PROJECT INFORMATION

Project# 04-0120F4

SUBJECT

Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6

METALLURGICAL TEAM

The testing and analysis of the failed anchor rods from shear keys S-1 and S-2 was performed jointly by Salim Brahimi, Rosme Aguilar and Conrad Christensen.

Mr. Brahimi is a consultant to ABF (American Bridge Fluor – joint venture). He is the president of IBECA Technologies. He is a licenced member of the Quebec Order of Professional Engineers and has over 24 years of experience in the fastener industry. Mr. Brahimi holds a masters of materials engineering from McGill University in Montreal. He is the current chairman of the ASTM Committee F16 on Fasteners. He also serves on the ISO TC2 (Technical Committee on Fasteners), ASTM committees B08 (Coatings), E28 (Mechanical Testing), A01 (Steel), F07 Aerospace and Aircraft, Industrial Fasteners Institute (IFI) Standards and Technical Practices Committee, and the Research Council on Structural Connections (RCSC). Mr. Brahimi is recognized and highly respected throughout the fastener industry as a leading expert in fastener manufacturing, fastener metallurgy, application engineering, corrosion prevention, failure analysis and hydrogen embrittlement.

Mr. Aguilar is the Branch Chief of the California Department of Transportation (Caltrans) Structural Materials Testing Branch, responsible for quality assurance testing of structural materials product used in construction projects throughout the state. He has over thirty (30) years of work experience as an Engineer. Twenty three (23) of these years as a Transportation Engineer in Caltrans, two (2) years as a Quality Assurance Auditor for INTEVEP, S.A. (The Technological Research Institute of the Venezuelan Petroleum Industry), and five (5) years as a Researcher in the area of New Products Development at SIDOR (a Venezuelan Steel Mill). Mr. Aguilar holds a Master of Science in Metallurgy (1982) and a B.S. in Metallurgical Engineering (1980) from the University of Utah, Salt Lake City, Utah. He is a Registered Professional Civil Engineer in the State of California. His areas of expertise and responsibility are Quality Assurance and materials testing but in addition he has performed or assisted in the performance of numerous materials characterization and failure analysis for Caltrans and other state agencies.

Mr. Christensen is a consultant to the California Department of Transportation (Caltrans). He is the principal and founder of Christensen Materials Engineering, which provides laboratory testing and materials engineering services. He has over 32 years of experience as a metallurgist specializing in materials testing and failure analysis. His areas of expertise include: microscopic

evaluation and characterization of materials, optical microscopy, scanning electron microscopy and fracture analysis. He holds a Bachelor of Science degree in materials science and engineering from the University of California at Berkeley (1981). He is a licenced professional metallurgical engineer in the states of California and Nevada.

EXECUTIVE SUMMARY

Metallurgical testing and fracture analysis was performed on two broken anchor rods that were removed from shear keys S1 and S2. The results indicate that hydrogen embrittlement was the cause of the recent anchor rod failures. Generally, the critical factor to consider when fasteners fail due to hydrogen embrittlement (HE) is the susceptibility of the material to hydrogen assisted cracking. Strength has a first order effect on susceptibility. When the specified tensile strength exceeds 180 ksi (i.e., hardness above 39 HRC), HE susceptibility increases very rapidly. Other variables such as microstructure, fracture toughness and notch sensitivity of the steel have a second order effect that can be significant. Given that (i) critical fasteners are often tensioned to maximize their clamping capacity, and (ii) hydrogen concentrations may be influenced by process conditions and environmental service conditions such as corrosion generated hydrogen, the most effective manner to prevent HE related failures of fasteners is to limit the susceptibility of the material. Conversely, in the rare cases where HE fastener failures do occur, they are often a consequence of the strength/hardness or the metallurgical condition of the material causing the material to become more susceptible than normal or than expected.

This scenario appears to fit the conditions that led to the shear key S1 and S2 anchor rod failures. Although the rods comply with the mechanical and chemical requirements specified in ASTM A354 grade BD, the metallurgical condition of the rods is less than ideal. There is a lack of uniformity in the microstructure which has resulted in regions of high hardness, which has a first order effect on HE susceptibility. Furthermore, the metallurgical structure and substructure of the steel, which are fundamentally a result of alloy selection and heat treatment conditions, has apparently made the rods less tough (i.e., more brittle) and therefore more susceptible to hydrogen embrittlement. These second order metallurgical factors become more critical given the large diameter and length of the rods. Given the material is susceptible, small variations in hydrogen concentrations and/or stress while in service can cause the rod to exceed its HE threshold stress, thus resulting in HE failure.

The metallurgical condition that has led to these failures can be effectively avoided for ASTM A354 BD rods with the addition of a number of supplementary requirements designed to ensure the selection of high quality, high hardenability steel that can be heat treated and galvanized to provide rods with an optimal combination of strength, toughness and uniform microstructure through the entire cross section.

BACKGROUND

A total of 288 ASTM A354 grade BD [1] bearing and shear key anchor rods (3 inch diameter) were installed at Pier E2 per the contract requirements (Figure 1). Ninety six (96) of these anchor rods are installed at shear keys S1 and S2 underneath the E-Line and W-Line OBG's, embedded into the concrete as shown in Figure 2. These rods were fabricated at Dyson between June 4, 2008 and September 6, 2008.

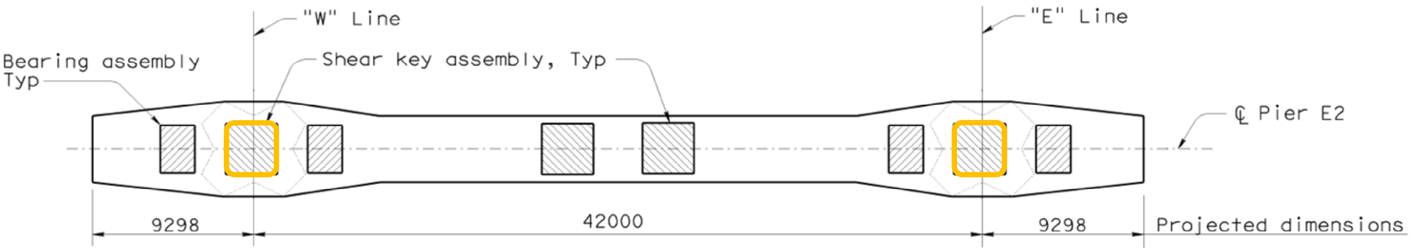


Figure 1: Plan View of Pier E2 Layout

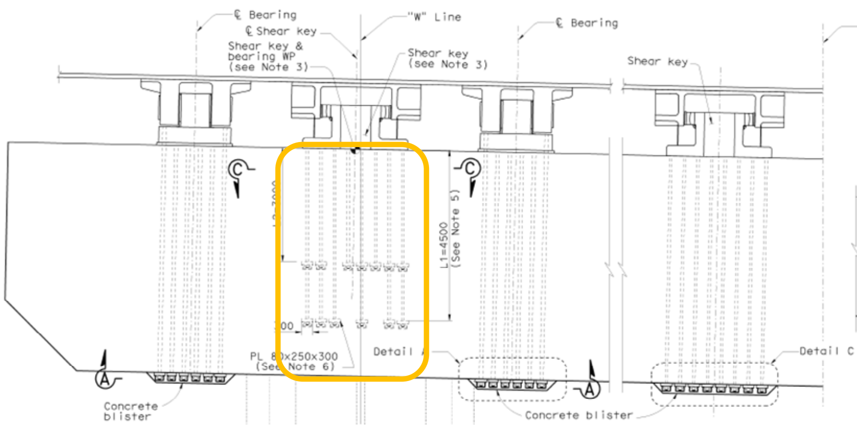


Figure 2: Cross sectional view of the Shear Key Rod Placement

The Contractor started tensioning S1 and S2 anchor rods between March 1, 2013 and March 5, 2013. In accordance with the Contract Documents and approved Submittal 2747, the rods were initially jacked to 0.75 Fu (i.e., 75% of ultimate tensile strength). Due to seating losses as the load is transferred from the jack to the nut, the load is expected to reduce to the final design load of 0.68 Fu. Between March 8, 2013, and March 15, 2013, 32 out of 96 rods fractured. The Contractor extracted three rods (Rod ID's S1-G1, S2-A6, and S2-H6) for further analysis. Figure 3 below shows a schematic of the shear key layout with the rod identification system. Due to small overhead clearance, the rods were extracted in multiple sections. The sections were numbered incrementally from top to the bottom. Therefore the first section pulled out from rod ID S2-A6 is identified as S2-A6 #1 and the bottom section (with the fractured surface) is

identified as S2-A6 #11. Pieces S1-G1 #11, S2-A6 #12, and S2-H6 #12 were transported to the Christensen Materials Engineering lab, where they were metallurgically analyzed and destructively tested. This report provides the details of the testing that was performed, and some of the conclusions that were made.

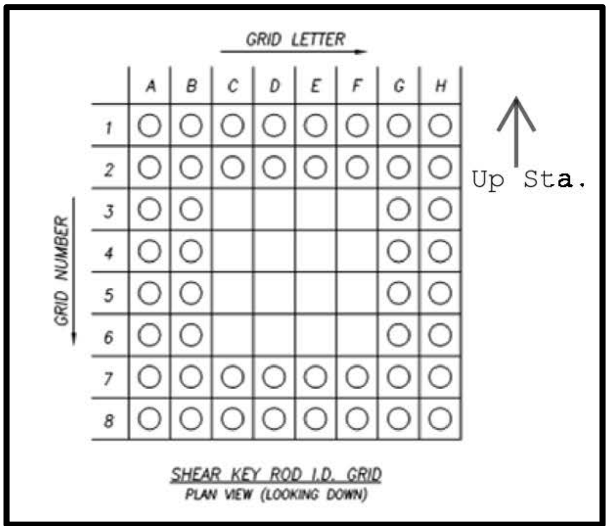


Figure 3: Shear Key Rod Identification Grid

ANCHOR ROD MATERIALS SPECIFICATION

The galvanized steel anchor rods were specified to be ASTM A354 grade BD *"Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and other Externally Threaded Fasteners"*.

The mechanical properties specified for A354 grade BD are as follows:

ASTM A354 Gr BD Mechanical Properties	
Yield Strength	115 psi min.
Tensile Strength	140 psi min.
Elongation in 2 inches	14% min.
Reduction in Area	40% min.
Hardness Rockwell C	31 -39

TEST PROCEDURES & RESULTS

I. Visual Examination/Observations

Approximate 20" sections, which included the retrievable fractured end of three failed anchor rods were provided for testing and identified as S1-G1 #11, S2-A6 #12, and S2-H6 #12. Fracture occurred in the lower threaded ends (i.e., embedded/grouted ends) of all three rods. Anchor rods S1-G1 #11 and S2-A6 #12 were chosen for metallurgical testing to determine the cause of the anchor rod failures.

It was observed that the threads and fracture surface of the as-received rod S1-G1 #11 were covered with Denso paste (part of the Denso Tape system) as required by the Contract Documents. There was Denso paste and grout in the threads and on the fracture surface of rod S2-A6 #12. The fracture surfaces were cleaned and the fractured ends cut from the rods to facilitate further visual and stereo microscopic (up to 80x magnification) examinations.

The overall appearance of both rod fractures was brittle (i.e., there was no thread elongation/stretching to suggest plastic deformation/yielding occurred prior to fracture). Photos 2-8 show the observed fracture features. There was evidence indicating that hydrogen assisted cracks were present in both rods prior to failure. The cracks initiated and extended from the thread root up to a depth of 0.6 inches in Rod S1-G1, and 0.4 inches in Rod S2-A6 (see Photos 4 and 8). The presence and appearance of the cracks, and the delayed nature of the fractures point to time dependence of the failure mechanism. Cracks developed and grew in both rods, which progressively exceeded their capacity with time, and resulted in final failure by fast fracture.

II. Scanning Electron Microscopy

The fracture surfaces were examined at high magnification with a scanning electron microscope (SEM) to further characterize the failure mechanism. Intergranular fracture morphology was observed at, and near, the thread root (i.e., crack origin). See Photos 9-14. Intergranular cracking is a characteristic feature indicative of a number of brittle fracture mechanisms, including hydrogen assisted cracking. Intergranular features were predominant at the thread root (i.e., crack origin). Gradually increasing mixed morphology was observed as the crack progressively grew and extended inward from the thread root (i.e., more ductile tearing, and less intergranular features). See Photos 15-17. Sudden fast fracture occurred when the crack reached a critical size, wherein the reduced capacity of the rod could no longer sustain the applied load. The morphology across the final fast fracture zone was almost exclusively cleavage (brittle fracture mechanism). See Photos 18-20. This observation is considered unusual. Final rupture of bolts (in the strength range of A354 grade BD) caused by tensile overload following crack propagation typically occurs in ductile mode.

Both rods were examined with the SEM and exhibit similar fracture characteristics.

III. Microstructural Examination

Cross-sections were cut from both rods and metallurgically prepared (i.e., mounted/potted, polished and etched). The location of the cross-sections is shown in Photos 21-22. The observed microstructure was generally tempered martensite, which is the normal structure associated with quenched and tempered AISI 4140 steel. However, many areas especially toward the center of the rod, showed evidence of incomplete martensitic transformation. The regions of incomplete transformation, as characterized by the observed presence of ferrite and pearlite, appeared to alternate in banded layers between regions of fully transformed martensitic structure. The banded nature of the microstructure is an indication that the material is not homogeneous. See Photos 23-26. Additionally, there was a relatively high amount of non-metallic stringer inclusions present in the microstructure. See Photos 27 and 28.

IV. Hardness Testing

The Knoop and Rockwell hardness tests are two different hardness testing techniques that correlate to a material’s tensile strength, wear resistance and ductility.

The Knoop microhardness test requires a rhombic-based pyramidal diamond indenter pressing into a smooth, polished specimen surface for a specified dwell time. The size of the indentation after removing the indenter, measured in micrometers, is determined using a microscope. The Rockwell test determines hardness using a conical diamond indenter. The specimen is preloaded with the indenter, then increased with an additional force, then unloaded back to the initial preload force. The indentation difference, measured in millimeters, is determined using a Rockwell hardness machine, automating the procedure with little operator influence.
The Contract requirement for the ASTM A354 BD Hardness test is either the Brinell or the Rockwell C hardness tests. The Knoop hardness test is not a Contract requirement.

A. Knoop Microhardness

Knoop microhardness testing was performed on the previously prepared microstructural cross-sections. The locations for microhardness testing include: (i) directly below (along) fracture surfaces, (ii) the contour of the first thread nearest the fracture surface, and (iii) inward from the thread root nearest the fracture surface up to a depth of ¾ in. The results provided in Appendix A generally indicate there are considerable variations in microscale hardness, ranging from 297 KHN to 446 KHN (equivalent to 28.0 to 43.6 HRC). This observation can be attributed to the non-homogeneous microstructure reported in Section III. (Note that KHN and HRC are the conventional abbreviations for Knoop Hardness Number and Hardness Rockwell C, respectively.)

The general trend of the microhardness results indicates repeated microstructural regions with local hardness exceeding the maximum bulk hardness of 39 HRC that is specified in ASTM A354 for grade BD (39 HRC is equivalent to 390 KHN).

Although these microhardness results are an indication of the metallurgical condition of the steel, microhardness testing is not appropriate or required for determination of

conformance to ASTM A354 grade BD specified bulk hardness. This can only be done by using a macro indenter such as Rockwell C (HRC).

B. Rockwell C Hardness

Rockwell C hardness measurements were made across the diameter and at mid-radius locations of both rods. The Rockwell hardness tests were performed by Anamet Inc. and their test reports are provided in Appendix B (see also plotted results in Figure A10 of Appendix A). The results of the Rockwell hardness test show variation in hardness, with the outer diameter approaching HRC 39. The center hardness drops to as low as HRC 25 indicating the material was not uniformly through-hardened. Completely uniform through-hardening is difficult to achieve in large diameter rods such as this case, however, the large disparity in hardness from center to edge indicates that the steel may not have had optimal through thickness hardenability or was improperly heat treated.

It should be noted that ASTM A354 refers to ASTM F606 [2] which specifies that *"…for purposes of arbitration between the purchaser and seller over reported test results, hardness tests shall be conducted at mid-radius (r/2) of a transverse section taken through the threads…"* The mid-radius Rockwell C hardness values were determined by Anamet and ranged between 32.5 and 36.2 HRC. The mid-radius results are in compliance with the A354 grade BD requirements of HRC 31-39.

V. Tensile Test

Tensile testing was performed on machined test specimens taken from near the outer diameter of each anchor rod. Two samples were tested from Rod S2-A6. Piece #12 was from the bottom theaded end of the rod near where the fracture occurred. Piece #2 was from the shank near the top of the rod. The tensile tests were performed by Anamet Inc. Anamet's test reports are provided in Appendix A and the results summarized in Table 1 below.

Table 1
Tensile Test Results

Identification	S2-A6 #12	S2-A6 #2	S1-G1 #11	ASTM A354 Gr BD Requirement
Yield Strength (psi)	149,000	146,000	136,000	115,000 min.
Tensile Strength (psi)	170,000	168,000	159,000	140,000 min.
Elongation in 2" Gage (%)	15.5	14	15	14 min.
Reduction of Area (%)	46.0	48.0	48.4	40 min.

The results indicate the material meets yield strength, tensile strength and elongation requirements for A354 grade BD, although elongation (i.e., ductility) was slightly above the minimum limit.

VI. Charpy V-Notch Impact Test

Notched bar impact tests were performed at room temperature (70° F) and at (40° F) on machined 10x10 mm Charpy test specimens taken from near the outer diameter of each anchor rod. The samples were taken longitudinal to the rod axis with the notched surface facing toward the outer diameter. The tests were performed by Anamet Inc. Anamet's test reports are provided in Appendix A and the results summarized in Table 2 below.

Table 2
Charpy V-Notch Impact Energy Test Results (ft-lb)

Identification	S2-A6 #12	S2-A6 #2	S1-G1 #11
Test Temperature	70ºF	70ºF	40ºF
Sample 1	18	15	13.5
Sample 2	18	14	13
Sample 3	17	15	14
Average	17.7	14.7	13.5

Charpy v-notch impact test results do not pertain to conformance of the rods to the product specification because ASTM A354 does not have any requirements for impact testing. However impact testing characterizes the toughness of the steel, which was called into question especially given the observation of cleavage morphology in the fast fracture region of the fracture surfaces (see Section II). When compared to requirements in other fastener material specifications such as ASTM A320 [3] and ISO 898-1 [4], where the minimum absorbed energy requirements begin at 20 ft-lb (at low test temperatures e.g., -4° F), the results are relatively low. Stated otherwise, this material appears to lack toughness even when tested at room temperature. A more definitive statement on the extent of lack of toughness requires further investigation.

