# S-N Fatigue Design Guidelines and Test Data for Low Alloy Steel Bolts

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# Introduction

The requirements for bolting fatigue assessment were a charge of the API CSOEM Multi-Segment Task Group on Bolting Failures. Due to documented subsea bolting failures defined in the BSEE QC-FIT Evaluation of Connector and Bolt Failures, the charge of the sub task group TGR-13 was the following:

"*Guidance should be issued by API on when and how to perform fatigue sensitivity analysis on bolting.*"

API CSOEM Bolting Report for TGR-13 and TGR-14 was issued. It defined the design guidelines and provided recommendations for performing a full-scale fatigue testing on bolting. Upon further approval, full-scale fatigue testing was performed.

The scope of work was conducted in two phases; Phase I: Evaluation of bolting under cyclic loading which meets the requirements of API 17D standard and Phase II: Evaluation of bolting which meets the requirements of API 6A/16A standards. The following guidelines are provided for both design verification fatigue analysis and corresponding full-scale fatigue testing that was performed.

Design verification analysis for fatigue assessment of bolting requires an evaluation for S-N or fatigue crack growth rate. The S-N fatigue evaluation can be based on either the stress concentrations of the thread profile, which will need stress concentration factor (SCF) and smooth tensile bar S-N testing, or the axial stress due to the load divided by the minimum root diameter area and full-scale bolt fatigue tests. The basis of this document is the S-N approach using full-scale fatigue testing. The full-scale fatigue testing was conducted for bolts manufactured to meet API 20E BSL-3. The testing was performed in two phases; phase I was conducted to obtain S-N fatigue curve with API 17D loading conditions, phase II was conducted with API 6A/16A loading conditions.

The fatigue testing was based on alternating axial stresses in the bolt with a defined preload. The preload was applied with the load frame to a value of 2/3*SMYS for Phase I testing and 0.5*SMYS for Phase II testing, based on the cross-section at the root radius of the thread. The defined bolt lengths represent API flange by flange connection conservative bolt lengths for a given bolt size. The bolt-to-nut thread engagement met the requirements of API 6A for all tests. Each bolt tested had two bolt/nut connections where the failure of the first connection was defined as the fatigue life.

The objective of the Phase I test program was to provide S-N fatigue curves for bolts that are preloaded per API Series 17 standards and are subjected to a range of alternating axial stresses. The objective of the phase II test program was to provide S-N fatigue curves for bolts that are preloaded per API 6A/16A standards. The preload and alternating stress ranges were defined based on the cross-sectional area at the root radius of the threads. The test program evaluated bolt size effects and environments of air and saltwater with cathodic protection (CP).

## 1 Scope

The scope of the test program was to obtain bolting material fatigue data required to perform design verification analysis of bolting subjected to fatigue loading to assure accurate design life estimation. The bolting fatigue testing program provided S-N fatigue curves for three alternating stress ranges in air and in saltwater with CP environments and for bolt sizes of 1 in., 2 in. (Grade L7), and 3 in. (Grade L43) in phase I and for bolt sizes 1 in. (Grade L7) and 3 in. (Grade L43) in phase II.

The results of these S-N fatigue tests allow the bolting design to be assessed for S-N fatigue through structural analysis using the nominal root area stresses in the bolt, avoiding the need to define stress and load concentrations in the bolt root radius of engaged threads.

The design guidelines and the fatigue data provided in the document are intended to be used for bolting with unified national thread with root radius (UNR) specifications of ASME B1.1 class 2A/2B.

# 2 Normative References

There are no referenced documents that are indispensable for the application of this document.

# 3 Terms, Definitions, Abbreviations, and Symbols

## 3.1 Terms and Definitions

**3.1.1**
**ambient air**
Room temperature and ambient pressure.

**3.1.2**
**high-stress range fatigue cycles**
**HFC**
Tested fatigue cycles to failure for a high-stress range or high force condition applied.

**3.1.3**
**low-stress range fatigue cycles**
**LFC**
Tested fatigue cycles to failure for a low-stress range or low force condition applied.

**3.1.4**
**mean stress**
Maximum axial stress plus minimum axial stress divided by two.

**3.1.5**
**medium-stress range fatigue cycles**
**MFC**
Tested fatigue cycles to failure for a medium-stress range or medium force condition applied.

**3.1.6**
**S-N fatigue**
Stress range (S) versus number of cycles to failure (N).

**3.1.7**
**stress range**
The difference between the maximum axial stress and minimum axial stress being applied.

## 3.2 Acronyms, Abbreviations, and Symbols

| | |
|---|---|
| CP | cathodic protection |
| EF | electric furnace |
| EDS | energy dispersive X-ray spectroscopy |
| HFC | high-stress range fatigue cycles |
| FSF | full-scale fatigue |
| LFC | low-stress range fatigue cycles |
| MFC | medium-stress range fatigue cycles |

MPS manufacturing process specification
SAF stress amplification factor
SCE saturated calomel electrode
SCF stress concentration factor
SEM scanning electron microscopy
SMYS specified minimum yield strength
S-N stress-number of cycles to failure
UNR unified national thread with root radius
YS yield strength
$\Delta\sigma$ stress range
2SD two times the standard deviation value

# 4 Bolting Fatigue Analysis Design Guidelines

## 4.1 Bolting Subjected to Cyclic Loading

Bolting that transfers loads of the riser systems to the wellhead should be considered fatigue-sensitive and should be evaluated for cyclic loading. This includes cyclic loadings from drilling risers, workover/completion risers, and production risers. Other bolting may require fatigue evaluation depending on the operating conditions and the load path.

Bolting subjected to cyclic loading should typically include the bolts and nuts for flanged connections, bolts that are threaded directly into components, and bolts for clamp connections.

## 4.2 Bolting S-N Fatigue Analysis Procedure

Fatigue-sensitive bolts using unified screw threads should be designed and analyzed per these methods. The steps for the bolt fatigue analysis using the S-N test data available in this document are defined as:

1) The evaluation of the connection for fatigue alternating stresses is to be performed without modeling the threads, as the fatigue curves have been defined based on full-scale bolt fatigue testing, as presented in Section 5. The bolt fatigue stress analysis, without the threads modeled, should be conducted using linear elastic material properties. The minimum specified yield strength outlined in the API Subcommittee 17 (phase I) and API 6A/16A (phase II) suite of documents should be used for the analysis.

2) Apply the bolt preload to a minimum of 67 % of bolt yield strength (phase I) or 50% of yield strength (phase II).

3) Apply the applicable loads. The analysis of bolting for fatigue should define the alternating stresses in the highest loaded bolt of the component for defined cyclic loads of pressure, temperature, and external loads. The maximum stress of the alternating stress range should not exceed the allowable axial stress limit as defined in the API Subcommittee 17 (phase I) and API 6A/16A (phase II) suite of standards. Both axial and bending stresses in the bolt should be considered for the fatigue evaluation. Bolt bending loads should be converted to equivalent tension loads and combined with the axial loads to define the total alternating stress range. Finite element analysis of the bolting should define a location which has the minimum and maximum axial surface stresses to determine the maximum alternating stress range.

NOTE: Bending or a combination of alternating tension plus bending would result in conservative values [10].

