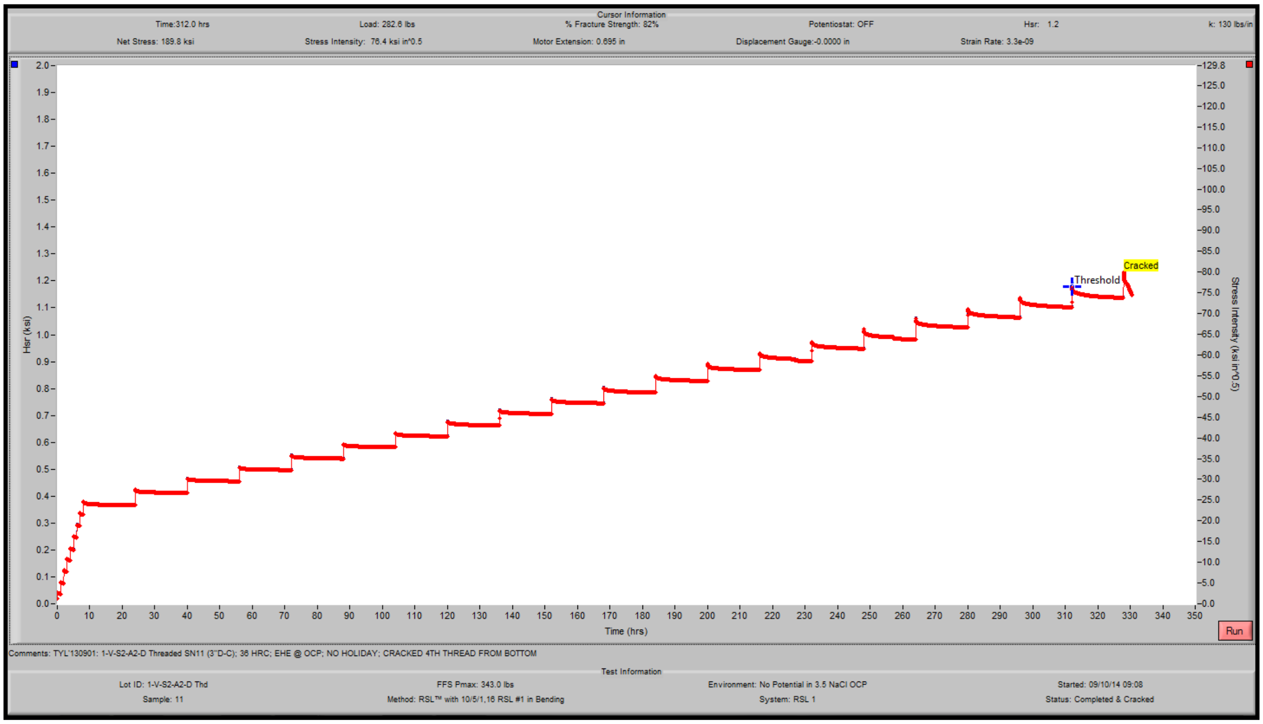


Figure BB.4-11: Rod 1-V-S2-A2-D Thd 11, Graphical EHE Results

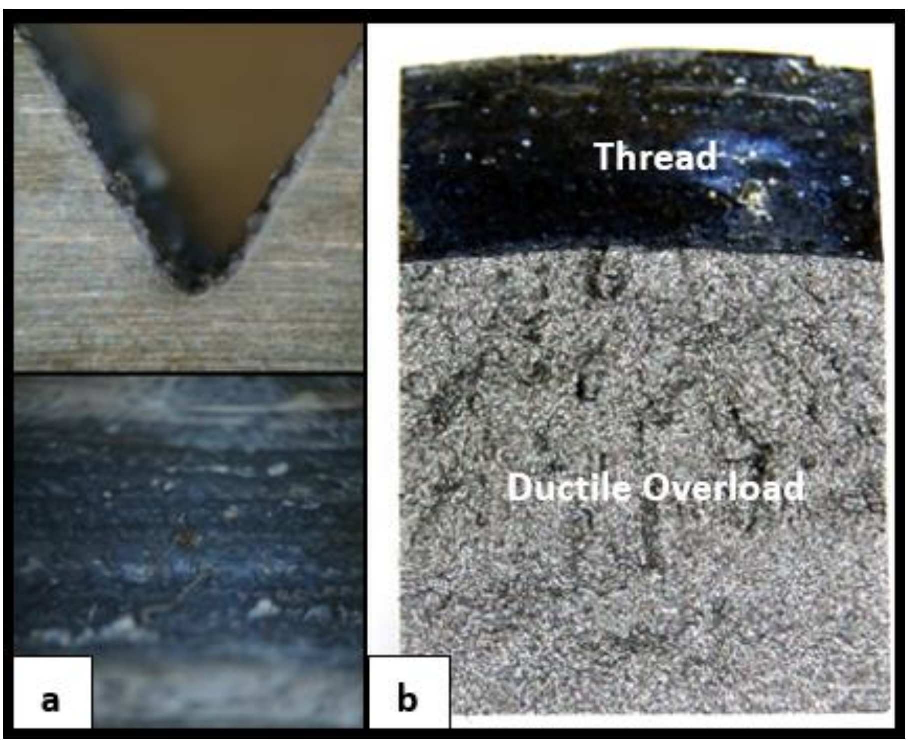


Figure BB.4-12: Rod 1-V-S2-A2-D Thd 11 a) Thread Root Post EHE Test V and Pre-Charpy Impact and b) EHE Fracture Face