VII. Chemical Analysis

A chemical analysis was performed on samples of material from each anchor rod by Anamet Inc. Anamet's test reports are provided in Appendix A and results summarized in the Table 3 below. The chemistry is consistent with AISI 4140 steel and meets the ASTM A354 grade BD requirements.

Table 3
Spectrochemical Analysis
(Reported as Wt. %)

		S2-A6 #12	S1-G1 #11	Mill Test Report(1)	Mill Test Report(2)	Requirement ASTM A354 Gr BD
Aluminum	Al	<0.005		0.001	0.001	
Carbon	C	0.40	0.43	0.41	0.41	0.33 -0.55
Chromium	Cr	0.97	0.98	0.98	0.98	
Cobalt	Co	0.01	0.01	0.007	0.007	
Copper	Cu	0.22	0.22	0.20	0.20	
Iron	Fe	Balance	Balance			
Manganese	Mn	0.93	0.93	0.92	0.92	0.57 min.
Molybdenum	Mo	0.16	0.15	0.16	0.16	
Nickel	Ni	0.10	0.10	0.10	0.10	
Phosphorus	P	0.012	0.012	0.014	0.014	0.040 max.
Silicon	Si	0.24	0.23	0.23	0.23	
Sulfur	S	0.034	0.039	0.034	0.034	0.045 max.
Titanium	Ti	<0.005	<0.005	0.002	0.002	
Tungsten	W	<0.005	<0.005			
Vanadium	V	0.03	0.03	0.030	0.030	
Zirconium	Zr	<0.005	<0.005			

Note 1) Taken from Gerdau Macsteel certified mill test report for heat no. M058938 reported to Dyson Corp. – Code MIS (Shipped 5/27/08)

Note 2) Taken from Gerdau Macsteel certified mill test report for heat no. M058925 reported to Dyson Corp. – Code MJF (Shipped 5/27/08)

DISCUSSION

The delayed nature of the failures, evidence of progressive intergranular cracking, marginally high surface hardness and apparent lack of toughness are consistent with hydrogen embrittlement (HE) as the cause of the rod failures. The definition of hydrogen embrittlement is as follows:

Hydrogen Embrittlement (HE) — a permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either externally applied or internal residual stress. Source: ASTM F 2078

Generally, hydrogen embrittlement is classified under two broad categories based on the source of hydrogen: internal hydrogen embrittlement (IHE) and environmental hydrogen embrittlement (EHE). IHE is caused by residual hydrogen from steelmaking or from processing steps such as pickling and electroplating. EHE is caused by hydrogen introduced into the metal from external sources while it is under stress, such as is the case with an in-service fastener. The term Stress

Corrosion Cracking (SCC) is a form of EHE that occurs when hydrogen is produced as a by-product of surface corrosion and is absorbed into the lattice. Cathodic hydrogen absorption (CHA) is a subset of SCC and can be explained as follows. Metallic coatings such as zinc are designed to sacrificially corrode to protect say a steel bolt from rusting. If the steel becomes exposed, a reduction process on the exposed steel surface simultaneously results in the evolution of hydrogen.

Three ingredients must be present to cause hydrogen embrittlement failure: (i) steel that is *susceptible* to hydrogen damage, (ii) *stress* (typically as an applied load), and (iii) *hydrogen*. All three of these elements are present in sufficient quantities, and given time, hydrogen damage results in crack initiation and growth until the occurrence of delayed fracture. Time to failure can vary, depending on the severity of the conditions and the source of hydrogen.

(i) ***Susceptibility*** – Material strength has a first order effect on HE susceptibility. As strength increases, steels become less ductile and less tough. By the same token, at equal strength, steel that exhibits lower toughness is inherently more brittle and more susceptible to hydrogen assisted cracking.

The susceptibility of steel fasteners increases significantly when the specified hardness is above 39 HRC. The rod hardness test results indicate the material hardness varies considerably. Bulk hardness readings near the outer diameter surface were high relative to the center of the rods, and Knoop microhardness readings varied up to KHN 446 (HRC 43.6), which significantly increases susceptibility to local hydrogen assisted cracking. However, hardness alone was not high enough to explain the occurrence of HE failure. The high degree of variability in the microhardness measurements and the observed variability in microstructure indicate the material is inhomogeneous. More significantly, the material has relatively low toughness, as measured by Charpy v-notch impact tests. The brittle cleavage features observed during the SEM examination of the “fast fracture” region are further evidence of a material with poor toughness. The tensile tests show that the elongation (i.e. ductility) is within the Contract requirements. However, the reported values show that the measured elongations approach the minimum requirement of ASTM A354BD. Additionally, the microstructure showed evidence of significant amounts of inclusions, which further increases the susceptibility of the steel. These observations together amount to a material that is susceptible to HE.

(ii) ***Stress –*** load induced stress is a normal service condition for mechanical fasteners. In this application, the fasteners were initially subjected to 0.75 Fu (627 kips) with a final target load for 0.68 Fu. Fasteners are capable by design to be tightened into yield or to the limit of their elastic range. Therefore, this application amounts to a normal but high loading condition by fastener standards. If all other conditions for HE are met, the greater the load on the fastener, the greater the chance that its HE threshold stress will be exceeded.

(iii) ***Hydrogen –*** there are two possible sources of hydrogen: “internal” and “environmental.” In this case, although hydrogen may have been available from both

sources, the relatively short amount of time between loading and failure (i.e., days) indicates that the hydrogen was already available and mobile in the steel.

a. The principal source of internal hydrogen was likely the freeing of trapped residual hydrogen by the upquenching effect of hot dip galvanizing. A research publication by Brahimi et al. [5] describes this phenomenon which can be summarized as follows. “The source of hydrogen is residual hydrogen trapped in the steel specimens, in reversible trap sites with high bonding energies. In this scenario, hydrogen is released by the up-quench/thermal shock upon immersion in the molten zinc bath. The presence of a thick zinc coating prevents hydrogen escaping, instead causing it to accumulate at grain boundaries. Lower hardness steel specimens, in the range of 25- 38 HRC are not embrittled by the galvanizing process, as evidenced by the fact that most high strength structural fasteners can be safely galvanized.”

b. Although there was no significant visible corrosion on the broken rods (white corrosion or red rust), some of the rods may have been exposed to water and the elements, especially at the bottom, in the period after 2008 when they were installed in the pier until when they were tensioned in March, 2013. More precisely, galvanic corrosion of the sacrificial zinc coating generates hydrogen, which is then absorbed by the cathode (i.e., steel). The quantity of hydrogen absorbed in this manner is exponentially higher than under normal anodic corrosion conditions (i.e., without a coating). If corrosion generated hydrogen contributed to the failures, it was already present and available (i.e., mobile) in the steel.

CONCLUSIONS AND RECOMMEDATIONS

1. The anchor rods failed as a result of hydrogen embrittlement, resulting from the applied tensile load and from hydrogen that was already present and available in the rod material as they were tensioned. The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement.

2. The steel rods comply with the basic mechanical and chemical requirements of ASTM A354 grade BD.

3. The metallurgical condition of the steel was found to be less than ideal. More precisely, the microstructure of the steel is inhomogeneous resulting in large difference in hardness from center to edge, and high local hardness near the surface. As an additional consequence of the metallurgical condition, the material exhibits low toughness and marginal ductility. The combination of all of these factors have caused the anchor rods to be susceptible to HE failure.

4. Procurement of future A354 grade BD anchor rods should include a number of standard supplemental requirements to assure against HE failure. The appropriate specification of supplemental requirements is currently under review.

REFERENCES

1.ASTM A354, *Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and other Externally Threaded Fasteners.*

2. ASTM F606 *Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets*.

3. ASTM A320/A320M, *Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service.*

4. ISO 898-1, *Mechanical properties of fasteners made of carbon steel and alloy steel Part 1:Bolts, screws and studs with specified property classes — Coarse thread and fine pitch thread*.

5. Brahimi, S., et al., *Effect of surface processing variables on hydrogen embrittlement of steel fasteners part 1: Hot dip galvanizing.* Canadian Metallurgical Quarterly, 2009. **48**(3): p. 293-302.

Photos1-28

Photo 1) Anchor rod installation at shear key with broken rod at arrow.

Photo 2) Broken anchor rod S1-G1.

Photo 3) Fracture surface of Rod S1-G1 after cleaning.

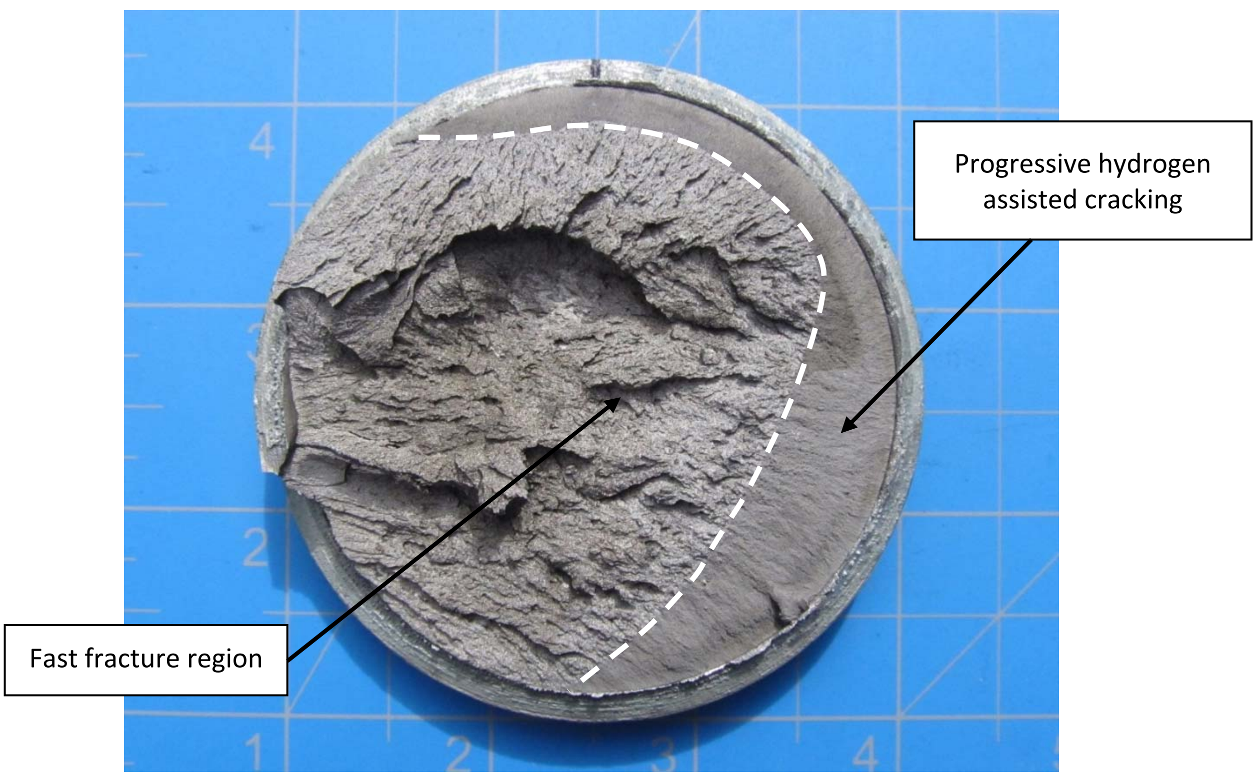


Photo 4) The fracture surface showing progressive hydrogen assisted cracking and fast fracture areas.


Photo 5) Broken end of Rod S2-A6. Grease and grout were present on the fracture and threads.


Photo 6) Another view of Rod S2-A6 fracture surface.

Photo 7) Fracture surface of Rod S2-A6 after cleaning.

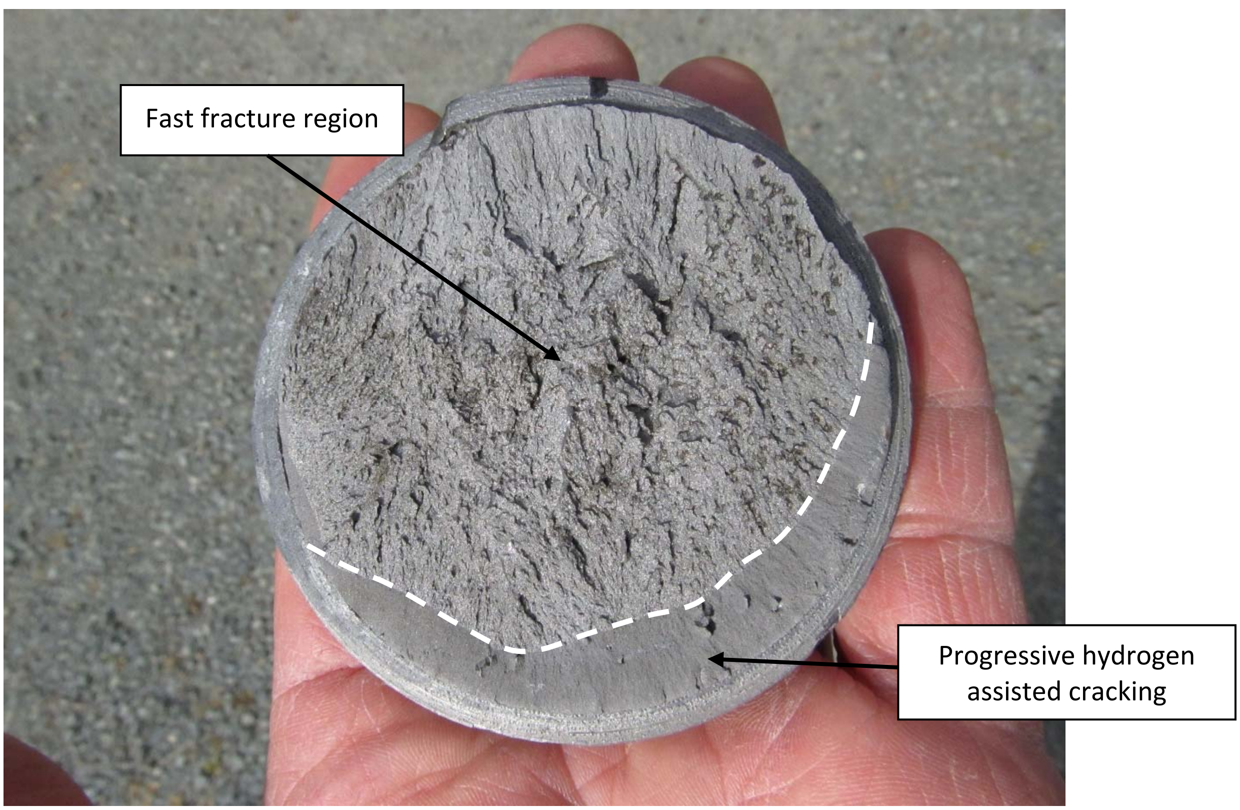


Photo 8) The fracture surface showing progressive hydrogen assisted cracking and fast fracture areas.

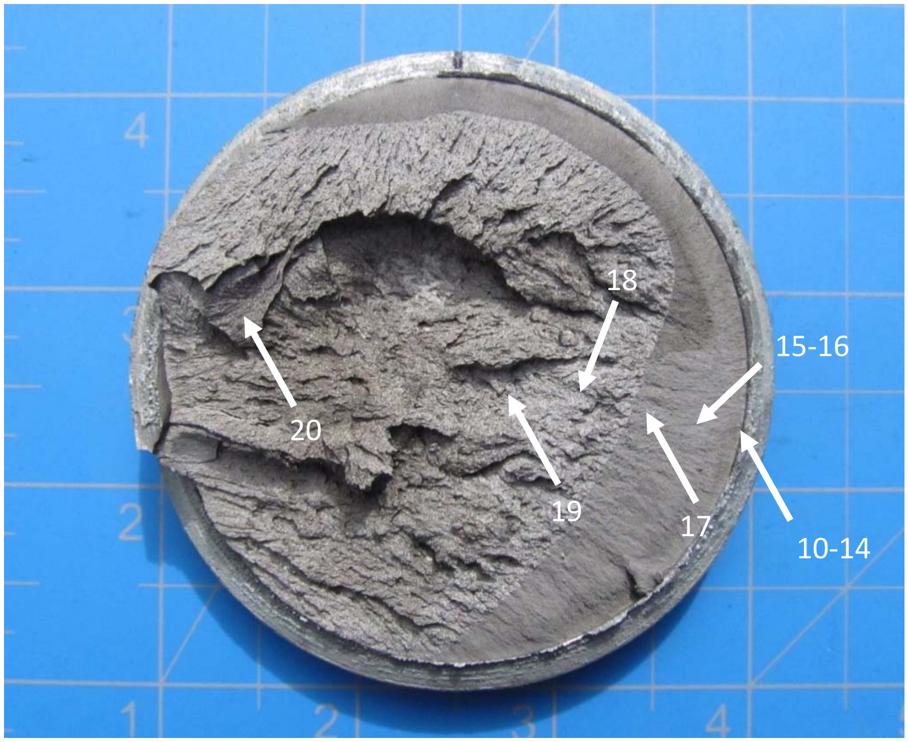


Photo 9) Fractured rod S1-G1 showing the locations of SEM photos 10-20.