Combinations of internal pressure, external bending/tension, and thermal-induced cyclic loads should be evaluated for fatigue of the bolting. Thermal loads should be evaluated for both thermal expansion/contraction loads that result in external load of the connection and the thermal expansion of the connection, which produces direct loads on the bolting. Cyclic loads should include axial preload and all external loads.

4) Calculate the stress range for the bolt. The stress range due to cyclic load should be defined as the and maximum axial stress minus the minimum axial stress due to bolt preload plus external cyclic loading defined based on minimum root area of the bolts.

5) Using the stress range, calculate the fatigue life for the bolt using the S-N test data in Section 5. The stress range of the bolt shank is the stress value to define the total cycles to failure for a given environment based on full-scale test data. No mean stress correction for applying this method is necessary. Palmgren-Miner's Rule should be used for accumulated damage for assessing different cyclic load cases.

   The bolts being assessed shall have the same parameters as the bolts that were used in the full-scale fatigue testing in Section 5. Key parameters are the thread form, thread processing, material, material properties, material processing, and bolt preload. Interpolation of fatigue curves is acceptable for bolt diameter sizes greater than 1 in. and smaller than 3 in. having an 8-UNR thread profile.

# 5 Full-Scale Fatigue Test Data for Bolting

## 5.1 Bolting Materials

### 5.1.1 General

Three sizes of (1 in., 2 in., and 3 in.) bolts and nuts in Phase I and two sizes of (1 in. and 3 in.) low-alloy steel bolts and nuts in Phase II were used for conducting the full-scale fatigue (FSF) testing. Depending on the diameter, bolt and nut sizes, materials, and corresponding standards are given in Table 1.

**Table 1—Bolts and Nuts used for Phase I and Phase II of FSF Testing.**

| Bolt Size, (in.) | Bolt Material and Corresponding Standards | Nut Size (in.) Heavy Hex | Nut Material and Corresponding Standards |
|---|---|---|---|
| 1 (8 UNCR class 2A) | ASTM A320, Grade L7 | 1 (8 UNCR class 2B) | ASTM A194, Grade 7L |
| 2 (8 UNR class 2A) | ASTM A320, Grade L7 | 2 (8 UNR class 2B) | ASTM A194, Grade 7L |
| 3 (8 UNR class 2A) | ASTM A320, Grade L43 | 3 (8 UNR class 2B) | ASTM A194, Grade 7L |

All bolts and nuts were manufactured in accordance with API 20E BSL-3. Two heats from each bolt size were procured from two different manufacturers, defined as supplier 1 (Heat 1) and supplier 2 (Heat 2). For each size, 23 bolts and 41 nuts in Phase I; 20 bolts and 40 nuts in Phase II were procured from each manufacturer.

### 5.1.2 Manufacturing Procedure

The low-alloy steel raw material was produced by electric furnace (EF), with secondary refinement using vacuum degassing. Hot rolled bars were heat treated to the targeted mechanical strength then machined to the specific sizes of bolts and nuts. Prior to the production, the manufacturing process specifications (MPS) from each supplier was reviewed and approved by the API technical team for this project.

All the threads were machined (cut) threads. The Heat 1 bolts were double-ended studs, and the Heat 2 bolts were full threaded bolts. All the nuts from heat 1 (supplier 1) were forged while the nuts from heat 2 (supplier 2) were machined from bar stock.

### 5.1.3 Chemical Compositions

Heat numbers, reduction ratio from hot working, and chemical compositions of the bolts and nuts for phase I and Phase II are given in Tables 2 and 3 respectively.

**Table 2—Bolt and Nut Heat Numbers, Reduction Ratios, and Chemical Compositions – Phase I**

| Bolt Heats | Heat No. | Forged Bar RR | Bolt/Nut | C | Mn | P | S | Si | Cr | Mo | B | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Heat 1 | J5568 | 788:1 | 1-in. bolt | 0.41 | 0.97 | 0.011 | 0.003 | 0.23 | 1.03 | 0.2 | 0.0004 | — |
| | W1577 (31 off) | 378:1 | 1-in. nut | 0.42 | 0.97 | 0.008 | 0.007 | 0.28 | 0.98 | 0.2 | 0.0002 | — |
| | L8484 (10 off) | 443:1 | 1-in. nut | 0.41 | 0.97 | 0.008 | 0.01 | 0.25 | 0.98 | 0.20 | 0.0002 | — |
| | L9638 | 159.7:1 | 2-in. bolt | 0.41 | 0.98 | 0.007 | 0.007 | 0.30 | 1.07 | 0.15 | 0.0002 | — |
| | L9500 | 132:1 | 2-in. nut | 0.41 | 0.97 | 0.008 | 0.001 | 0.26 | 0.98 | 0.20 | 0.0002 | — |
| | W1084 | 102.2:1 | 3-in. bolt | 0.41 | 0.78 | 0.009 | 0.002 | 0.25 | 0.87 | 0.27 | 0.0002 | 1.79 |
| | W0884 | 49.3:1 | 3-in. nut | 0.41 | 0.98 | 0.008 | 0.005 | 0.27 | 0.99 | 0.2 | 0.0002 | — |
| Heat 2 | 632560 | 189.8:1 | 1-in. bolt | 0.41 | 0.86 | 0.008 | 0.002 | 0.29 | 1.09 | 0.25 | 0.0002 | — |
| | 633517 | 109.6:1 | 1-in. nut | 0.40 | 0.88 | 0.008 | 0.002 | 0.34 | 1.01 | 0.23 | 0.0003 | — |
| | 633517 | 76.1:1 | 2-in. bolt | 0.40 | 0.88 | 0.008 | 0.002 | 0.34 | 1.01 | 0.23 | 0.0003 | — |
| | 633860 | 27.4:1 | 2-in. nut | 0.41 | 0.88 | 0.007 | 0.003 | 0.27 | 1.03 | 0.24 | 0.0004 | — |
| | 631641 | 34.6:1 | 3-in. bolt | 0.40 | 0.74 | 0.007 | 0.004 | 0.28 | 0.82 | 0.3 | 0.0003 | 1.91 |
| | 631641 | 34.6:1 | 3-in. bolt | 0.40 | 0.74 | 0.007 | 0.004 | 0.28 | 0.82 | 0.3 | 0.0003 | 1.91 |
| | 633860 | 14:1 | 3-in. nut | 0.41 | 0.88 | 0.007 | 0.003 | 0.27 | 1.03 | 0.24 | 0.0004 | — |

**Table 3 –Bolts and Nuts Heat Numbers, Reduction Ratios, and Chemical Compositions – Phase II**

| Bolt Heats | Heat No. | Forged Bar RR | Bolt/Nut | C | Mn | P | S | Si | Cr | Mo | B | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Heat 1 | W8684 | 788.7:1 | 1-in. bolt | 0.41 | 0.94 | 0.008 | 0.003 | 0.23 | 1.04 | 0.21 | 0.0002 | - |
| | W3379 | 443.7:1 | 1-in. nut | 0.41 | 0.94 | 0.012 | 0.002 | 0.21 | 1.02 | 0.20 | 0.0001 | - |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | W1084 | 102.2:1 | 3-in. bolt | 0.41 | 0.78 | 0.009 | 0.002 | 0.25 | 0.87 | 0.27 | 0.0002 | 1.79 |
| | L4355 | 49.2:1 | 3-in. nut | 0.42 | 0.97 | 0.009 | 0.004 | 0.22 | 0.99 | 0.21 | 0.0002 | - |
| Heat 2 | 636641 | | 1-in. bolt | 0.40 | 0.90 | 0.009 | 0.001 | 0.33 | 1.03 | 0.23 | 0.0004 | 0.23 |
| | 639494 | | 1-in. nut | 0.41 | 0.89 | 0.007 | 0.004 | 0.35 | 1.03 | 0.21 | 0.0005 | 0.21 |
| | 636773 | | 3-in. bolt | 0.40 | 0.80 | 0.008 | 0.013 | 0.24 | 0.82 | 0.27 | 0.0004 | 1.89 |
| | 636641 | | 3-in. nut | 0.4 | 0.9 | 0.009 | 0.001 | 0.33 | 1.03 | 0.23 | 0.0004 | 0.23 |

### 5.1.4 Heat Treatment

Heat treatment conditions of the bolts and nuts performed by the manufacturers prior to machining for Phase I and Phase II are given in Tables 4 and 5 respectively.