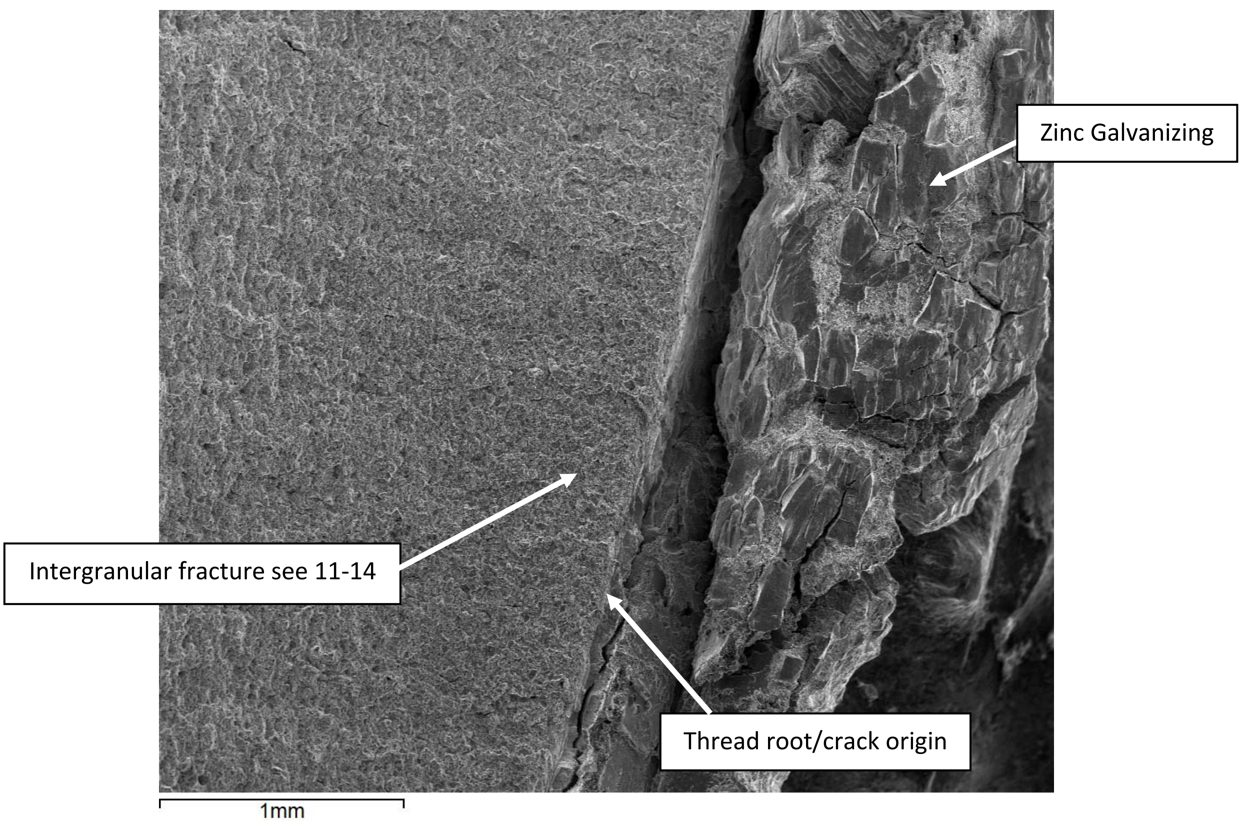


Photo 10) SEM image of S1-G1 at crack origin.

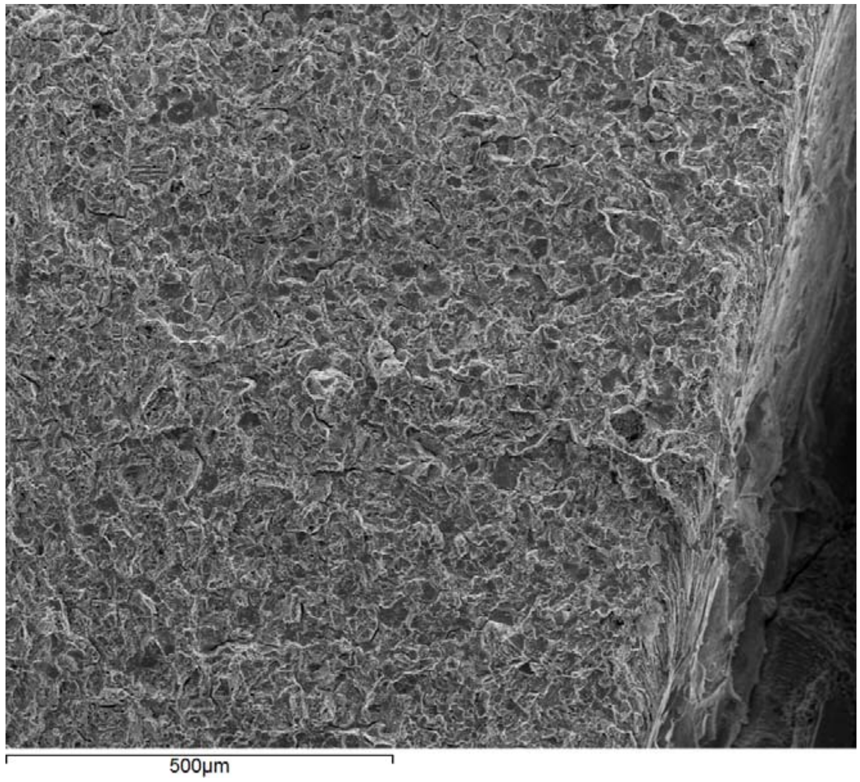


Photo 11) Same as Photo 10 except higher magnification.

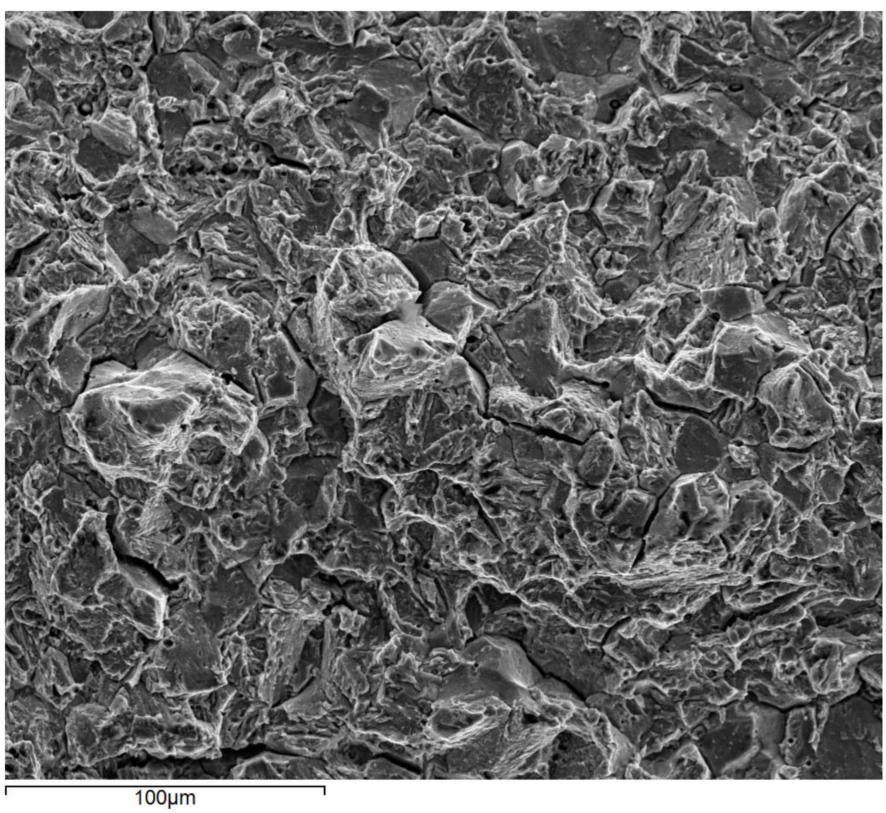


Photo 12) Same as Photo 11 except higher magnification.

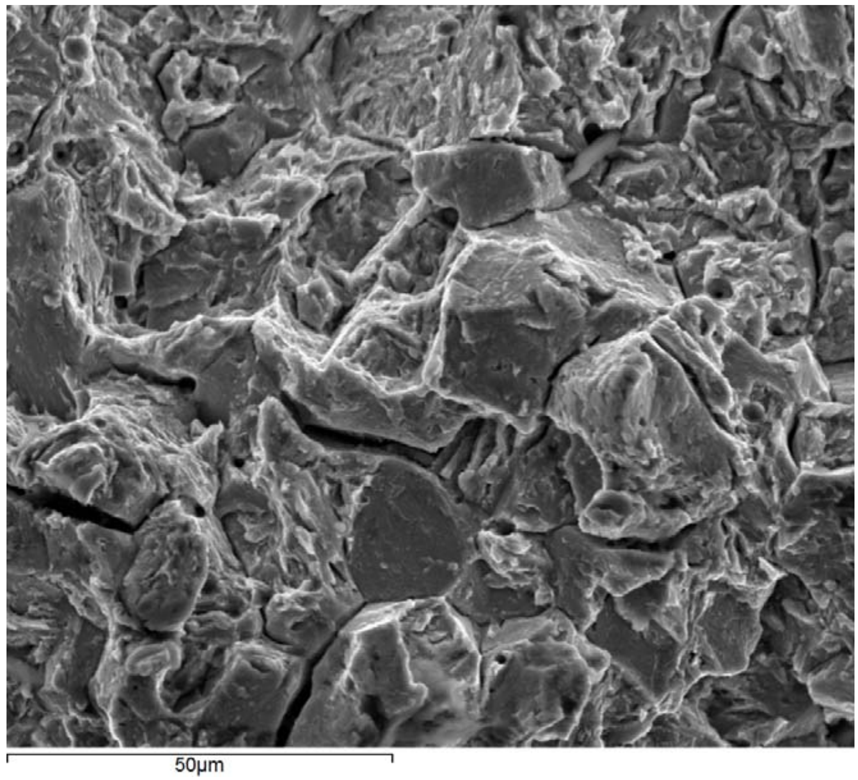


Photo 13) Same as Photo 12 except higher magnification showing intergranular fracture features.

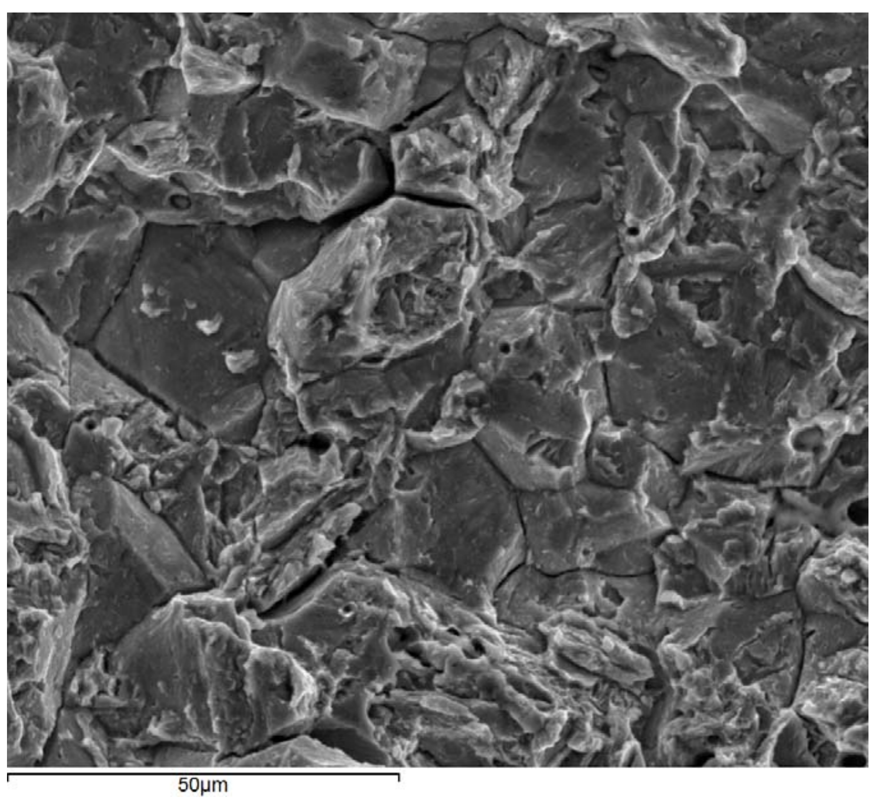


Photo 14) Same as Photo 11 except higher magnification showing more intergranular fracture features.

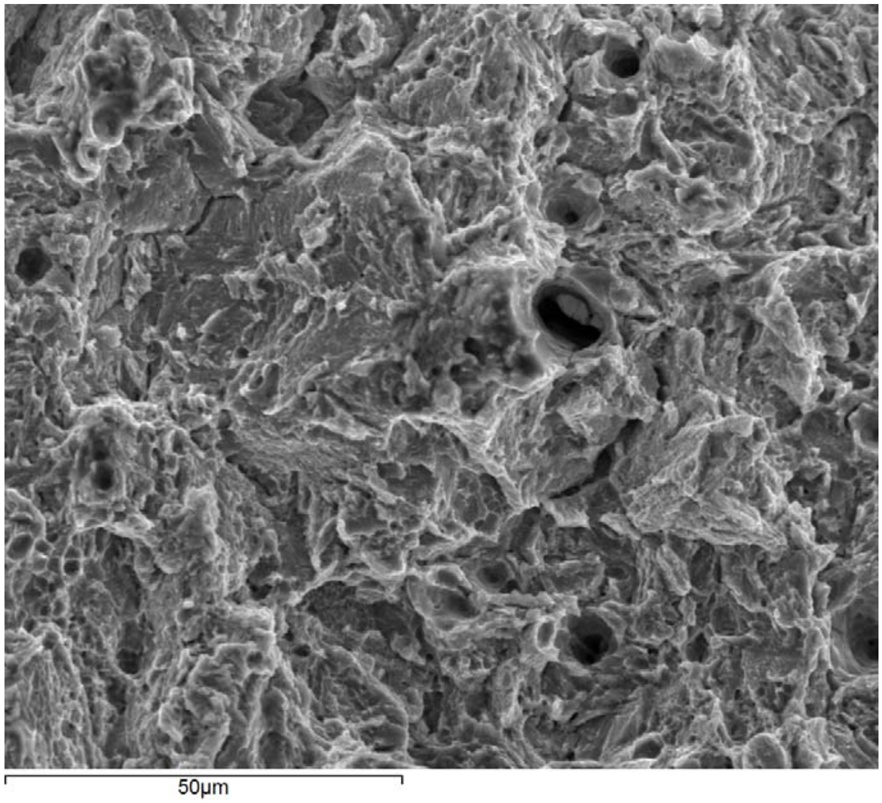


Photo 15) Mixed ductile tearing and intergranular fracture features.

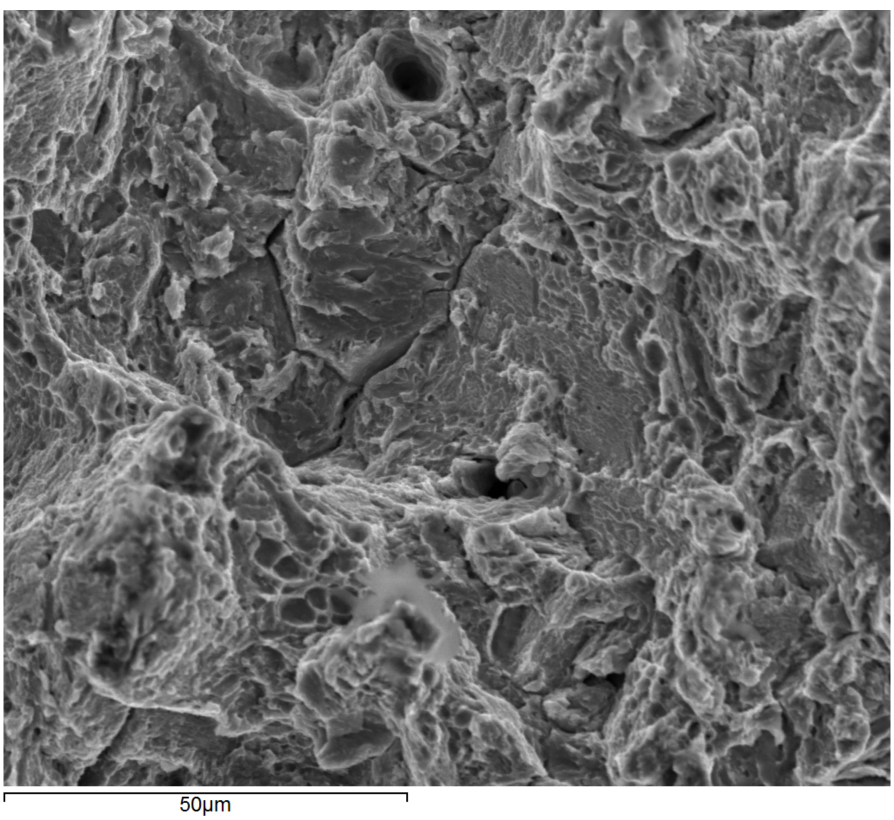


Photo 16) Mixed ductile tearing and intergranular fracture features.

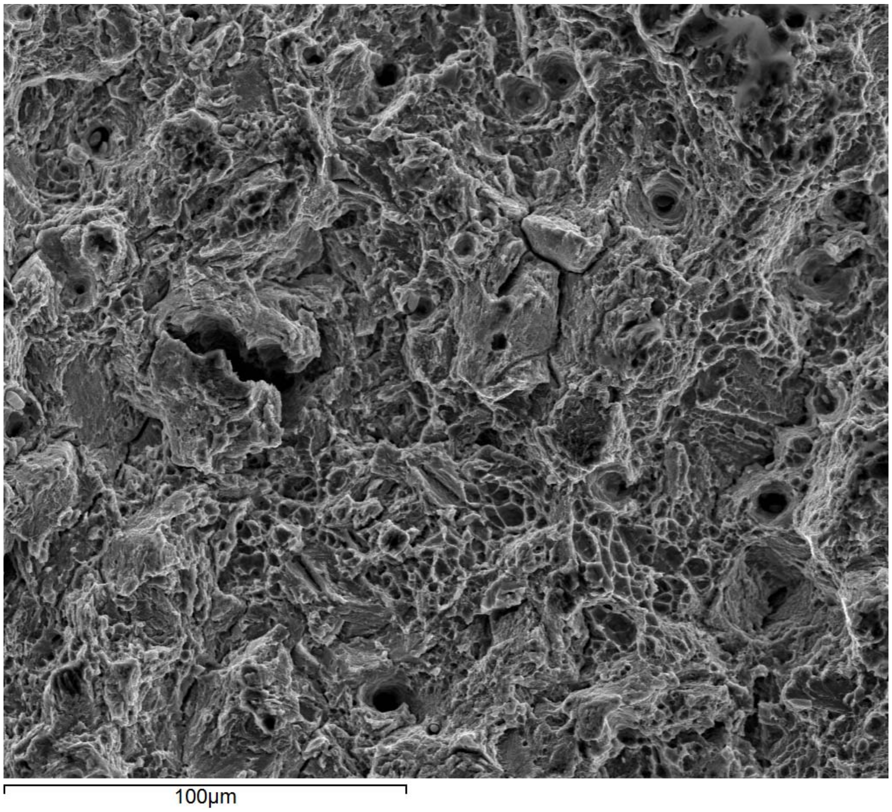


Photo 17) Mixed ductile tearing and intergranular fracture features.

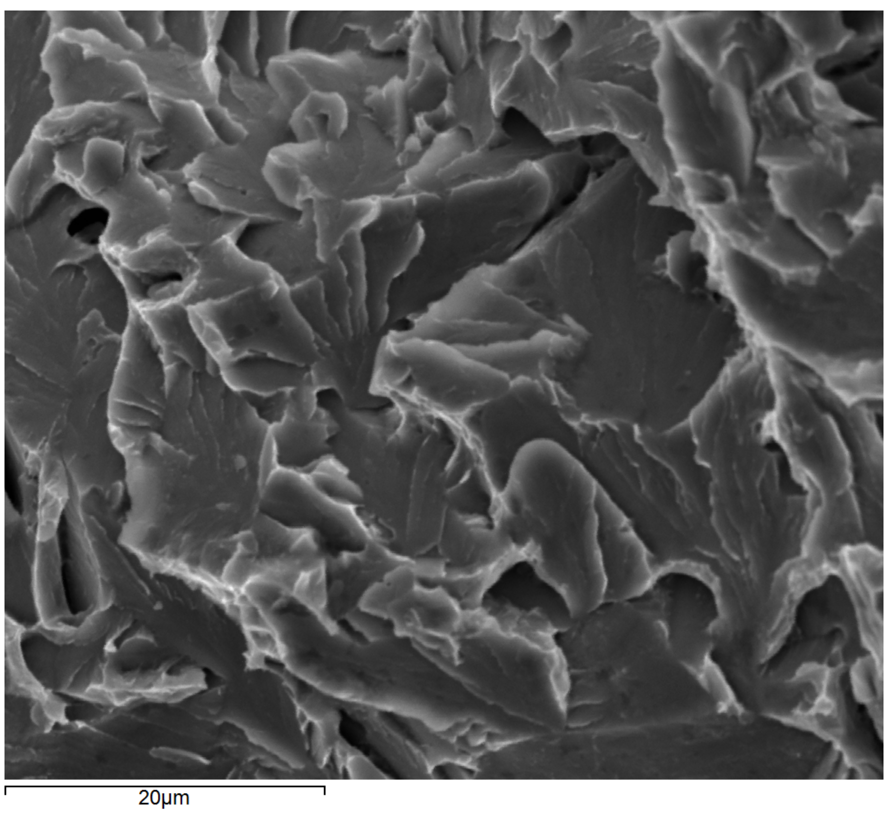


Photo 18) Cleavage fracture features – brittle fast fracture.

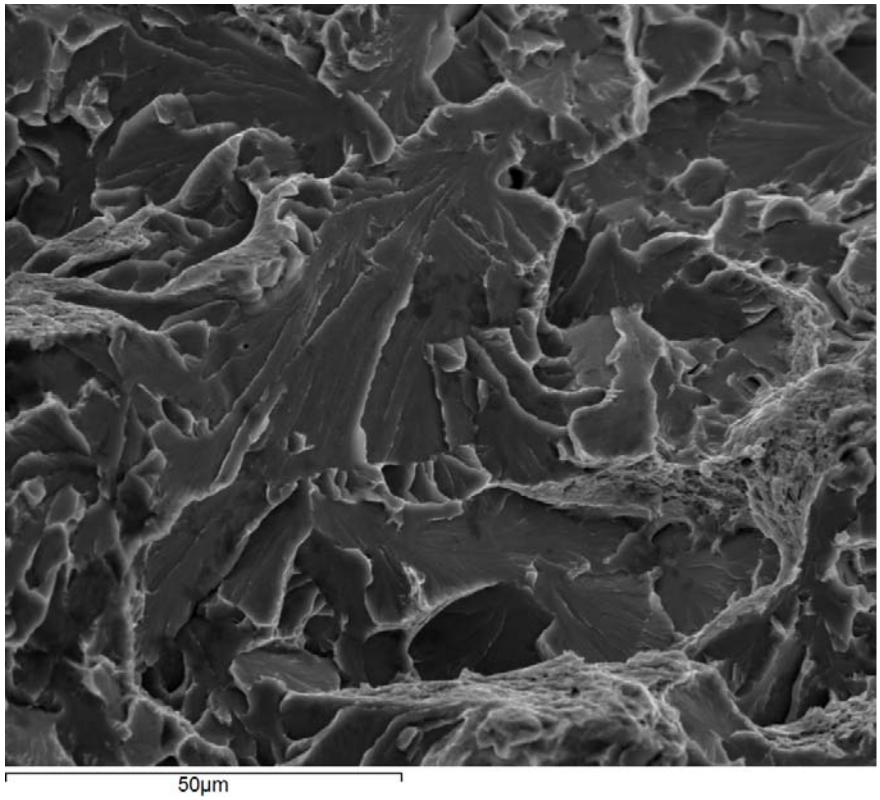


Photo 19) Cleavage fracture features – brittle fast fracture.

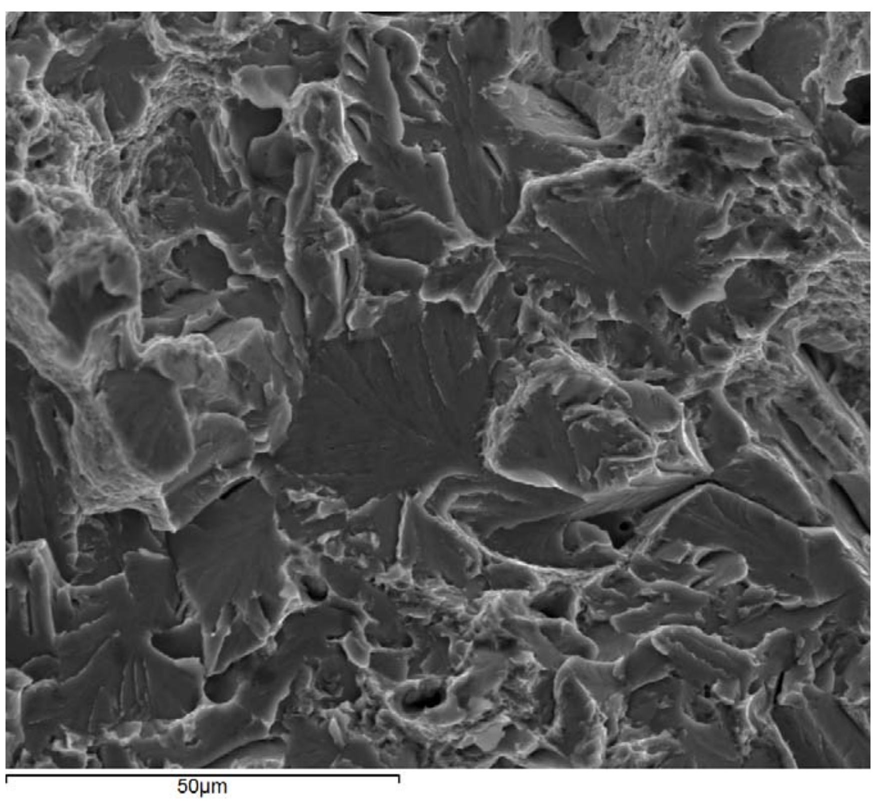


Photo 20) Cleavage fracture features – brittle fast fracture.

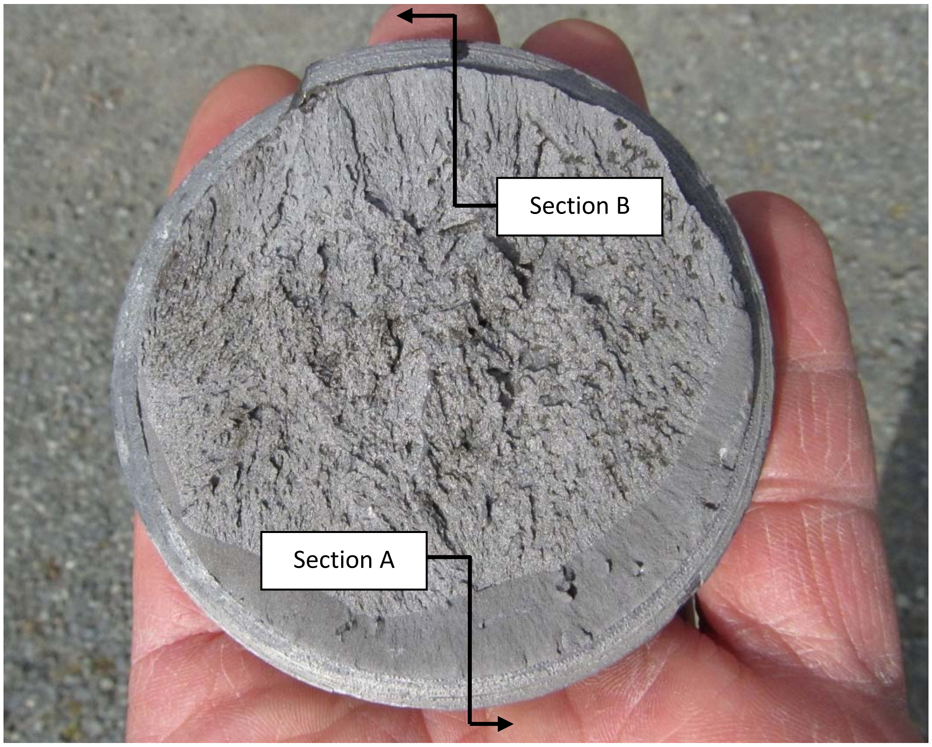


Photo 21) Fractured rod S2-A6 showing the location of cross-sections for microstructural examination and microhardness tests.

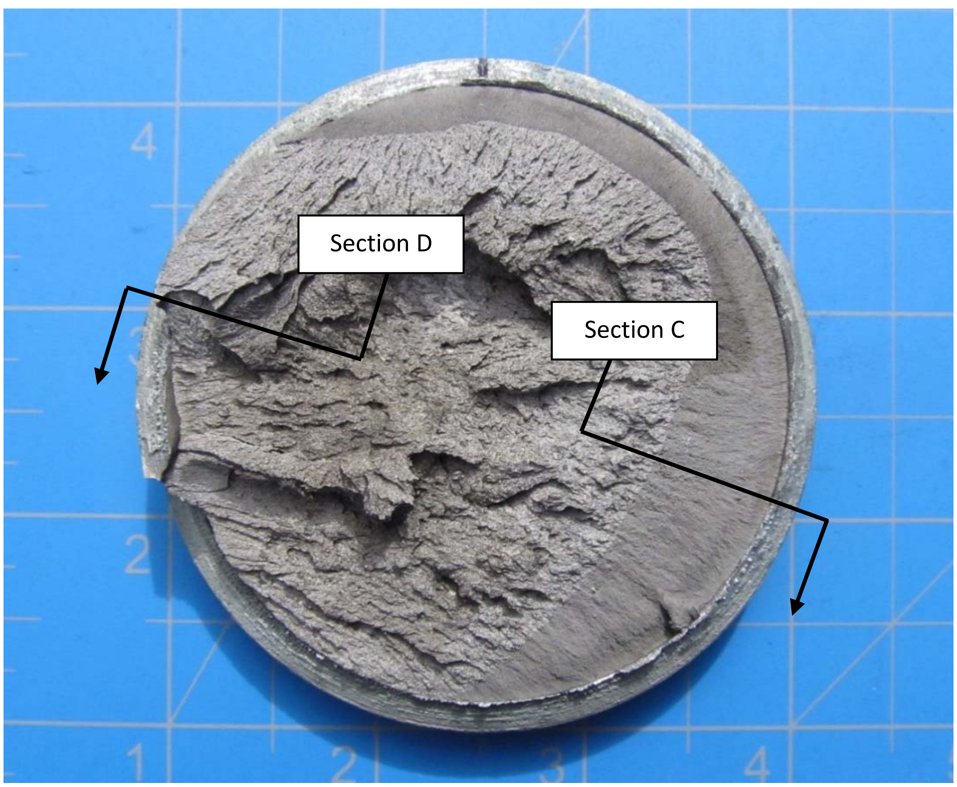


Photo 22) Fractured rod S1-G1 showing the location of cross-sections for microstructural examination and microhardness tests.

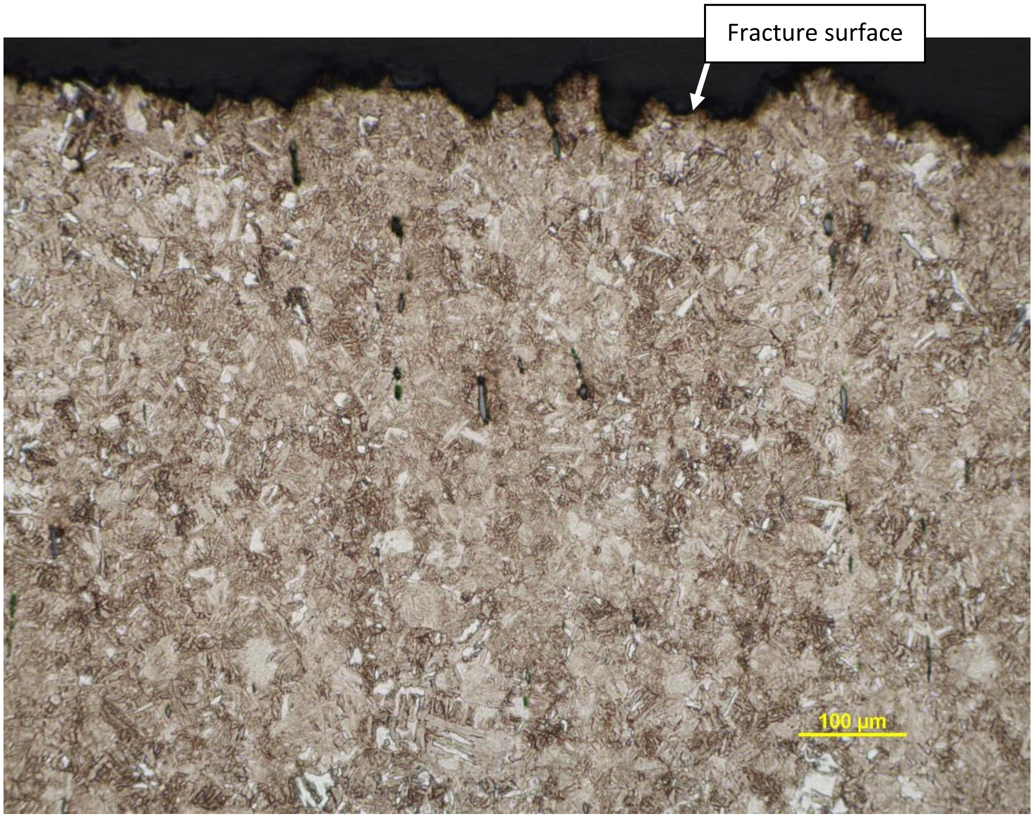


Photo 23) Example of microstructure observed in S2-A6 at Section A. (Etchant 2%Nital)

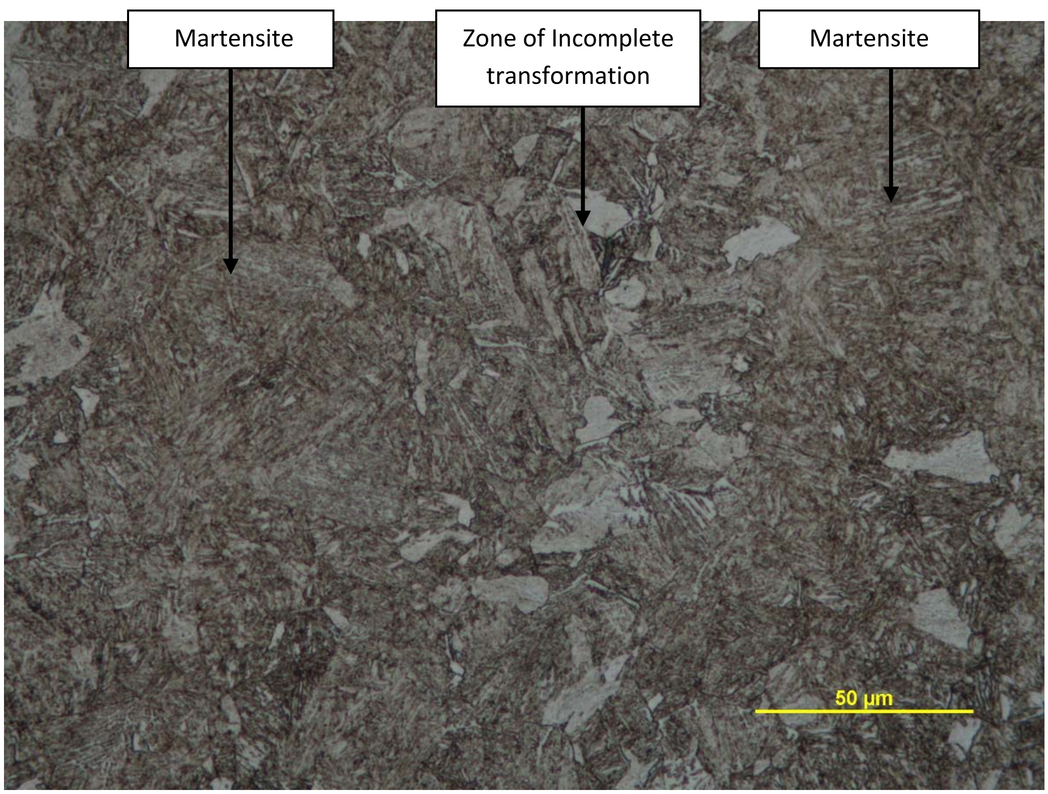


Photo 24) Same as above except higher magnification. Note the structure is not fully tempered martensite. The center region did not fully transformed to martensite.