**Table 4—Heat Treatment Details of the Bolts and Nuts Prior to Machining – Phase I**

| Bolt Heats | Heat No. | Bolt/ Nut | Normalizing | | | Austenitizing | | | Tempering | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | — | — | Temp (°F) | Time (h) | Cooling Media | Temp (°F) | Time (h) | Cooling Media | Temp. (°F) | Time (h) | Cooling Media |
| Heat 1 | J5568 | 1-in. bolt | 1650 | 2.5 | Air | 1575 | 2.5 | Polymer | 1160 | 3.0 | Water |
| | W1577 (31 off) | 1-in. nut | 1650 | 2.5 | Air | 1550 | 2.5 | Polymer | 1160 | 3.0 | Water |
| | L8484 (10 off) | 2-in. bolt | 1650 | 3.0 | Air | 1575 | 3.0 | Polymer | 1160 | 3.5 | Water |
| | L9638 | 2-in. nut | 1650 | 3.0 | Air | 1550 | 3.0 | Polymer | 1160 | 3.5 | Water |
| | L9500 | 3-in. bolt | 1650 | 3.0 | Air | 1575 | 3.0 | Oil | 1st: 1165<br>2nd: 1115 | 3.5<br>3.5 | Water<br>Water |
| | W1084 | 3-in. nut | 1650 | 3.5 | Air | 1550 | 3.5 | Polymer | 1160 | 3.5 | Water |
| Heat 2 | 632560 | 1-in. bolt | — | — | — | 1580 | 1.67 | Oil | 1148 | 2.33 | Polymer |
| | 633517 | 1-in. nut | — | — | — | 1580 | 1.5 | Oil | 1148 | 2.33 | Polymer |
| | 633517 | 2-in. bolt | — | — | — | 1580 | 1.67 | Oil | 1148 | 2.33 | Polymer |
| | 633860 | 2-in. nut | — | — | — | 1580 | 1.5 | Oil | 1148 | 2.33 | Polymer |
| | 631641 (11 off) | 3-in. bolt | — | — | — | 1580 | 1.67 | Oil | 1st: 1148<br>2nd: 1148 | 2.5<br>2.5 | Polymer<br>Polymer |
| | 631641 (12 off) | — | — | — | — | 1580 | 1.67 | Oil | 1st: 1148<br>2nd: 1148 | 2.5<br>2.5 | Polymer<br>Polymer |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 633860 | 3-in. nut | — | — | — | 1580 | 1.5 | Oil | 1148 | 2.33 | Polymer |

**Table 5 - Heat Treatment Details of the Bolts and Nuts Prior to Machining – Phase II**

| Bolt Heats | Heat No. | Bolt/ Nut | Normalizing | | | Austenitizing | | | Tempering | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Heat 1 | - | - | Temp (°F) | Time (h) | Cooling Media | Temp (°F) | Time (h) | Cooling Media | Temp. (°F) | Time (h) | Cooling Media |
| | W8684 | 1-in. bolt | 1650 | 3.0 | Air | 1600 | 3.0 | Oil | 1155 | 3.0 | Water |
| | W3379 | 1-in. nut | 1650 | 2.5 | Air | 1575 | 2.5 | Polymer | 1155 | 2.5 | Water |
| | W1084 | 3-in. bolt | 1650 | 3.5 | Air | 1575 | 3.5 | Oil | 1st:1166<br>2nd:1115 | 3.5<br>3.5 | Water<br>Water |
| | L4355 | 3-in. nut | 1650 | 3.5 | Air | 1600 | 3.5 | Oil | 1155 | 3.5 | Water |
| Heat 2 | 636641 | 1-in. bolt | - | - | - | 1580 | 1.5 | Oil | 1148 | 3.5 | Polymer |
| | 639494 | 1-in. nut | - | - | - | 1580 | 1.67 | Oil | 1148 | 2.33 | Polymer |
| | 636773 | 3-in. bolt | - | - | - | 1580 | 2.0 | Oil | 1st:1148<br>2nd:1148 | 2.33<br>3.0 | Polymer<br>Polymer |
| | 636641 | 3-in. nut | - | - | - | 1580 | 1.67 | Oil | 1148 | 2.33 | Polymer |

### 5.1.5 Mechanical Properties

Mechanical properties including yield strength at 0.2 % offset line, ultimate tensile strength (UTS), percent elongation, percent reduction in area (RA), hardness in Rockwell C scale, and Charpy V-Notch impact value at −75 °F (Heat 1) and −150 °F (Heat 2) for Phase I and Phase II are given in Tables 6 and 7 respectively.

NOTE: The bolting actual yield strength was limited to a maximum value of 120 ksi (828 MPa).

**Table 6—Mechanical Properties of the Bolts and Nuts – Phase I**

| Bolt Heats | Heat No. | Bolt/ Nut | Yield Strength (ksi) | UTS (ksi) | Elongation % | RA % | Hardness HRC or (HB) | CVN Impact Value |
|---|---|---|---|---|---|---|---|---|
| Heat 1 | J5568 | 1-in. bolt | 116.7 | 133.3 | 23.5 | 63 | 28–28 | 88, 82, 82 ft-lbs at −75 °F |
| | W1577 (31 off) | 1-in. nut | — | — | — | — | 28–31 | 74, 74, 76 ft-lbs at −75 °F |
| | L8484 (10 off) | 1-in. nut | — | — | — | — | 27–30 | 74, 74, 72 ft-lbs at −75 °F |
| | L9638 | 2-in. bolt | 117.4 | 135.0 | 23 | 63.2 | 28–29 | 62, 66, 77 ft-lbs at −75 °F |
| | L9500 | 2-in. nut | — | — | — | — | 28–30 | 79, 76, 77 ft-lbs at −75 °F |
| | W1084 | 3-in. bolt | 120.9 | 138.7 | 24.0 | 63.2 | 29–30 | 76, 80, 80 ft-lbs at −75 °F |
| | W0884 | 3-in. nut | — | — | — | — | 30–32 | 32, 46, 33 ft-lbs at −75 °F |
| Heat 2 | 632560 | 1-in. bolt | 113.8 | 130.7 | 22.4 | 62.1 | 28–29 (272–279) | 33, 26, 31 ft-lbs at −150 F |
| | 633517 | 1-in. nut | — | — | — | — | 29–30 (281–294) | 26.5, 28, 29.5 ft-lbs at −150 F |
| | 633517 | 2-in. bolt | 105.9 | 128.9 | 24.0 | 63.1 | 28–29 (273–294) | 21.4, 20.7, 20.7 ft-lbs at −150 F |
| | 633860 | 2-in. nut | — | — | — | — | 29–29 (278–293) | 34.7, 33.2 29.5 ft-lbs at −150 F |
| | 631641 (11 off) | 3-in. bolt | 113.9 | 132.3 | 25.0 | 62.3 | 28–28 (283–291) | 31, 31, 32.5 ft-lbs at −150 F |
| | 631641 (12 off) | 3-in. bolt | 115.3 | 133.5 | 24.4 | 63.4 | 28–29 (278–293) | 26.6, 25.8 28.8 ft-lbs at −150 F |
| | 633860 | 3-in. nut | — | — | — | — | 26–26 (278–297) | 21.4, 26.5, 28.03 ft-lbs at −150 F |