Photo 25) Another example of microstructure observed in S2-A6. Note vertical banding (alternating light-dark streaks) in grain direction. (Etchant: 2% Nital)

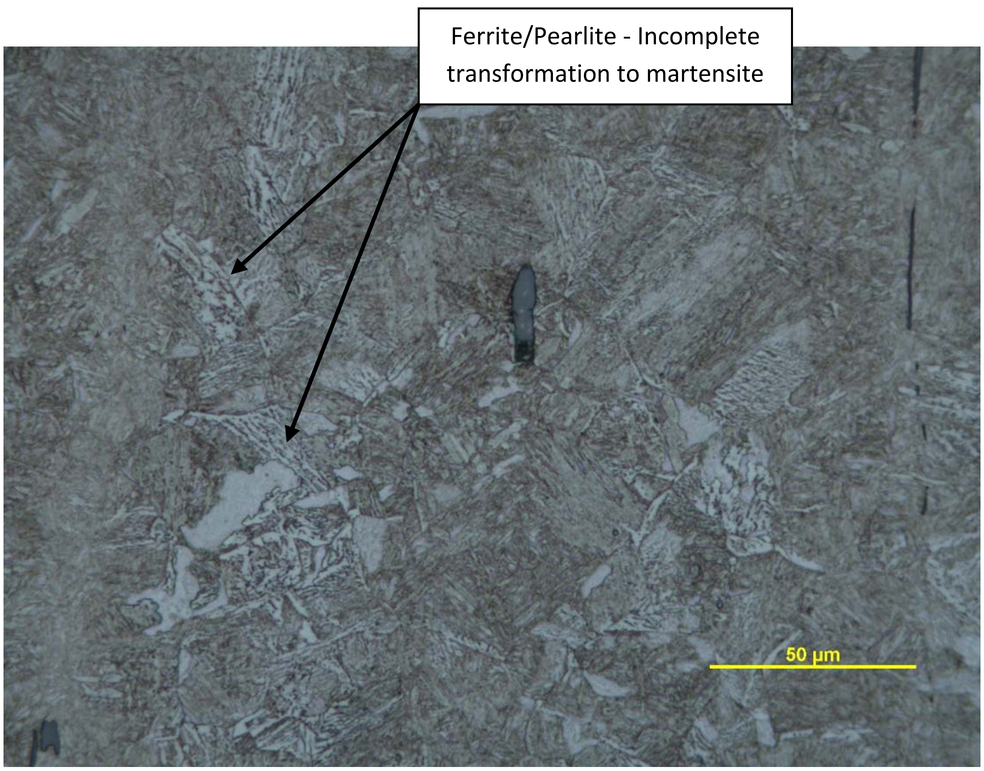


Photo 26) Same as above except higher magnification. Note ferrite/pearlite where the structure is not fully tempered martensite. (Etchant: 2% Nital)

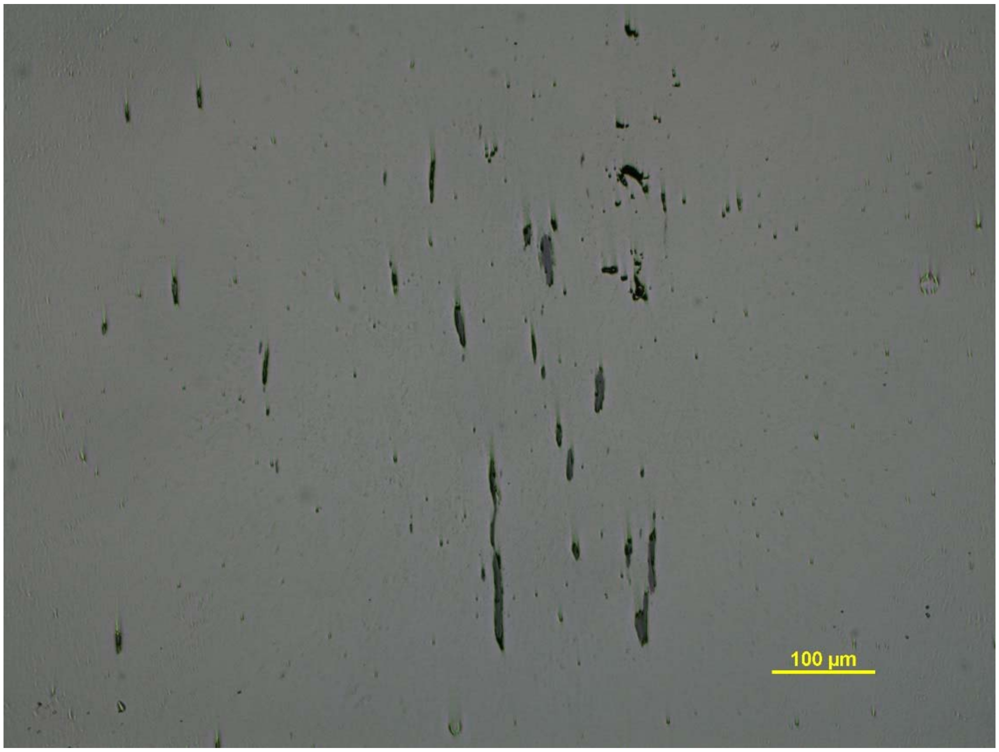


Photo 27) Example of stringer inclusions observed in microstructure. (Unetched)

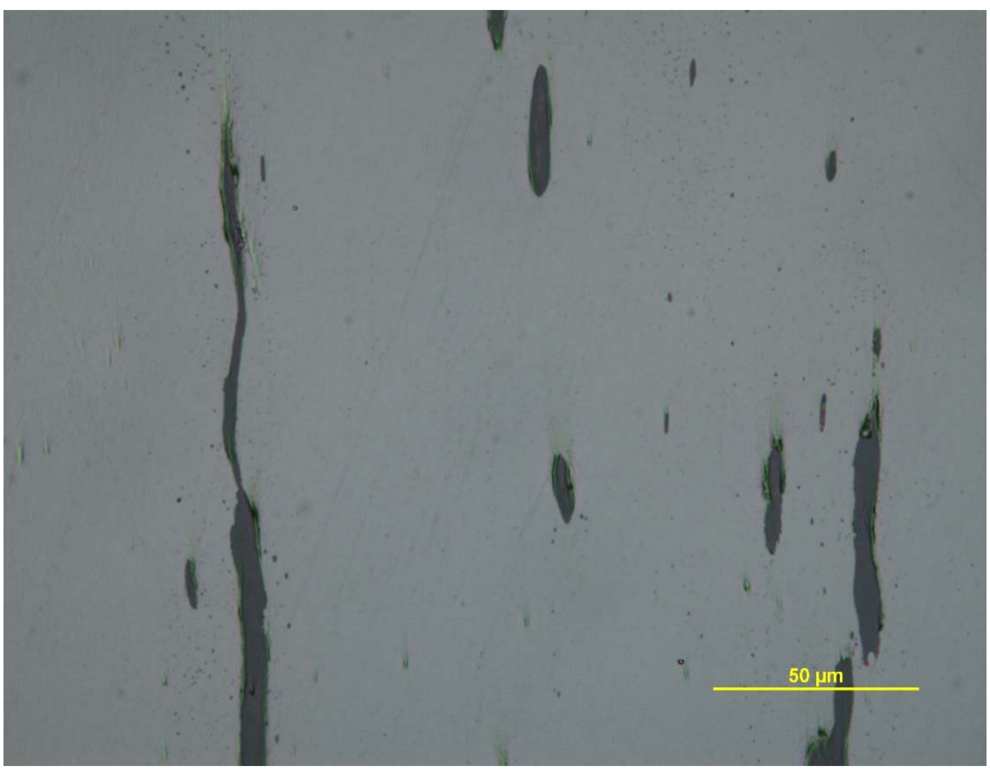
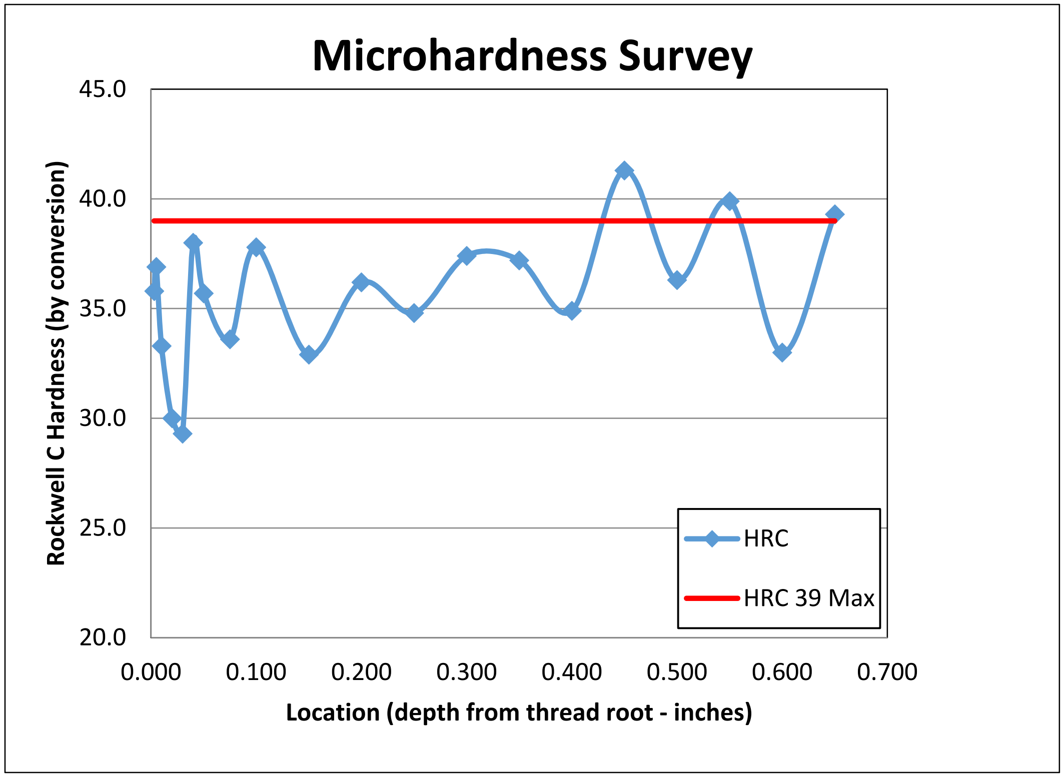


Photo 28) Same as Photo 28 except higher magnification of non-metallic stringer inclusions.

Appendix A
Hardness Test Results

Table 1 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
0.003	358	35.8
0.005	369	36.9
0.010	336	33.3
0.020	311	30.0
0.030	306	29.3
0.040	380	38.0
0.050	357	35.7
0.075	339	33.6
0.100	378	37.8
0.150	333	32.9
0.200	362	36.2
0.250	349	34.8
0.300	374	37.4
0.350	372	37.2
0.400	350	34.9
0.450	418	41.3
0.500	363	36.3
0.550	401	39.9
0.600	334	33.0
0.650	**394**	**39.3**



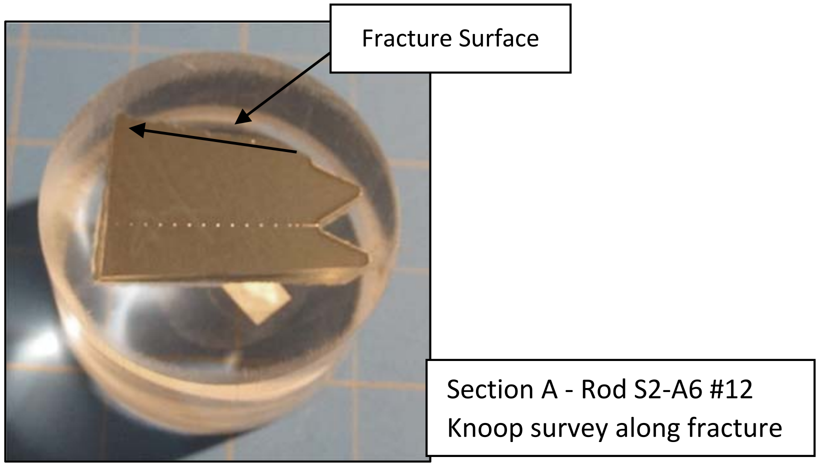


Figure A1
(Rod S2-A6 Section A)

Table 2 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
0.003	359	35.9
0.005	409	40.6
0.010	376	37.6
0.020	364	36.4
0.030	378	37.8
0.040	376	37.6
0.050	387	38.8
0.075	367	36.7
0.100	392	39.1
0.150	399	39.8
0.200	387	38.8
0.250	390	38.9
0.300	405	40.2
0.350	423	41.8
0.400	403	40.1
0.450	417	41.2
0.500	391	39.0
0.550	365	36.5
0.600	378	37.8
0.650	419	41.4
0.700	400	39.8

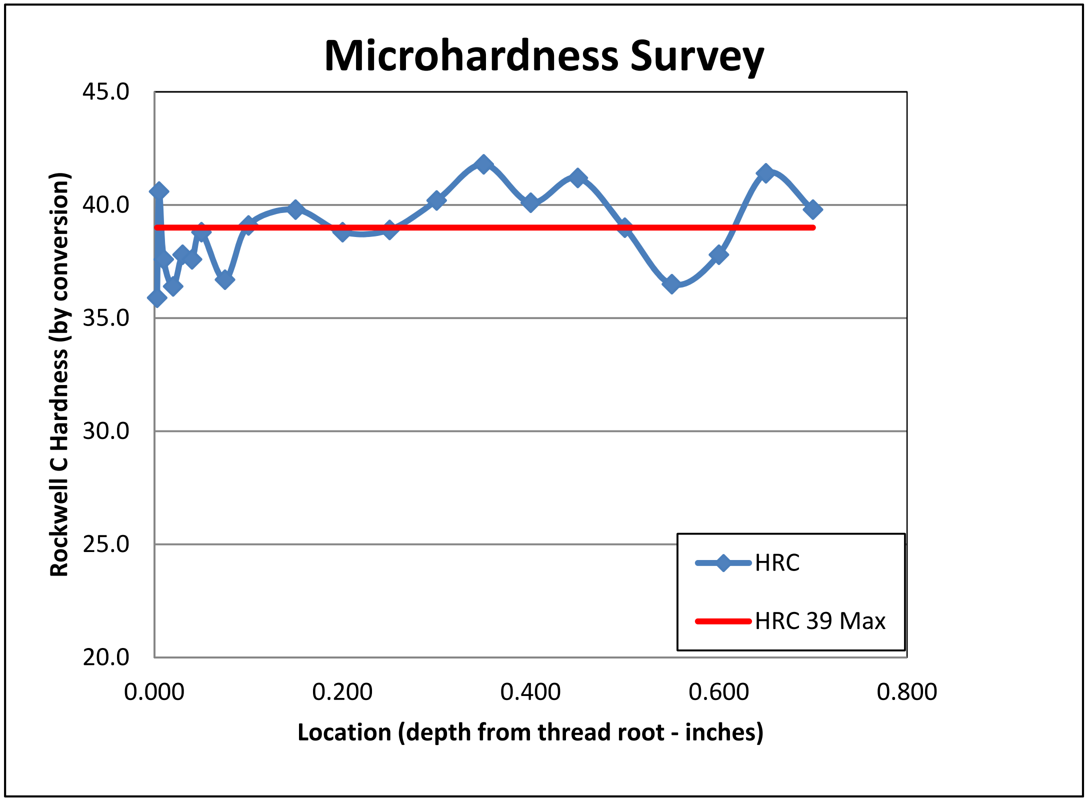


Figure A2
(Rod S2-A6 Section A)

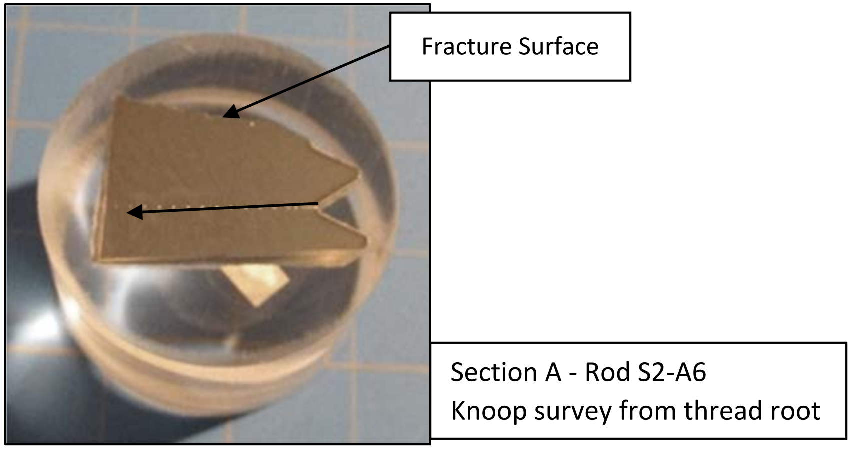
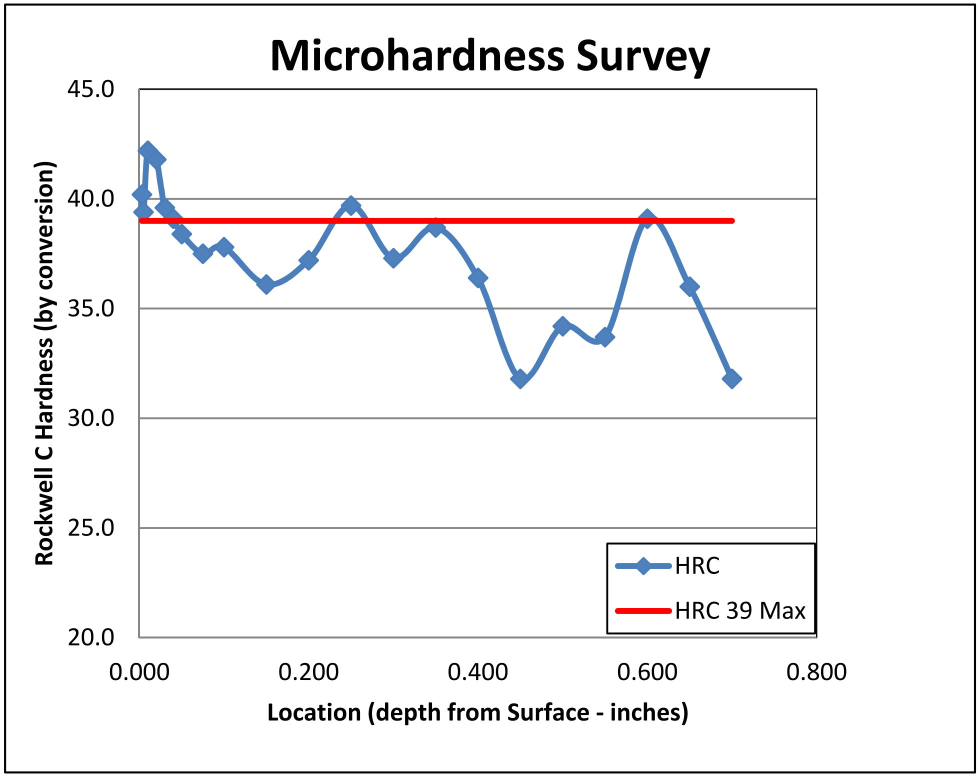
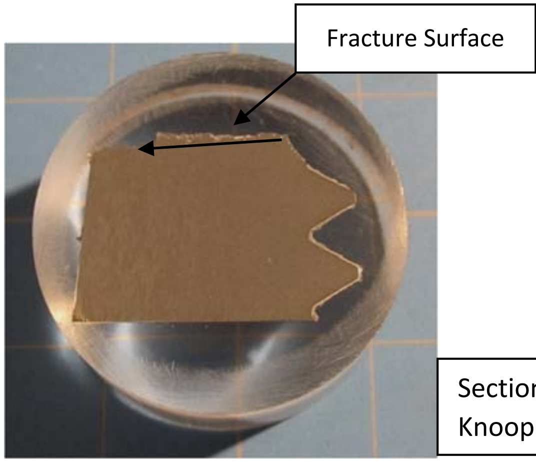