**Table 7 - Mechanical Properties of the Bolts and Nuts – Phase II**

| Bolt Heats | Heat No. | Bolt/ Nut | Yield Strengt h (ksi) | UTS (ksi) | Elongation % | RA % | Hardness HRC or (HBW) | CVN Impact Value |
|---|---|---|---|---|---|---|---|---|
| Heat 1 | W8684 | 1-in. bolt | 115 | 133.7 | 24.5 | 64 | 29-31 | 75, 76, 84 ft-lbs at -75 °F |
| | W3379 | 1-in. nut | - | - | - | - | 30-32 | 36, 42, 36 ft-lbs at -75 °F |
| | W1084 | 3-in. bolt | 114.3 | 133.3 | 23.4 | 65 | 29-31 | 69, 67, 68 ft-lbs at -75 °F |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | L4355 | 3-in. nut | - | - | - | - | 29-30 | 76, 77, 77 ft-lbs at -75 °F |
| Heat 2 | 636641 | 1-in. bolt | 115.7 | 129.5 | 22 | 58.9 | 28-29 | 36, 40, 41 ft-lbs at -150 F<br>81, 73, 88 ft-lbs at -75 F |
| | 639494 | 1-in. nut | - | - | - | - | 26-27 (258-264) | 45, 43, 46 ft-lbs at -150 F<br>80, 82, 81 ft-lbs at -75 F |
| | 636773 | 3-in. bolt | 113.9 | 132.7 | 22.9 | 62.0 | 29-30 | 35, 35, 38 ft-lbs at -150 F<br>74, 69, 74 ft-lbs at -75 F |
| | 636641 | 3-in. nut | - | - | - | - | 26-27 (264) | 33, 34, 38 ft.lbs at -150 F<br>79, 83, 83 ft.lbs at -75 F |

## 5.2 S-N Fatigue Testing

### 5.2.1 General

Full-scale fatigue testing programs of low-alloy steel bolts were conducted for bolt sizes of 1 in., 2 in. and 3 in. in Phase I and for bolt sizes of 1 in. and 3 in in Phase II. Bolts and nuts for each size (diameter) were from two different heats and manufacturers. To develop S-N fatigue curves, the bolts were fatigue tested at three different load levels within the specified load range provided in Tables 8 and 9 for Phase I and Phase II respectively. Each bolt size was threaded in accordance with ASME B1.1, class 2 or 3, with 1-in. 8UNCR, 2-in. 8UNR, and 3-in. 8UNR threads, respectively. The stress ranges are based on the root diameter of the threads for each bolt size. Three alternating load/stress levels were applied to each bolt tested. These load/stress levels were defined as: low-stress range fatigue cycles (LFC), medium-stress range fatigue cycles (MFC) and high-stress range fatigue cycles (HFC). Each alternating load/stress level is defined in Tables 8 and 9 for Phase I and Phase II, respectively.

**Table 8—Load Levels Applied to Bolts (SMYS = 105ksi [725 MPa]) – Phase I**

| Stress Range Designation | Minimum Axial Stress %SMYS, ksi (MPa) | Maximum Axial Stress %SMYS, ksi (MPa) |
|---|---|---|
| LFC | 67 %, 70 (485) | 75 %, 79 (544) |
| MFC | 67 %, 70 (485) | 83 %, 87 (602) |
| (MFC + 10%)[a] | 67 %, 70 (485) | 91 %, 95 (627) |
| HFC | 67 %, 70 (485) | 100 %, 105 (725) |

[a] 10% increase in maximum load.

**Table 9—Load Levels Applied to Bolts (SMYS = 105ksi [725 MPa]) – Phase II**

| Stress Range Designation | Minimum Stress %SMYS, ksi (MPa) | Maximum Stress %SMYS, ksi (MPa) |
|---|---|---|
| HFC | 50 %, 52.5 (362) | 100 %, 105 (725) |
| MFC | 50 %, 52.5 (362) | 83 %, 87.2(602) |
| LFC | 50 %, 52.5 (362) | 67 %, 70.4 (486) |

Table 10 shows the bolt dimensions and the calculated nominal root diameter and corresponding nominal root area for each bolt size.

**Table 10—Bolt Dimensions and Calculated Nominal Root Area for Each Bolt Size**

| Bolt Diameter in. (cm) | Bolt Length in. (cm) | Class 2A Nominal Root Diameter in. (cm) | Nominal Root Area in.$^2$ (cm$^2$) |
|---|---|---|---|
| 1 (2.54) | 7 (17.8) | 0.8390 (2.131) | 0.5528 (3.566) |
| 2 (5.08) | 18 (45.7) | 1.8382 (4.669) | 2.6538 (17.121) |
| 3 (7.62) | 28 (71.1) | 2.8376 (7.208) | 6.3239 (40.799) |

Tables 11 and 12 show the stress range designation, stress ranges corresponding loads, and mean stress that were applied to each bolt size during testing in Phase I and Phase II respectively, in both ambient air (dry) and SW+CP (wet) environments. The S-N tests in ambient air were conducted to produce reference S-N curves for each bolt size.

**Table 11—Applied Stress Ranges and Corresponding Loads for Each Bolt Size – Phase I**

| Bolt Diameter in. (cm) | Stress Range Designation | Stress Range, Δσ, ksi (MPa) | Min. Load, lbs (kN) | Max. Load, lbs (kN) | Mean Stress, ksi (MPa) |
|---|---|---|---|---|---|
| 1 (2.54) | HFC | 35 (241) | 38,890 (173) | 58,223 (259) | 88 (607) |
| | MFC + 10% | 25 (174) | 38,890 (173) | 52,828 (215) | 83 (572) |
| | MFC | 17 (116) | 38,890 (173) | 48,332 (194) | 79 (545) |
| 2 (5.08) | HFC | 35 (241) | 186,584 (830) | 278,527 (1,239) | 88 (607) |
| | MFC | 17 (116) | 186,584 (830) | 231,094 (928) | 79 (545) |
| | LFC+4% | 11.5 (79) | 186,584 (830) | 217,156 (966) | 76 (524) |

| | | | | | |
|---|---|---|---|---|---|
| 3 (7.62) | HFC | 35 (241) | 445,554 (1,982) | 664,958 (2,958) | 88 (607) |
| | MFC | 17 (118) | 445,554 (1,982) | 551,884 (2,455) | 79 (545) |
| | LFC | 9 (62) | 445,554 (1,982) | 502,428 (2,235) | 75 (517) |

**Table 12—Applied Stress Ranges and Corresponding Loads for Each Bolt Size – Phase II**

| Bolt Diameter in. (cm) | Stress Range Designation | Stress Range, Δσ, ksi (MPa) | Min. Load, lbs (kN) | Max. Load, lbs (kN) | Mean Stress, ksi (MPa) |
|---|---|---|---|---|---|
| 1 (2.54) | HFC | 52.5 (362) | 29,068 (129) | 58,136 (259) | 78.9 (544) |
| | MFC | 34.7 (239) | 29,068 (129) | 48,244 (215) | 69.9 (482) |
| | LFC + 10%[a] | 24.9 (172) | 29,068 (129) | 42,849 (191) | 65 (448) |
| | LFC + 7.5%[b] | 22.8 (157) | 29,068 (129) | 41,702 (186) | 64 (441) |
| | LFC + 5%[c] | 21.5 (148) | 29,068 (129) | 40,960 (182) | 63.3 (436) |
| 3 (7.62) | HFC | 52.5 (362) | 332,494 (1,479) | 664,988 (2,958) | 78.9 (544) |
| | MFC | 34.7 (239) | 332,494 (1,479) | 551,909 (2,455) | 69.9 (482) |
| | LFC | 17.9 (123) | 332,494 (1,479) | 445,573 (1,982) | 61.5 (424) |

a. 10% increase in maximum load.
b. 7.5% increase in maximum load.
c. 5% increase in maximum load.

### 5.2.2 S-N Fatigue Testing in Ambient Air (Dry) Environment

#### 5.2.2.1 Phase I

Prior to S-N testing and after any major changes to the test frames/test equipment, the alignment of the test frames (machines) was verified in accordance with ISO 23788:2012. To expedite the testing, two load frames (MTS 1000 kN and Instron 300 kN) were used to test the 1-in. bolts. The 2-in. and 3-in. bolts were tested using an Instron 4000 kN load frame. The test frequency for 1 in. bolt size was 10 Hz and for 2 in. and 3 in. bolt sizes was between 1.5 and 3 Hz.For all bolt sizes, the maximum/minimum applied loads and displacements at the specific applied stress range, were recorded and saved for post-test review. The stress range designation for all bolt sizes in air are shown in Table 11. The stress range designations of MFC + 10 %, which indicates 10% increase in maximum load, for 1-in. bolts and LFC + 4%, which indicates 4% increase in maximum load, for 2 in. bolts were defined and applied to avoid run-out. This is because 1-in. bolts at MFC and 2 in. bolts at LFC exhibited run-out.

#### 5.2.2.2 Phase II

Prior to S-N testing and after any major changes to the test frames/test equipment, the alignment of the test frames (machines) was verified in accordance with ISO 23788:2012. A 500 kN load frame was used for in-air (dry) testing of 1 in. bolts and the experiments were conducted at 5 Hz loading frequency. For testing of the 3 in. bolts a 4000 kN test machine and a loading frequency of 0.3 Hz was used. For both bolt sizes, the maximum/minimum applied loads and displacements at the specific applied stress range were recorded and saved for post-test review.

The stress range designations for both bolt sizes are shown in Table 12. 1 in. bolts at LFC exhibited infinite lives (run-out). Therefore, the maximum load increased 10%, 7.5%, and finally 5% to obtain finite lives or to avoid run-outs.

### 5.2.3 S-N Fatigue Testing in Saltwater with CP (Wet) Environment

For SW+CP testing, the same load frames were used for each specific bolt size. Each load frame was again subjected to a complete and thorough load frame alignment and calibration procedure as in the ambient air tests.

The saltwater test solution consisted of 3.5 wt.% sodium chloride (NaCl) in deionized water. The purpose of using deionized water was to avoid precipitation of calcareous scale on the surface of the bolts during testing, which can reduce hydrogen uptake during cathodic protection. The target solution pH of 8.2 was achieved and kept constant with the addition of either NaOH/NaCl solution of pH = 12 or HCl/NaCl solution of pH = 2. The saltwater oxygen concentration was reduced and maintained at less than 20 ppb during each test. The saltwater temperature in the test chamber was controlled and maintained at 39.2 °F (4 °C).

Prior to cyclic loading, each bolt was pre-charged at an applied potential of −1050 mV versus saturated calomel electrode (SCE) for four days under the defined pre-load, and the applied potential was maintained until termination of the test. After the pre-charging period, the alternating stress given in Tables 11 and 12 was applied to each bolt at the frequency of 0.3 Hz until the bolt failure.

For each bolt tested in SW+CP, the following data were recorded:

— Test solution temperature in the test chamber;

— Maximum/minimum load, as well as maximum/minimum displacement;

— Oxygen concentration;

— Solution pH;

— Applied cathodic protection potential;

— Number of cycles to failure.

### 5.2.4 S-N Fatigue Testing in Air and Saltwater with CP Environments – Phase I

#### 5.2.4.1 General

Tables 13-18 show the S-N test results for the 1-in., 2-in. and 3-in. bolts, respectively. For each bolt size from each heat, the defined plan was to perform three (3) S-N tests at HFC (H), three (3) at MFC (M), and three (3) at LFC (L). The bolting exhibited better than expected life and therefore, with the limited and defined total cycles allocated for the test program, the original test plan was not met lacking information for some of the bolt sizes and stress ranges.

**Table 13—S-N Fatigue Test Results for 1-in. Bolts in Air – Phase I**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 1-D-H-U-1 | 1 | 35 (241) | 46,373 | — |
| 1-D-H-U-2 | 1 | 35 (241) | 46,788 | — |
| 1-D-M-U-3 | 1 | 17 (118) | 3,249,584 | runout |
| 1-D-M-U-3–2 | 1 | 25 (174) | 139,104 | MFC + 10 % |
| 1-D-M-U-4 | 1 | 25 (174) | 141,828 | MFC + 10 % |
| 1-D-H-U-5 | 1 | 35 (241) | 44,212 | — |
| 1-D-M-U-6 | 1 | 17 (118) | 3,590,920 | runout |
| 1-D-M-U-6–2 | 1 | 25 (174) | 202,464 | MFC + 10 % |
| 1-D-M-U-7 | 1 | 17 (118) | 717,557 | — |
| 1-D-M-U-8 | 1 | 17 (118) | 24,181,373 | runout |
| 1-D-H-O-1 | 2 | 35 (241) | 60,415 | — |
| 1-D-H-O-2 | 2 | 35 (241) | 68,082 | — |
| 1-D-H-O-3 | 2 | 35 (241) | 49,611 | — |
| 1-D-M-O-4 | 2 | 17 (118) | 2,493,418 | runout |
| 1-D-M-O-4–2 | 2 | 25 (174) | 29,4771 | MFC + 10 % |
| 1-D-M-O-5 | 2 | 17 (118) | 703,439 | — |
| 1-D-M-O-6 | 2 | 17 (118) | 12,933,856 | runout |
| 1-D-M-O-7 | 2 | 17 (118) | 1,141,077 | — |