Table 3 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
0.003	404	40.2
0.005	395	39.4
0.010	429	42.2
0.020	423	41.8
0.030	397	39.6
0.040	392	39.1
0.050	384	38.4
0.075	375	37.5
0.100	378	37.8
0.150	361	36.1
0.200	372	37.2
0.250	399	39.7
0.300	373	37.3
0.350	387	38.7
0.400	364	36.4
0.450	324	31.8
0.500	344	34.2
0.550	339	33.7
0.600	392	39.1
0.650	360	36.0
0.700	324	31.8

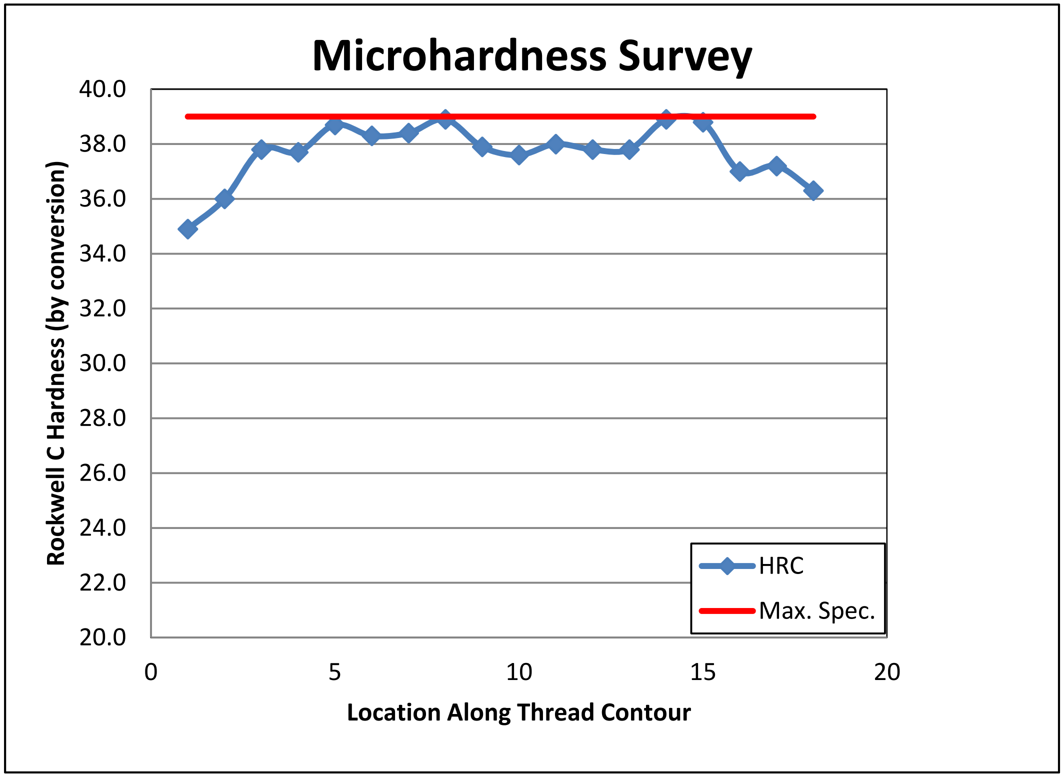
Figure A3
(Rod S2-A6 Section B)

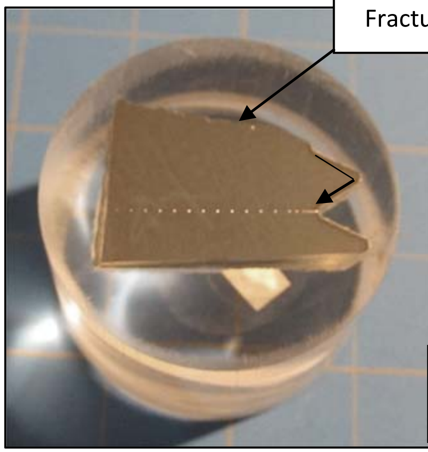




Section B - Rod S2-A6
Knoop survey along fracture

Table 4 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
1	350	34.9
2	360	36.0
3	378	37.8
4	377	37.7
5	387	38.7
6	383	38.3
7	384	38.4
8	390	38.9
9	379	37.9
10	376	37.6
11	380	38.0
12	378	37.8
13	378	37.8
14	390	38.9
15	389	38.8
16	370	37.0
17	372	37.2
18	363	36.3



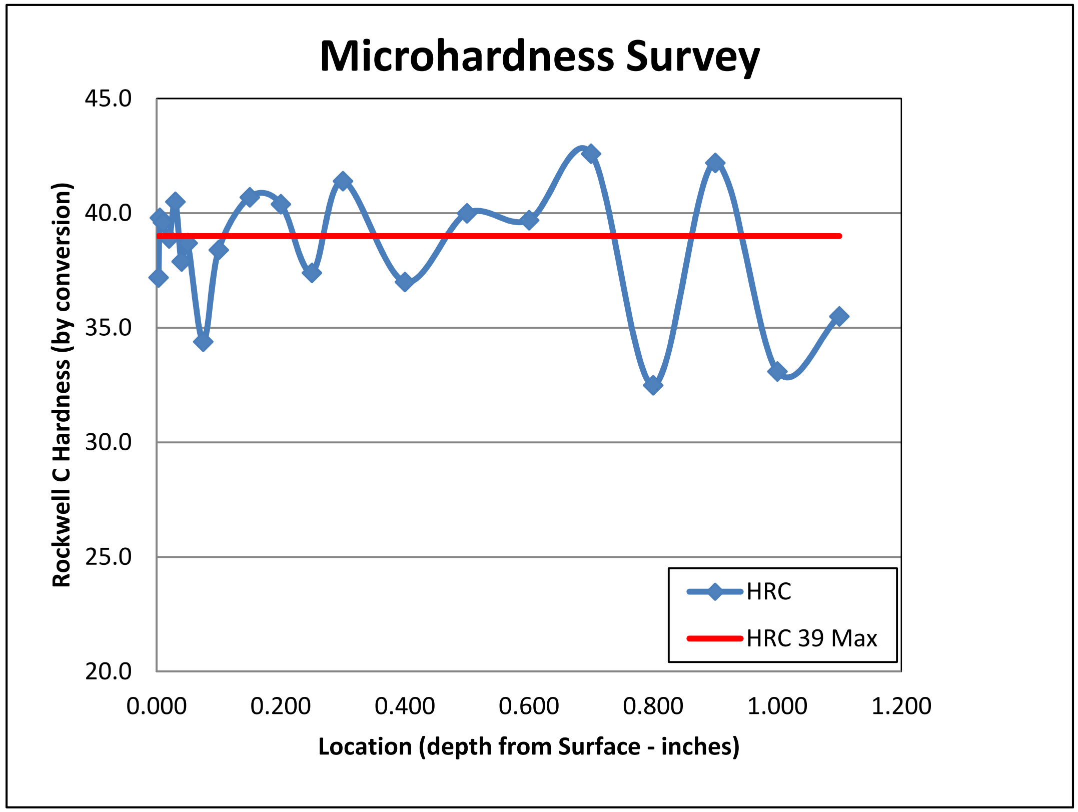


Fracture Surface

Section A - Rod S2-A6
Knoop survey along thread contour

Figure A4
(Rod S2-A6 Section A)

Table 5 Knoop Microhardness Results		
Location Depth from surface (in.)	**Knoop Hardness Number**	**HRC (by conversion table)**
0.003	372	37.2
0.005	400	39.8
0.010	397	39.6
0.020	390	38.9
0.030	408	40.5
0.040	379	37.9
0.050	389	38.7
0.075	346	34.4
0.100	384	38.4
0.150	410	40.7
0.200	407	40.4
0.250	374	37.4
0.300	419	41.4
0.400	370	37.0
0.500	402	40.0
0.600	398	39.7
0.700	433	42.6
0.800	330	32.5
0.900	428	42.2
1.000	335	33.1
1.100	355	35.5



Rod S2-A6 #12
Readings taken radially inward from the thread root at a location approximately ¾ inch from the fracture.

Figure A5
(Rod S2-A6 #12)

Table 6 Knoop Microhardness Results		
Location Depth from surface (in.)	**Knoop Hardness Number**	**HRC (by conversion table)**
0.003	370	37.0
0.005	404	40.2
0.010	383	38.3
0.020	360	36.0
0.030	361	36.1
0.040	353	35.2
0.050	386	38.6
0.075	369	36.9
0.100	356	35.5
0.150	354	35.3
0.200	335	33.1
0.250	348	34.7
0.300	328	32.2
0.350	367	36.7
0.400	316	30.7
0.450	353	35.2
0.500	297	28.0
0.550	346	34.4
0.600	357	35.7
0.650	328	32.2
0.700	334	33.0
0.750	407	40.5

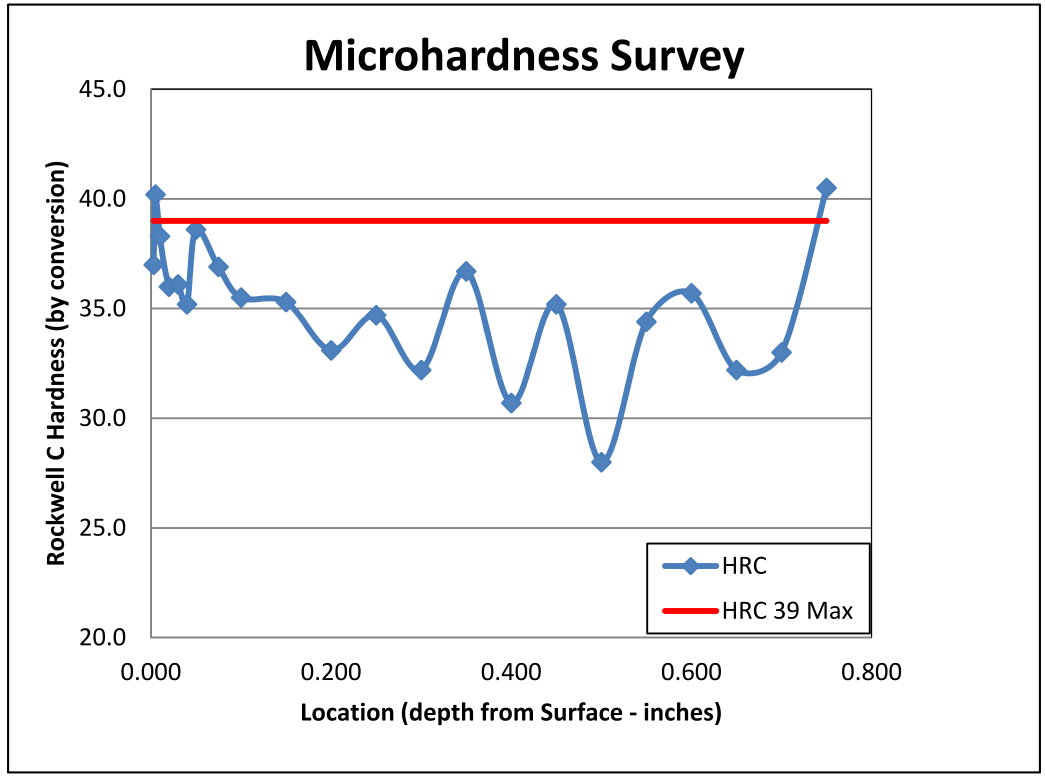


Figure A6
(Rod S1-G1 Section C)

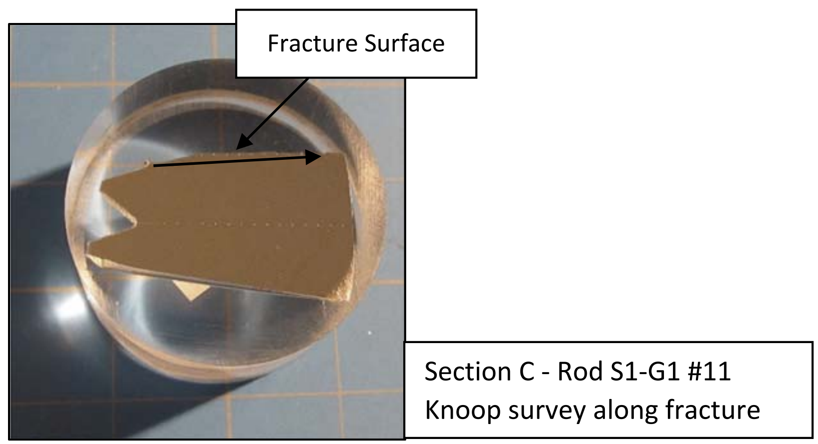
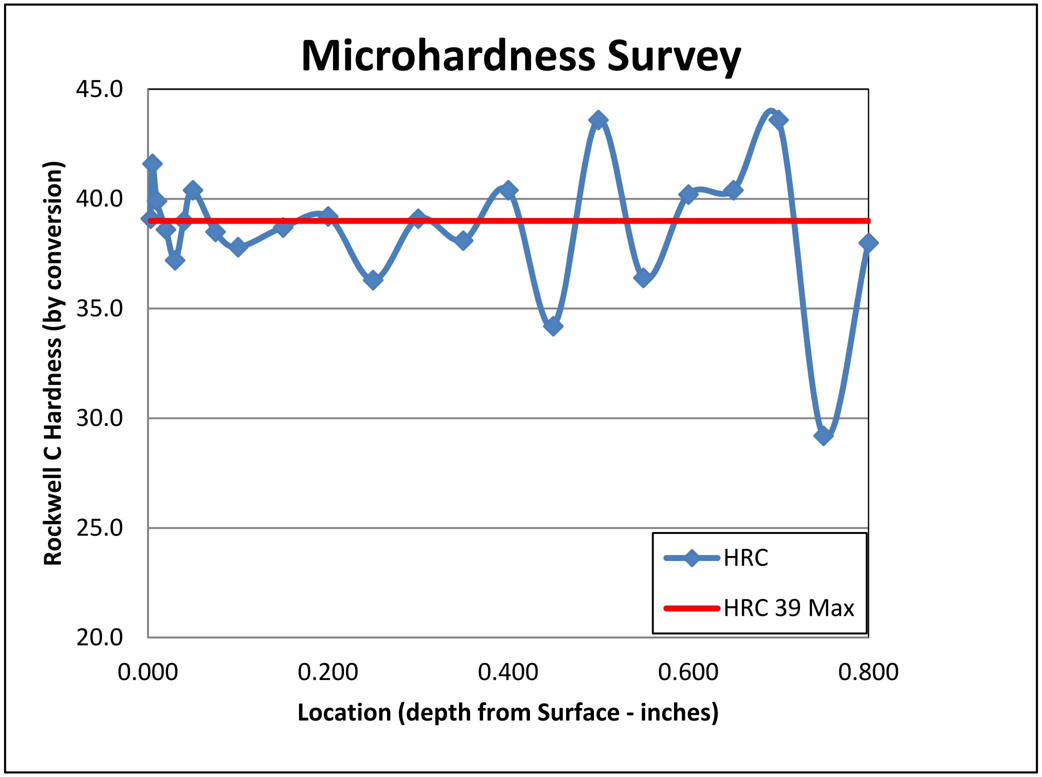


Table 7 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
0.003	392	39.1
0.005	421	41.6
0.010	369	39.9
0.020	386	38.6
0.030	372	37.2
0.040	391	39.0
0.050	407	40.4
0.075	386	38.5
0.100	378	37.8
0.150	387	38.7
0.200	393	39.2
0.250	363	36.3
0.300	392	39.1
0.350	381	38.1
0.400	407	40.4
0.450	344	34.2
0.500	446	43.6
0.550	364	36.4
0.600	404	40.2
0.650	407	40.4
0.700	446	43.6
0.750	306	29.2
0.800	380	38.0



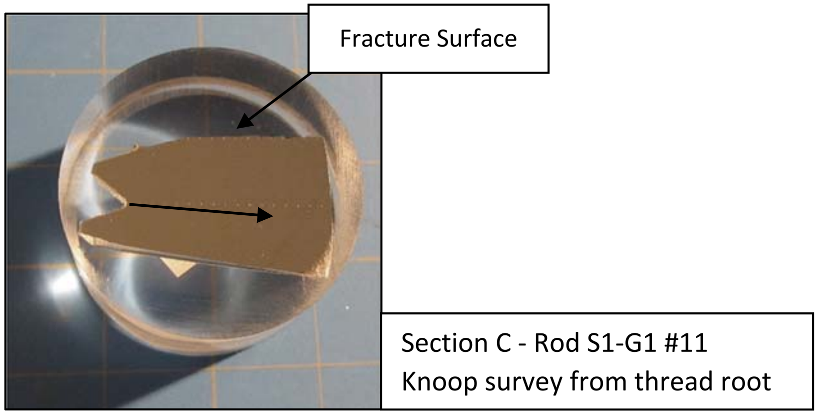
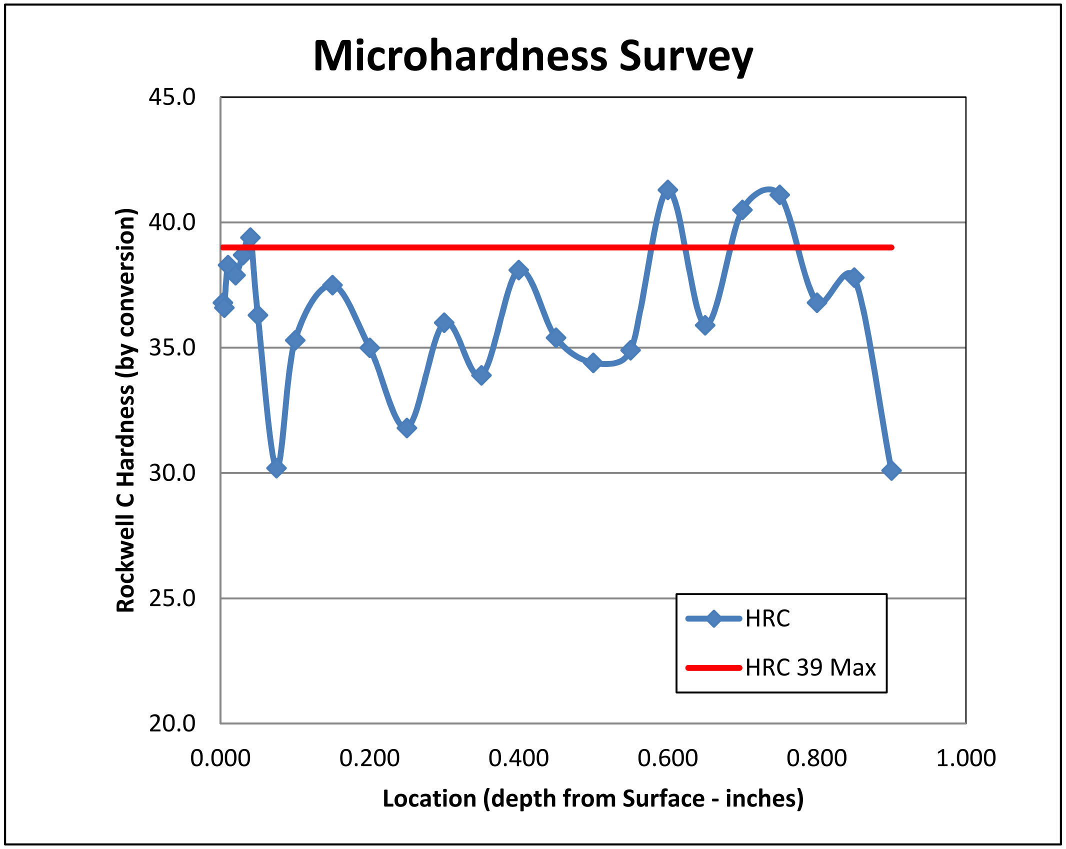