**Table 14—S-N Fatigue Test Results for 1-in. Bolts in SW+CP Condition – Phase I**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 1-W-H-U-1 | 1 | 35 (241) | 22,699 | — |
| 1-W-H-U-2 | 1 | 35 (241) | 21,144 | — |
| 1-W-H-U-3 | 1 | 35 (241) | 19,981 | — |
| 1-W-M-U-4 | 1 | 25 (174) | 41,875 | MFC + 10 % |
| 1-W-M-U-5 | 1 | 25 (174) | 36,311 | MFC + 10 % |
| 1-W-M-U-6 | 1 | 17 (118) | 149,290 | — |
| 1-W-M-U-7 | 1 | 17 (118) | 147,983 | — |
| 1-W-M-U-8 | 1 | 17 (118) | 133,662 | — |
| 1-W-M-U-9 | 1 | 17 (118) | 163,450 | — |
| 1-W-H-O-1 | 2 | 35 (241) | 19,423 | — |
| 1-W-H-O-2 | 2 | 35 (241) | 21,147 | — |
| 1-W-H-O-3 | 2 | 35 (241) | 26,837 | — |
| 1-W-M-O-4 | 2 | 17 (118) | 189,014 | — |
| 1-W-M-O-5 | 2 | 17 (118) | 256,895 | — |
| 1-W-M-O-6 | 2 | 17 (118) | 189,002 | — |
| 1-W-M-O-7 | 2 | 17 (118) | 158,313 | — |
| 1-W-M-O-9 | 2 | 17 (118) | 149,135 | correct potential |
| 1-W-M-O-10 | 2 | 17 (118) | 299,241 | correct potential |
| 1-W-M-O-11 | 2 | 17 (118) | 180,708 | correct potential |
| 1-W-L-O-8 | 2 | 9 (59) | 1,635,607 | LFC[a], runout. Test stopped |

| | | | | |
|---|---|---|---|---|
| 1-W-L-O-12 | 2 | 12 (80) | 1,260,569 | LFC[a]+4%, runout. Test stopped |
| [a] tests were conducted for information. | | | | |

**Table 15—S-N Fatigue Test Results for 2-in. Bolts in Air – Phase I**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 2-D-H-U-1 | 1 | 35 (239) | 33,824 | — |
| 2-D-H-U-2 | 1 | 35 (239) | 31,852 | — |
| 2-D-H-U-3 | 1 | 35 (239) | 35,448 | — |
| 2-D-M-U-4 | 1 | 17 (118) | 299,286 | — |
| 2-D-M-U-5 | 1 | 17 (118) | 322,676 | — |
| 2-D-M-U-6 | 1 | 17 (118) | 285,899 | — |
| 2-D-L-U-7 | 1 | 11.6 (80) | 16,735,547 | LFC[a]+4%, run out. Test stopped |
| 2-D-H-O-1 | 2 | 35 (239) | 42,600 | — |
| 2-D-H-O-2 | 2 | 35 (239) | 41,957 | — |
| 2-D-H-O-3 | 2 | 35 (239) | 40 975 | — |
| 2-D-M-O-4 | 2 | 17 (118) | 353,630 | — |
| 2-D-M-O-5 | 2 | 17 (118) | 352,474 | — |
| 2-D-M-O-6 | 2 | 17 (118) | 257,321 | — |
| [a] test was conducted for information. | | | | |

**Table 16—S-N Fatigue Test Results for 2-in. Bolts in SW+CP Condition – Phase I**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 2-W-H-U-1 | 1 | 35 (239) | 22,753 | — |
| 2-W-H-U-2 | 1 | 35 (239) | 24,290 | — |
| 2-W-H-U-3 | 1 | 35 (239) | 25,807 | — |
| 2-W-M-U-4 | 1 | 17 (118) | 123,493 | — |
| 2-W-H-O-1 | 2 | 35 (239) | 28,133 | — |
| 2-W-H-O-2 | 2 | 35 (239) | 26,871 | — |
| 2-W-H-O-3 | 2 | 35 (239) | 27,206 | — |

**Table 17—S-N Fatigue Test Results for 3-in. Bolts in Air – Phase I**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 3-D-H-U-1 | 1 | 35 (239) | 28,931 | — |
| 3-D-H-U-2 | 1 | 35 (239) | 28,990 | — |
| 3-D-H-U-3 | 1 | 35 (239) | 28,968 | — |
| 3-D-M-U-4 | 1 | 17 (118) | 245,237 | — |
| 3-D-M-U-5 | 1 | 17 (118) | 327 091 | — |
| 3-D-M-U-6 | 1 | 17 (118) | 238 083 | — |
| 3-D-M-U-7 | 1 | 8.4 (58) | 10,482,717 | LFC, run out |
| 3-D-H-O-1 | 2 | 35 (239) | 30,095 | — |
| 3-D-H-O-2 | 2 | 35 (239) | 29,989 | — |
| 3-D-H-O-3 | 2 | 35 (239) | 30,254 | — |
| 3-D-M-O-4 | 2 | 17 (118) | 199,318 | — |
| 3-D-M-O-5 | 2 | 17 (118) | 223,213 | — |
| 3-D-M-O-6 | 2 | 17 (118) | 203,548 | — |
| 3-D-L-O-7 | 2 | 8.4 (58) | 10,883,093 | LFC, run out |

**Table 18—S-N Fatigue Test Results for 3-in. Bolts in SW+CP Conditions – Phase I**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 3-W-H-U-1 | 1 | 35 (239) | 23,676 | — |
| 3-W-M-U-4 | 1 | 17 (118) | 116,184 | — |
| 3-W-M-U-5 | 1 | 17 (118) | 112,301 | — |
| 3-W-H-O-1 | 2 | 35 (239) | 25,649 | — |
| 3-W-H-O-2 | 2 | 35 (239) | 24,395 | — |
| 3-W-H-O-3 | 2 | 35 (239) | 25,516 | — |
| 3-W-M-O-4 | 2 | 17 (118) | 115,689 | — |
| 3-W-M-O-5 | 2 | 17 (118) | 128,350 | — |

A couple samples (1-D-M-O-5 and 1-D-M-U-7) tested at MFC in air exhibited lower fatigue life than rest of the samples which exhibited either run-outs or over one million cycles of fatigue life. To assess this large variation in results, an investigation was conducted on the two load frames that were used to test the 1-in. bolts, as well as the thread root profiles of the bolts that showed different fatigue lives.

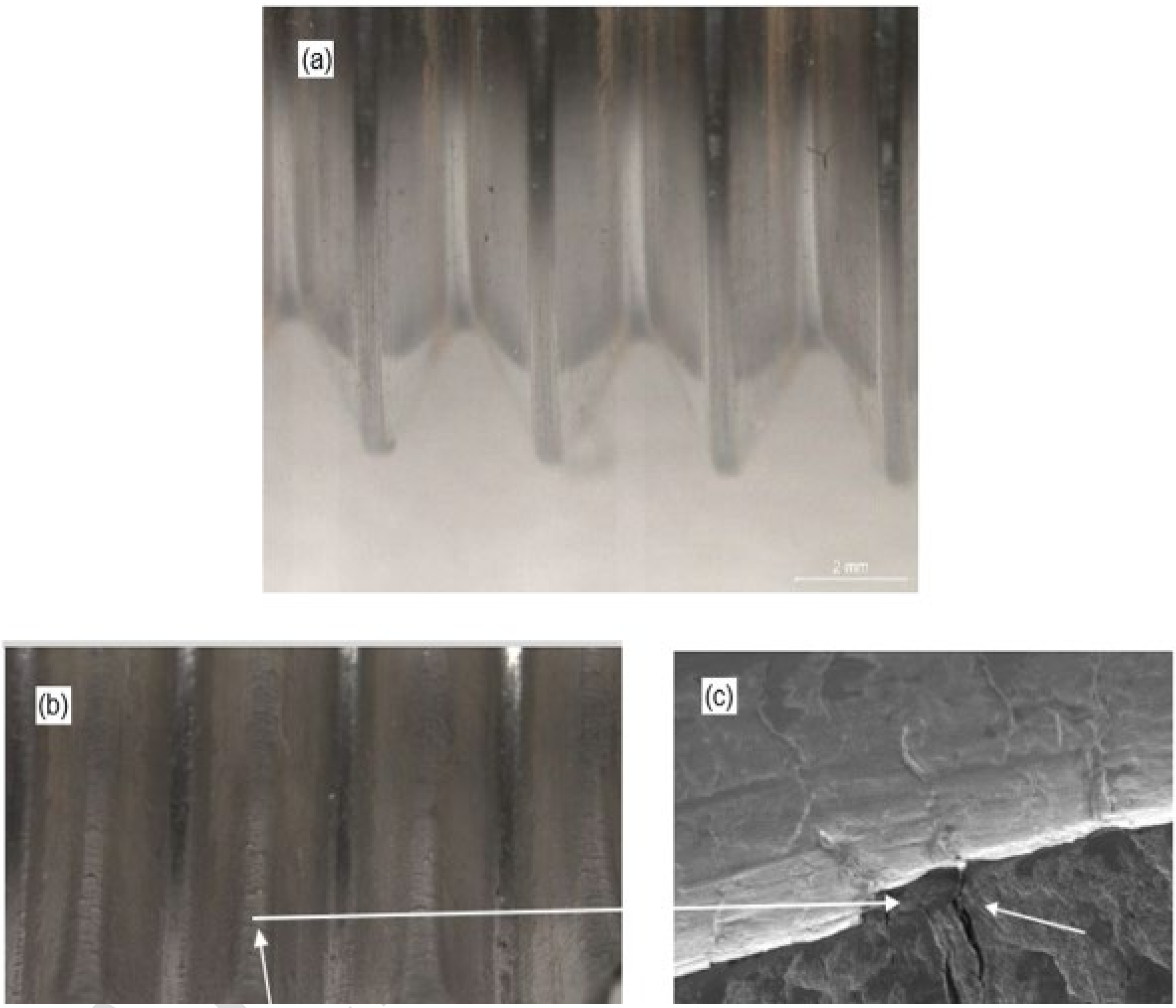
Thorough investigation of the applied maximum and minimum loads at $\Delta\sigma$ = 17ksi (118 MPa) between the two load frames using dummy test specimens showed that the test result discrepancy for 1-in. bolts in ambient air is not due to the load frames.

Figure 1 shows high magnification images taken from bolt sample 1-D-M-U-7 (717, 557 cycles of fatigue life) and 1-D-M-O-5 (703,439 cycles of fatigue life), respectively. Bolt sample 1-D-M-U-7 (Figure 1a) contains a smoother thread root profile than bolt sample 1-D-M-O-5 which contains a rougher surface (white arrow in Figure 1b). Additionally, the bolt in Figure 1a had a non-uniform loading on the thread flank that appeared to cause an uneven load distribution on the threads (see Figure 2).

The rougher thread root profile in Figure 1b could be due to a worn or dull tool during threading. The surface imperfections of the root profile will act as a stress riser and can have an effect on reducing the number of cycles to fatigue crack initiation and hence, total fatigue life of the bolts. The scanning electron microscopy (SEM) image in Figure 1c clearly shows fatigue crack initiation from the surface imperfections on the thread root, which can result in a finite life at the applied stress range of $\Delta\sigma$ = 17 ksi (118 MPa).

Further investigation of bolt sample 1-D-M-U-7 with smooth thread root profiles showed that the bolt contained an imperfection (e.g., potentially due to machining) that went all the way around the first thread flank, as shown in Figure 2. Even with a smooth thread root profile, such imperfections on the thread flanks will act as stress risers and can have an effect on reducing the number of cycles for crack initiation, and hence, total fatigue life of the bolt.

The metallurgical investigation suggested that the lower fatigue life observed from certain bolt samples such as 1-D-M-O-5 and 1-D-M-U-7 are likely associated with rougher thread surface profiles or imperfections on the thread flank, although all the tested bolts from the two heats were conforming with the requirements of API 20E BSL-3.






**Key**

(a) Thread profile of Sample 1-D-M-U-7 indicating a smoother surface roughness.

(b) Rougher surface roughness (white arrow) of Sample 1-D-M-O-5 perhaps due to dull machine tool.

(c) SEM image illustrating crack initiation (white arrow) from the rougher thread root.

**Figure 1—Thread Root Profiles**

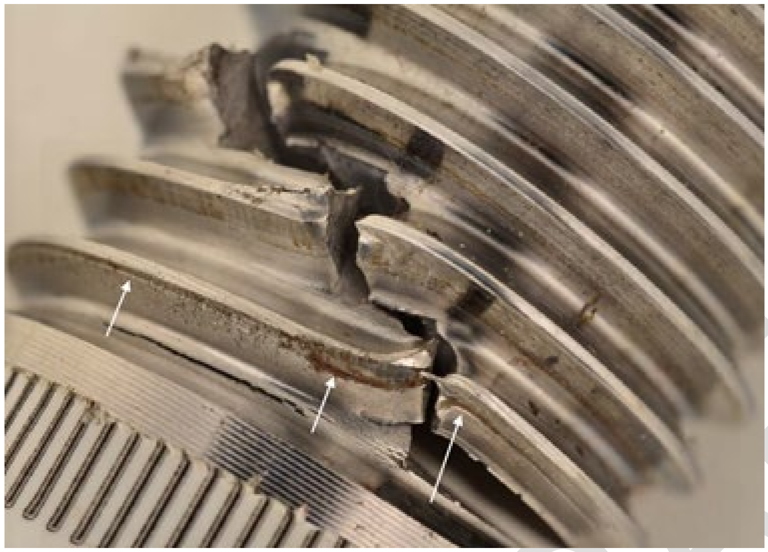


**Figure 2—1-in. Bolt,1-D-M-U-7, Showing an Imperfection in the thread flank (white arrows)**

**5.2.4.2 Applied Cathodic Potential Effects**

Midway through testing of 1-in. bolts in SW+CP environment, it was realized that the tested bolts were exposed to a more negative potential (−1095 mV versus SCE) instead of −1050 mV versus SCE. The higher negative applied potential was due to using an SCE reference electrode with a different salt concentration. The higher negative applied potential meant that the already tested 1-in. bolts could have higher absorbed atomic hydrogen, and hence, higher hydrogen permeation through the bolts, which could have resulted in lower fatigue life.

To check this difference in applied potential and its effect on fatigue lives, three extra 1-in. bolts were tested at the correct applied potential of −1050 mV (versus SCE with the correct salt concentration), as shown in Table 14. All bolts were exposed to a stress range of $\Delta\sigma$ = 17ksi (118 MPa). The results in Table 14 illustrate that at the correct applied potential, the corresponding fatigue lives are in the same range as the bolts exposed to the higher negative potential. This ensured that the initial tests in SW+CP were not adversely affected by the slightly more negative applied potential.