Figure A7
(Rod S1-G1 Section C)

Table 8 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
0.003	368	36.8
0.005	366	36.6
0.010	383	38.3
0.020	379	37.9
0.030	387	38.7
0.040	395	39.4
0.050	363	36.3
0.075	313	30.2
0.100	354	35.3
0.150	375	37.5
0.200	351	35.0
0.250	324	31.8
0.300	360	36.0
0.350	341	33.9
0.400	381	38.1
0.450	355	35.4
0.500	346	34.4
0.550	350	34.9
0.600	417	41.3
0.650	357	35.9
0.700	408	40.5
0.750	415	41.1
0.800	368	36.8
0.850	378	37.8
0.900	312	30.1



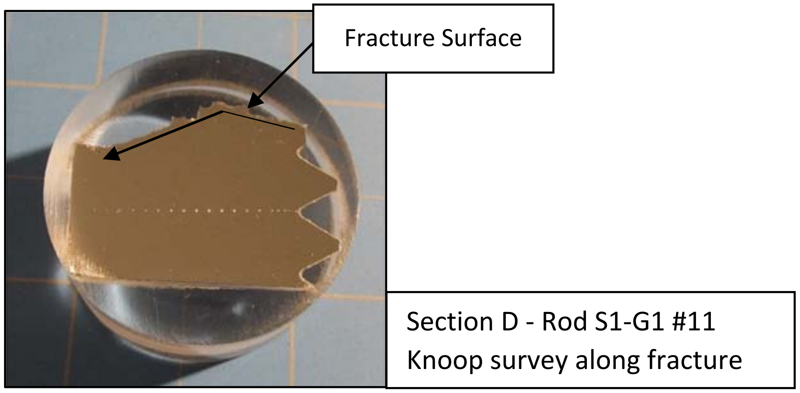
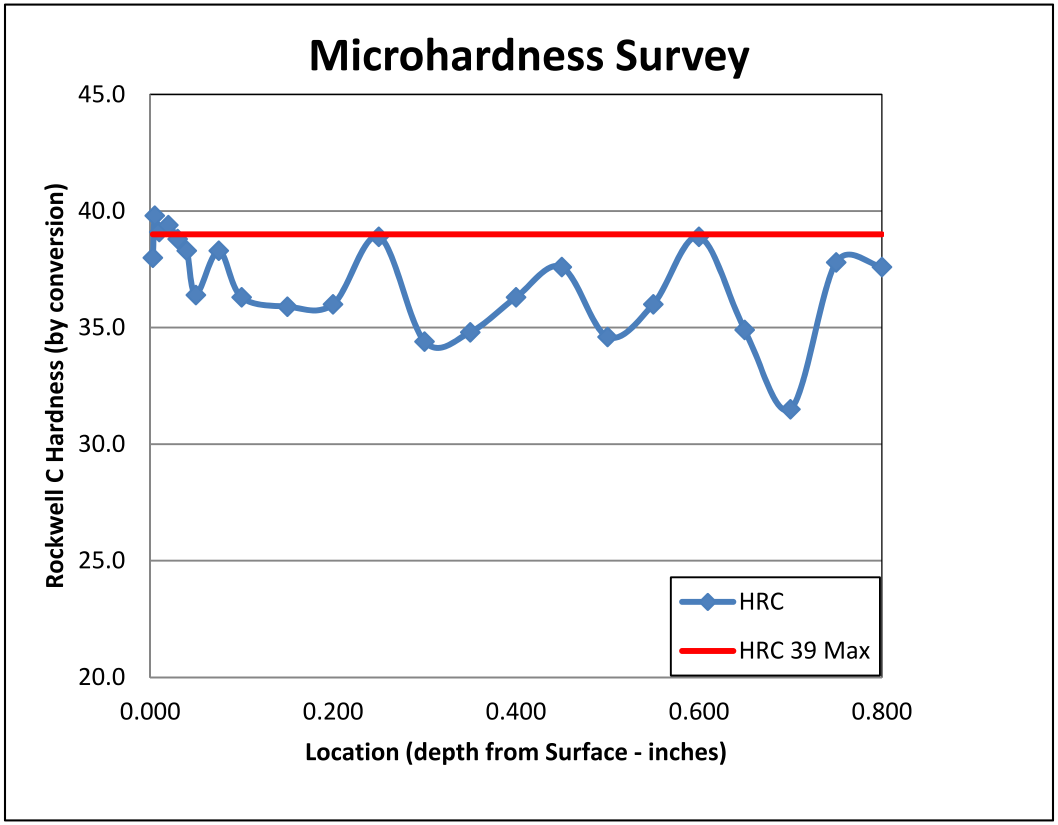
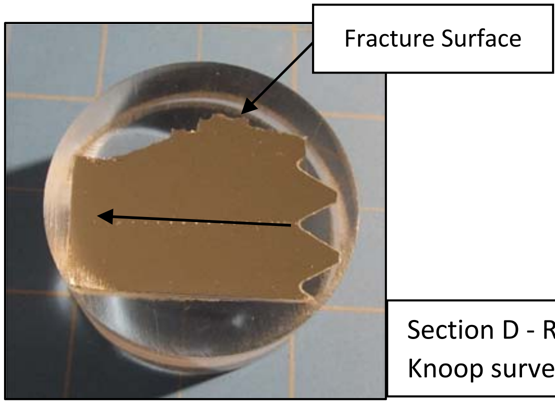


Figure A8
(Rod S1-G1 Section D)

Table 9 Knoop Microhardness Results		
Location Depth from surface (in.)	Knoop Hardness Number	HRC (by conversion table)
0.003	380	38.0
0.005	399	39.8
0.010	392	39.1
0.020	395	39.4
0.030	388	38.8
0.040	383	38.3
0.050	364	36.4
0.075	383	38.3
0.100	363	36.3
0.150	359	35.9
0.200	360	36.0
0.250	390	38.9
0.300	346	34.4
0.350	349	34.8
0.400	363	36.3
0.450	376	37.6
0.500	347	34.6
0.550	360	36.0
0.600	389	38.9
0.650	350	34.9
0.700	321	31.5
0.750	378	37.8
0.800	376	37.6

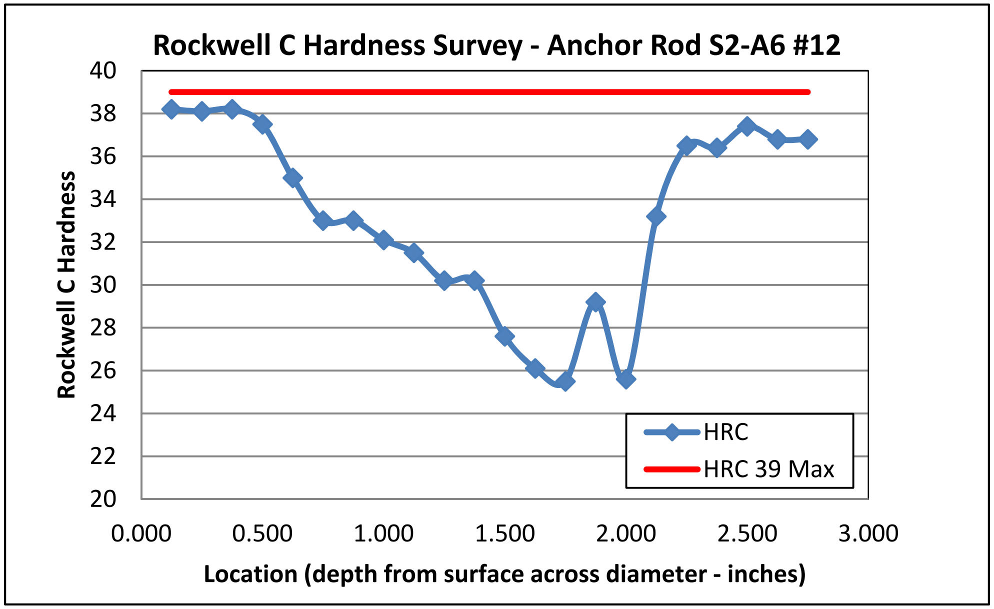




Section D - Rod S1-G1 #11
Knoop survey from thread root

Figure A9
(Rod S1-G1 Section D)

Rockwell C Hardness Results		
Location (in.)	S2-A6 #12	S1-G1 #11
0.125	38.2	36.9
0.250	38.1	36.0
0.375	38.2	36.1
0.500	37.5	34.1
0.625	35	34.9
0.750	33	34.6
0.875	33	32.0
1.000	32.1	28.5
1.125	31.5	31.0
1.250	30.2	33.1
1.375	30.2	29.2
1.500	27.6	30.0
1.625	26.1	29.5
1.750	25.5	30.8
1.875	29.2	29.2
2.000	25.6	30.1
2.125	33.2	35.1
2.250	36.5	35.6
2.375	36.4	35.1
2.500	37.4	36.1
2.625	36.8	36.5
2.750	36.8	36.6



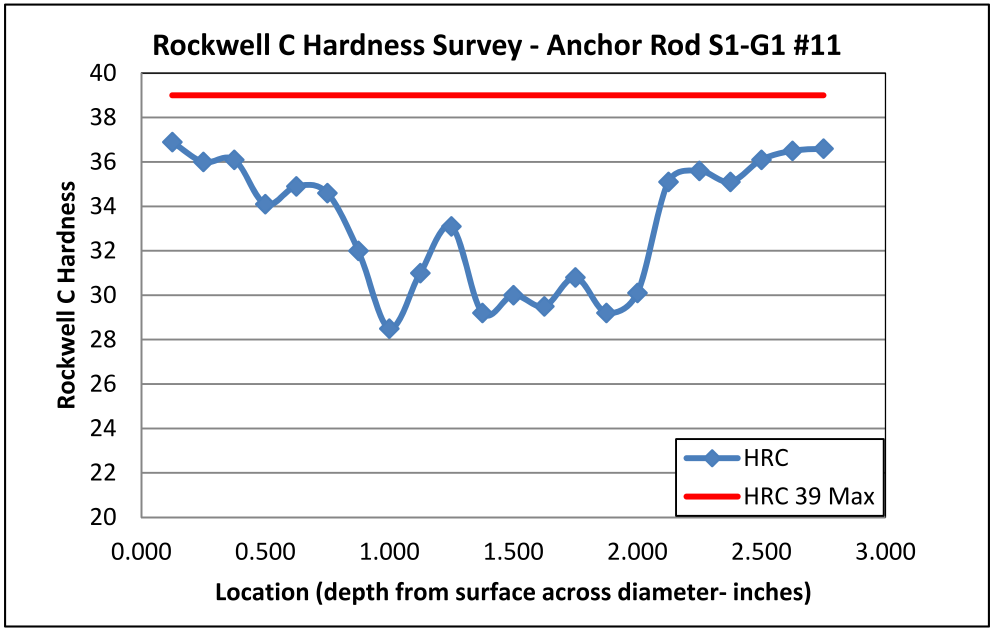


Figure A10

Rockwell C Hardness Across the Rod Diameter

Appendix B
Anamet Labs Test Reports

LABORATORY CERTIFICATE

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Note this testing was performed on Rod ID: S2-A6 #12
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Anamet, inc

	March 21, 2013
LABORATORY NUMBER:	5004.8623
CUSTOMER AUTHORIZATION:	Credit Card
DATE SUBMITTED:	March 20, 2013
REPORT TO:	The Dyson Corporation Attn: Patrick Linehan 53 Freedom Rd. Painesville, OH 440177

SUBJECT:
One steel sample was submitted for chemical analysis, tensile and charpy impact testing. The sample was identified as Bay Bridge anchor rod, 3" ASTM A354 Grade BD (approximately 23" long threaded on one end).

The following results relate only to the item tested

SPECTROCHEMICAL ANALYSIS (Reported as Wt. %)			Requirement ASTM A354 Alloy Steel Min.	Max.
Aluminum	(Al)	<0.005	Information	
Carbon*	(C)	0.40	0.33	0.55
Chromium	(Cr)	0.97	Information	
Cobalt	(Co)	0.01	Information	
Copper	(Cu)	0.22	Information	
Iron	(Fe)	Balance	Balance	
Manganese	(Mn)	0.93	0.57	-
Molybdenum	(Mo)	0.16	Information	
Nickel	(Ni)	0.10	Information	
Phosphorus	(P)	0.012	-	0.040
Silicon	(Si)	0.24	Information	
Sulfur*	(S)	0.034	-	0.045
Titanium	(Ti)	<0.005	Information	
Tungsten	(W)	<0.005	Information	
Vanadium	(V)	0.03	Information	
Zirconium	(Zr)	<0.005	Information	

* Determined by LECO combustion

26102 Eden Landing Road, Suite 3, Hayward, California 94545-3811 Phone: **510-887-8811** Fax: **510-887-8427** www.anametinc.com

LABORATORY CERTIFICATE

Anamet, inc

Lab. No. 5004.8623

TENSILE TEST (ASTM A370-10)		Requirement ASTM A354 Grade BD
Diameter of Specimen (in.)	0.506	
Area (in^2)	0.201	
Tensile Strength (psi)	170000	140000 min.
Yield Strength 0.2% Offset (psi)	149000	115000 min.
Elongation in 2.0" Gage (%)	15-1/2	14 min.
Reduction of Area (%)	46.0	40 min.

CHARPY IMPACT TEST (ASTM A370-10)
Type: V-Notch
Size: 10mm x 10mm x 55mm
Location: Per Drawing
Temperature: Room Temperature (+70°F actual)

Energy Absorbed (ft·lbs)
18
18
17

Requirements: Energy – Information

This testing was completed on March 20, 2013 and was performed in accordance with the customer's authorization. The testing was under Anamet, Inc. Quality Control Program QCM 66-10, Rev.13 (1/6/2012). The results meet the listed requirements.

Submitted by:

Edward A. Foreman

Edward A. Foreman
Quality Manager

yv

Anamet, inc *Materials Engineering & Laboratory Testing*
26102 EDEN LANDING ROAD, SUITE 3 • HAYWARD, CALIFORNIA 94545 • (510) 887-8811 • FAX (510) 887-8427

Report No. 5004.8612 **March 18, 2013**

ROCKWELL HARDNESS TESTING OF AN ANCHOR ROD SECTION

Customer Authorization: PO# 615126

Report To: Christensen Materials Engineering
Attn: Conrad Christensen
89 Stephanie Lane
Alamo, CA 94507

REPORT[1]

One anchor rod section, identified as Bay Bridge 3-inch diameter anchor rod S2-A6 12, was submitted for a Rockwell hardness test. The anchor rod was reportedly an A354 Grade BD alloy steel with a hardness range from 31 to 39 HRC.

The anchor rod section was milled flat with a surface grinder and cleaned with acetone. Rockwell hardness testing was performed at four mid-radii and at twenty-two locations traverse through the cross section at 1/8-inch increments. The photograph in Figure 1 indicates the locations on the anchor rod cross section that were tested. Tables 1 and 2 present the results of the hardness testing and Table 3 presents the hardness readings on two check standards.

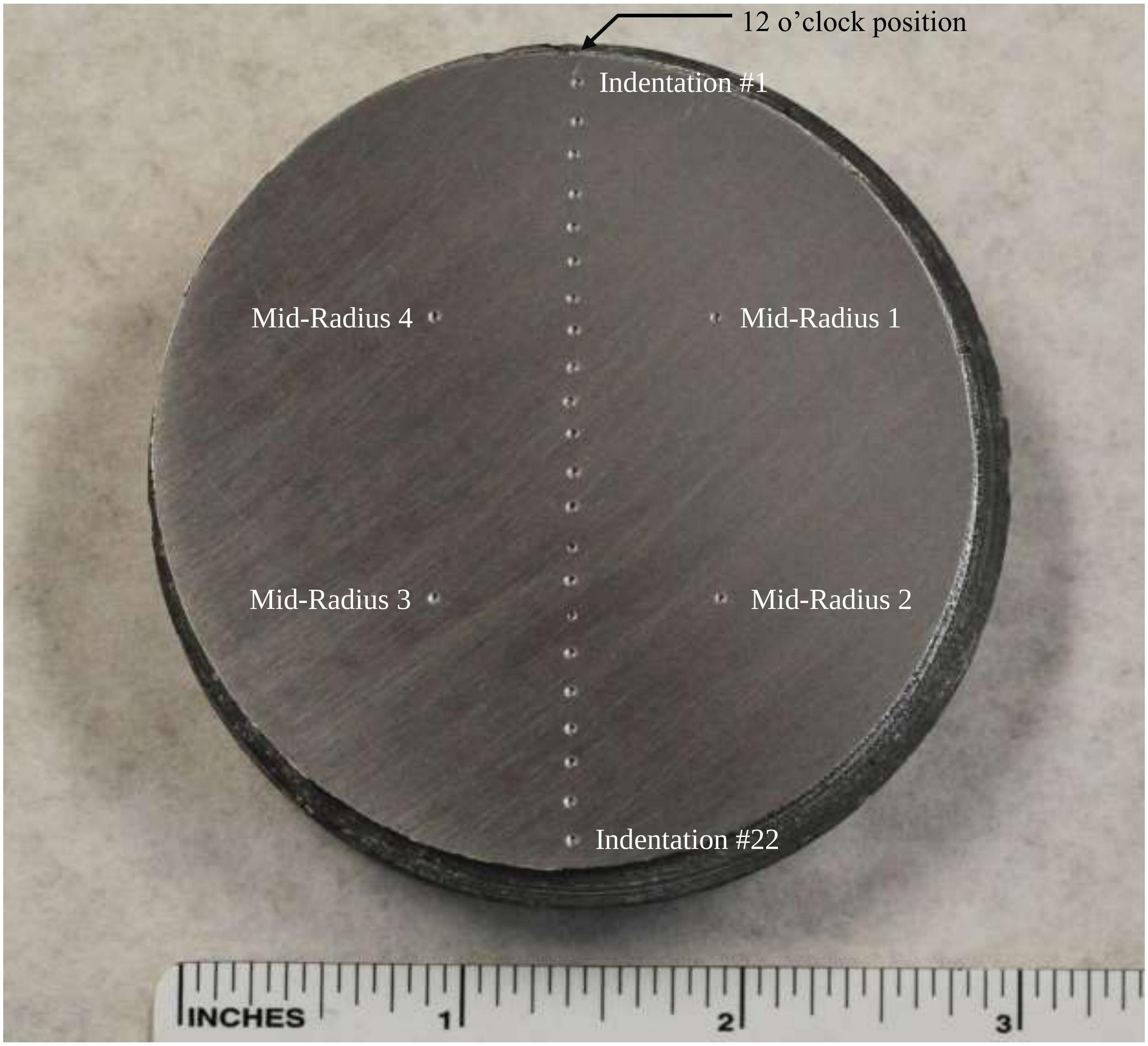
Prepared by:

Norman Yuen
Materials Engineer

Reviewed by:

Audrey Fasching, Ph.D., P.E.
Senior Materials Engineer

[1] The magnifications of the optical and scanning electron micrographs in this report are approximate and should not be used as a basis for dimensional analyses unless otherwise indicated.
The conclusions in this report are based upon the available information and evidence provided by the client and gathered by Anamet, within the scope of work authorized by the client, and they are hereby presented by Anamet to a reasonable degree of engineering and scientific certainty. Anamet reserves the right to amend or supplement its conclusions or opinions presented in this report should additional data or information become available, or further work be approved by the client.



(a)

Figure 1 Photograph of the anchor rod with Rockwell hardness indentations at the four mid-radii and traverse through the cross section.

Table 1
Rockwell Hardness Traverse Measurements

Indentation Number	Distance from the 12 o'clock position (inches)	Rockwell Hardness (HRC)
1	0.125	38.2
2	0.250	38.1
3	0.375	38.2
4	0.500	37.5
5	0.625	35.0
6	0.750	33.0
7	0.875	33.0
8	1.000	32.1
9	1.125	31.5
10	1.250	30.2
11	1.375	30.2
12	1.500	27.6
13	1.625	26.1
14	1.750	25.5
15	1.875	29.2
16	2.000	25.6
17	2.125	33.2
18	2.250	36.5
19	2.375	36.4
20	2.500	37.4
21	2.625	36.8
22	2.750	36.8

Table 2
Rockwell Hardness Measurements at Mid-Radii

Mid-Radii Number	Rockwell Hardness (HRC)
1	34.2
2	36.2
3	35.9
4	33.2

Table 3
Rockwell Hardness Standards

Standard – 33.19 HRC	
Indentation Number	Rockwell Hardness (HRC)
1	32.5
2	32.8
3	32.9

Standard – 44.57 HRC	
Indentation Number	Rockwell Hardness (HRC)
1	42.5
2	43.4
3	44.1
4	43.8
5	44.1

LABORATORY CERTIFICATE

Anamet, inc

April 5, 2013

LABORATORY NUMBER:	5004.8677
CUSTOMER AUTHORIZATION:	Verbal
DATE SUBMITTED:	April 1, 2013
REPORT TO:	Alta Vista Solutions Attn: Aaron Prchlik 6475 Christie Ave., Ste 425 Emeryville, CA 94608

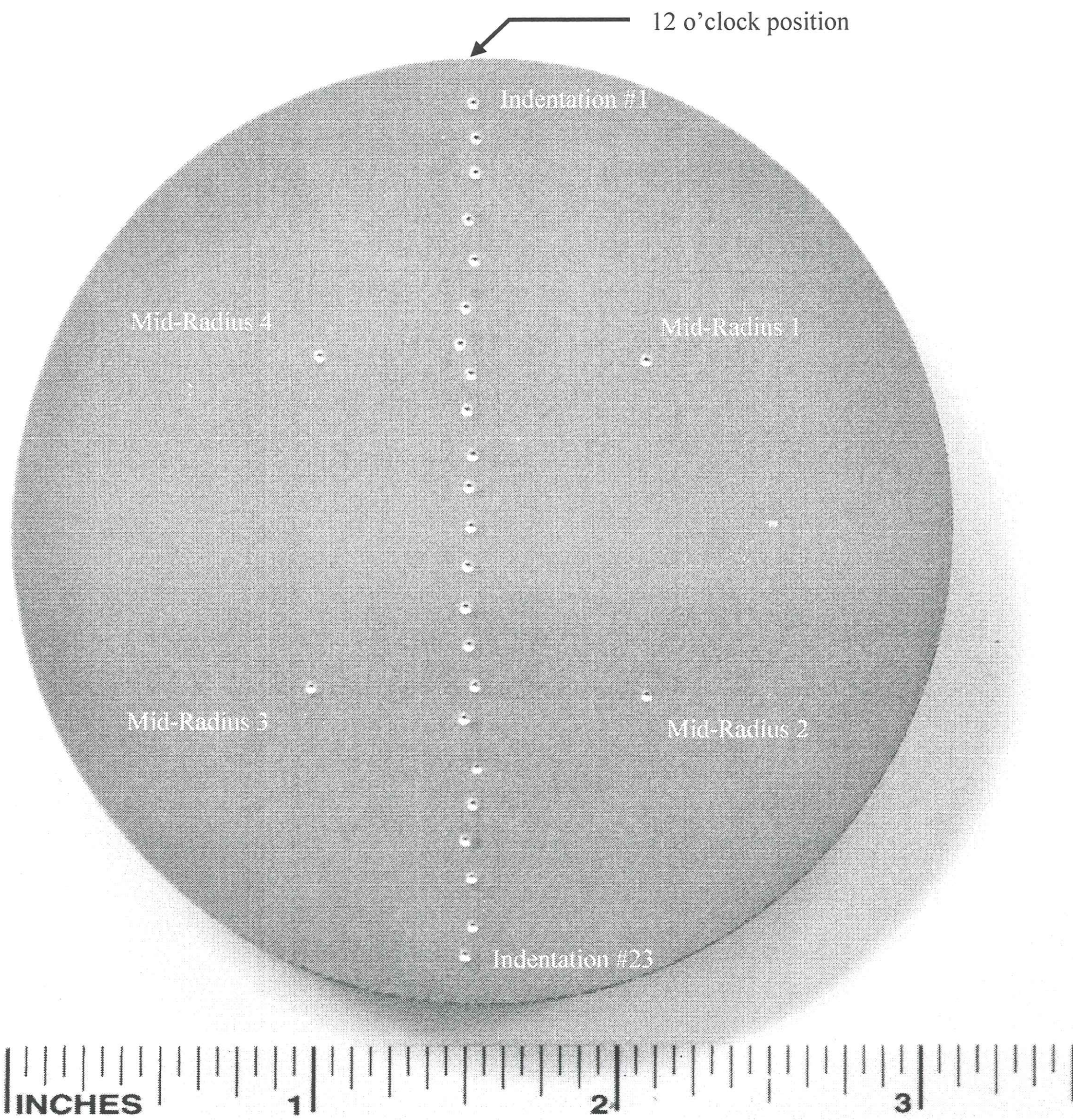
SUBJECT:
One anchor rod was submitted for mechanical testing. The sample was identified as Bay Bridge 3" Diameter Anchor Rod I.D: S2-A6 #2, ASTM A354 Grade BD steel.

TENSILE TEST (ASTM A370-10)		Requirement ASTM A354-11 Grade BD
Diameter of Specimen (in.)	0.505	
Area (in^2)	0.200	
Tensile Strength (psi)	168000	140000 psi min.
Yield Strength 0.2% Offset (psi)	146000	115000 psi min.
Elongation in 2.0″ Gage (%)	14	14 min.
Reduction of Area (%)	48.0	40 min.

CHARPY IMPACT TEST (ASTM A370-10)
Type: V-Notch
Size: 10mm x 10mm x 55mm
Orientation: Longitudinal
Location: Close to Outside (Surface Notch)
Temperature: Room Temperature

Energy Absorbed (ft·lbs)
15
14
15

Lab. No. 5004.8677



(a)

Figure 1 Photograph of the anchor rod with Rockwell hardness indentations at the four mid-radii and traverse through the cross section.

Anamet, inc

Lab. No. 5004.8677

Table 1
Rockwell Hardness Traverse Measurements

Indentation Number	Distance from the 12 o'clock position (inches)	Rockwell Hardness (HRC)
1	0.125	36.1
2	0.250	35.1
3	0.375	36.2
4	0.500	35.3
5	0.625	33.3
6	0.750	33.4
7	0.875	32.0
8	1.000	32.7
9	1.125	32.4
10	1.250	30.4
11	1.375	28.5
12	1.500	31.8
13	1.625	36.9
14	1.750	30.6
15	1.875	31.2
16	2.000	34.5
17	2.125	35.4
18	2.250	35.4
19	2.375	35.2
20	2.500	36.2
21	2.625	37.3
22	2.750	36.1
23	2.875	36.4

Table 2
Rockwell Hardness Measurements at Mid-Radii

Mid-Radii Number	Rockwell Hardness (HRC)
1	32.5
2	34.9
3	35.7
4	34.3

Lab. No. 5004.8677

Table 3
Rockwell Hardness Standards

Standard – 33.19 HRC	
Indentation Number	Rockwell Hardness (HRC)
1	32.5
2	32.6
3	33.1

Standard – 44.57 HRC	
Indentation Number	Rockwell Hardness (HRC)
1	43.3
2	43.8
3	43.8

The testing was completed on April 4, 2013 and was performed in accordance with the customer's authorization. The tests were conducted under Anamet, Inc. Quality Program QCM 66-10, Rev. 13 (1/6/2012). The tensile test results meet the listed requirements.

Submitted by:

Edward A. Foreman
Quality Manager

yv

Anamet, inc

April 12, 2013

LABORATORY NUMBER:	5004.8710
CUSTOMER AUTHORIZATION:	Verbal
DATE SUBMITTED:	April 9, 2013
REPORT TO:	Alta Vista Solutions Attn: Aaron Prchlik 6475 Christie Ave., Ste 425 Emeryville, CA 94608

SUBJECT:
One anchor rod was submitted for chemical analysis and mechanical testing. The sample was identified as Bay Bridge 3" Diameter Anchor Rod I.D: S1-G1 #11, ASTM A354 Grade BD steel.

The following results relate only to the item tested

SPECTROCHEMICAL ANALYSIS (ASTM E415-08)
(Reported as Wt. %)

Requirement: ASTM A354, Gr. BD Alloy Steel, Product Analysis

Element	Symbol	Result	Min.	Max.
Carbon*	(C)	0.43	0.33	0.55
Chromium	(Cr)	0.98	Information	
Cobalt	(Co)	0.01	Information	
Columbium	(Cb)	<0.005	Information	
Copper	(Cu)	0.22	Information	
Iron	(Fe)	Balance	Balance	
Manganese	(Mn)	0.93	0.57	-
Molybdenum	(Mo)	0.15	Information	
Nickel	(Ni)	0.10	Information	
Phosphorus	(P)	0.012	-	0.040
Silicon	(Si)	0.23	Information	
Sulfur*	(S)	0.039	-	0.045
Titanium	(Ti)	<0.005	Information	
Tungsten	(W)	<0.005	Information	
Vanadium	(V)	0.03	Information	
Zirconium	(Zr)	<0.005	Information	

* Determined by LECO combustion (ASTM E1019-11)

26102 Eden Landing Road, Suite 3, Hayward, California 94545-3811 Phone: **510-887-8811** Fax: **510-887-8427** www.anametinc.com

Anamet, inc

Lab. No. 5004.8710

TENSILE TEST (ASTM A370-10)		Requirement ASTM A354 Grade BD
Diameter of Specimen (in.)	0.504	
Area (in^2)	0.200	
Tensile Strength (psi)	159000	140000 psi min.
Yield Strength 0.2% Offset (psi)	136000	115000 psi min.
Elongation in 2.0″ Gage (%)	15	14 min.
Reduction of Area (%)	48.4	40 min.

CHARPY IMPACT TEST (ASTM A370-10)
Type: V-Notch
Size: 10mm x 10mm x 55mm
Orientation: Longitudinal (Surface Notched)
Location: Per drawing
Temperature: +40°F

Energy Absorbed (ft·lbs)
13-1/2
13
14

Requirements: Energy – Information

Lab. No. 5004.8710

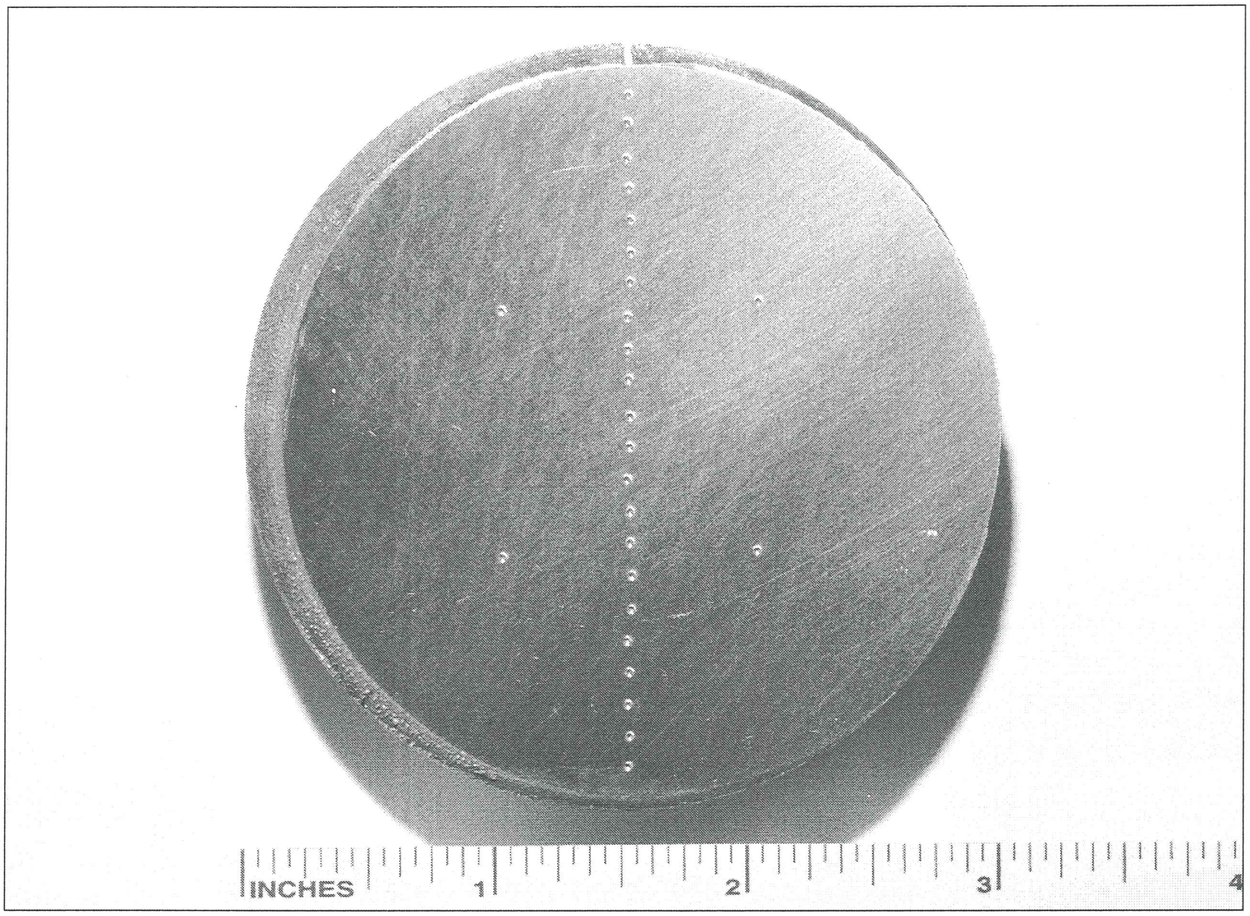


Figure 1 Photograph of the anchor rod with Rockwell hardness indentations at the four mid-radii and traverse through the cross section.

Lab. No. 5004.8710

Table 1
Rockwell Hardness Traverse Measurements

Indentation Number	Distance from the 12 o'clock position (inches)	Rockwell Hardness (HRC)
1	0.125	36.9
2	0.250	36.0
3	0.375	36.1
4	0.500	34.1
5	0.625	34.9
6	0.750	34.6
7	0.875	32.0
8	1.000	28.5
9	1.125	31.0
10	1.250	33.1
11	1.375	29.2
12	1.500	30.0
13	1.625	29.5
14	1.750	30.8
15	1.875	29.2
16	2.000	30.1
17	2.125	35.1
18	2.250	35.6
19	2.375	35.1
20	2.500	36.1
21	2.625	36.5
22	2.750	36.6

Table 2
Rockwell Hardness Measurements at Mid-Radii

Mid-Radii Number	Rockwell Hardness (HRC)
1	34.0
2	34.6
3	31.9
4	31.5

Anamet, inc

Lab. No. 5004.8710

The testing was completed on April 11, 2013 and was performed in accordance with the customer's authorization. The tests were conducted under Anamet, Inc. Quality Program QCM 66-10, Rev. 13 (1/6/2012). The results meet the listed requirements.

Submitted by:

Edward A. Foreman

Edward A. Foreman
Quality Manager

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