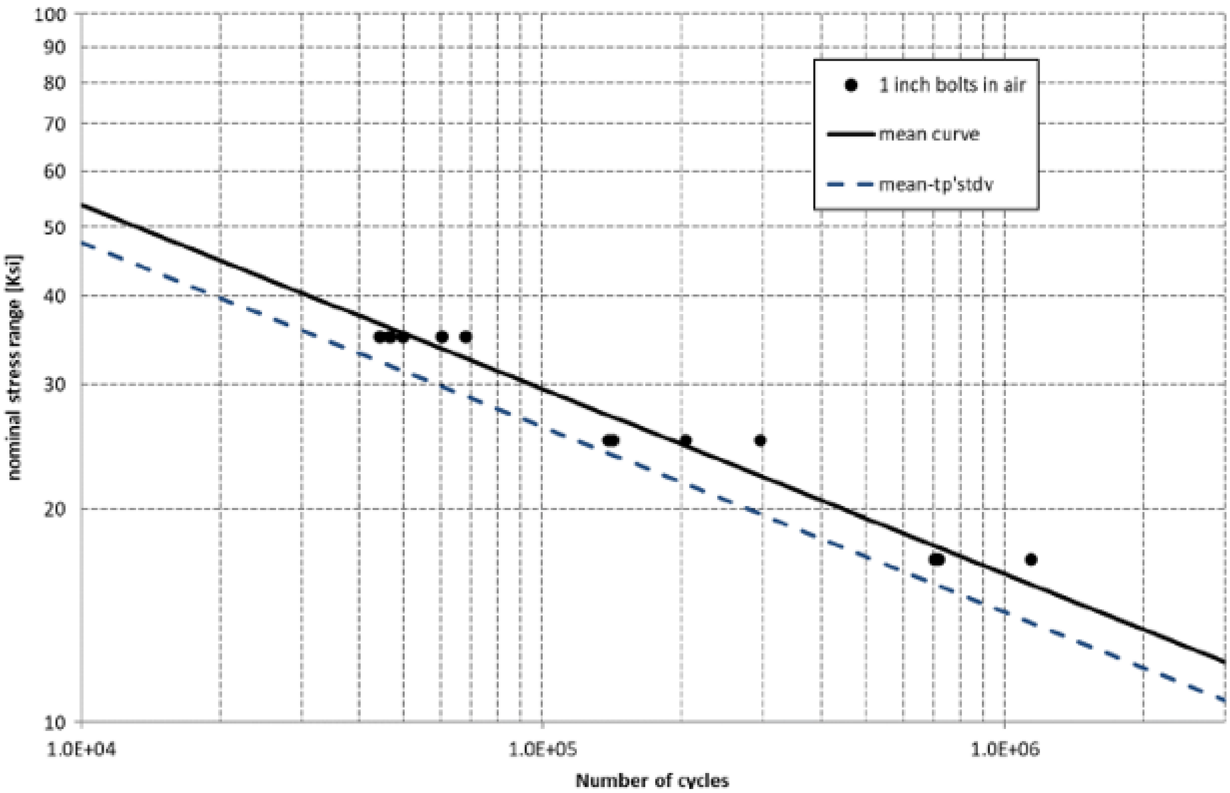
**5.2.5 S-N Fatigue Curves in Air and SW+CP Environments – Phase I**

Figure 3, Figure 4, and Figure 5 show the S-N fatigue curves obtained for the 1-in., 2-in., and 3-in. bolts in air, respectively. The plots also show the mean and mean −2SD (standard deviation). The statistical analysis was performed in accordance with the requirements of ASTM E739. One of the requirements of ASTM E739 is that only data points with finite life can be used for statistical analysis. The figures also contain the regression analysis data for each bolt size below each plot. The regression analysis was conducted for the S-N curve with the following power law equation:

$$N = a\left(\Delta\sigma\right)^{-m}$$

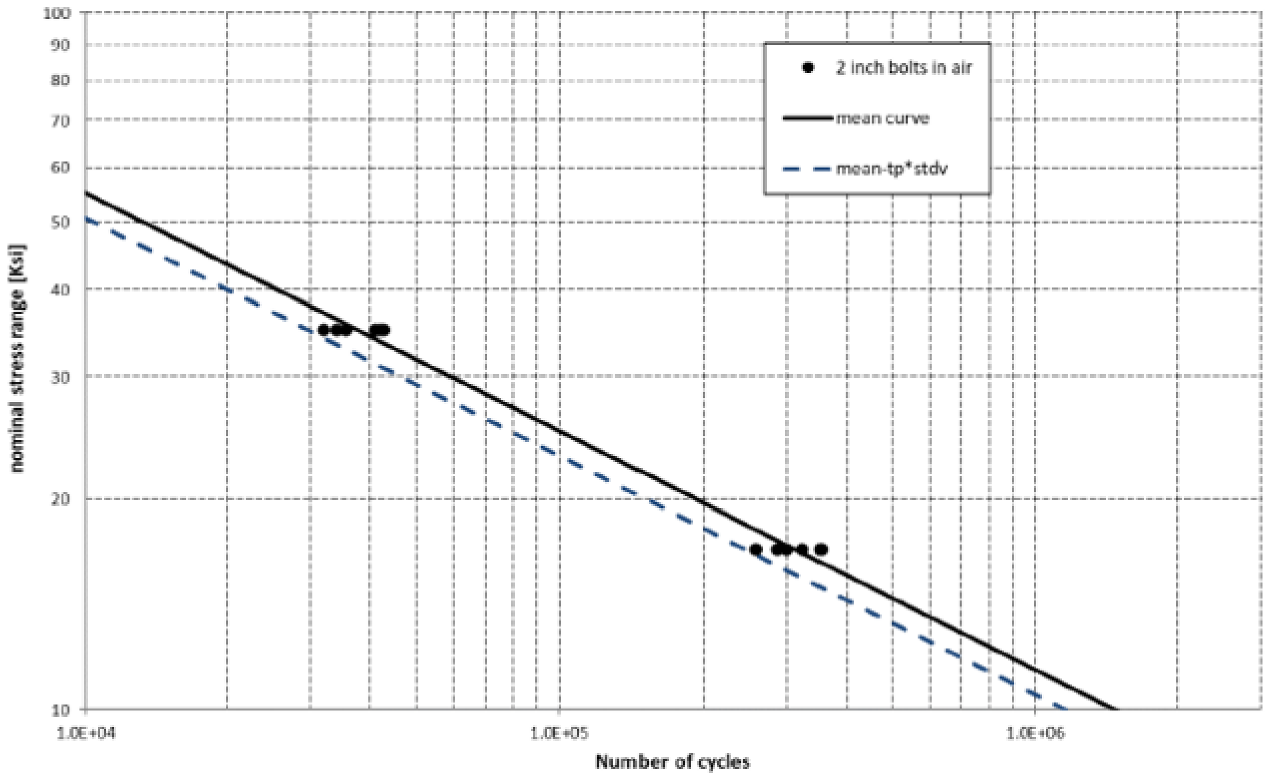
$$or$$

$$logN = loga - mlog\Delta\sigma$$



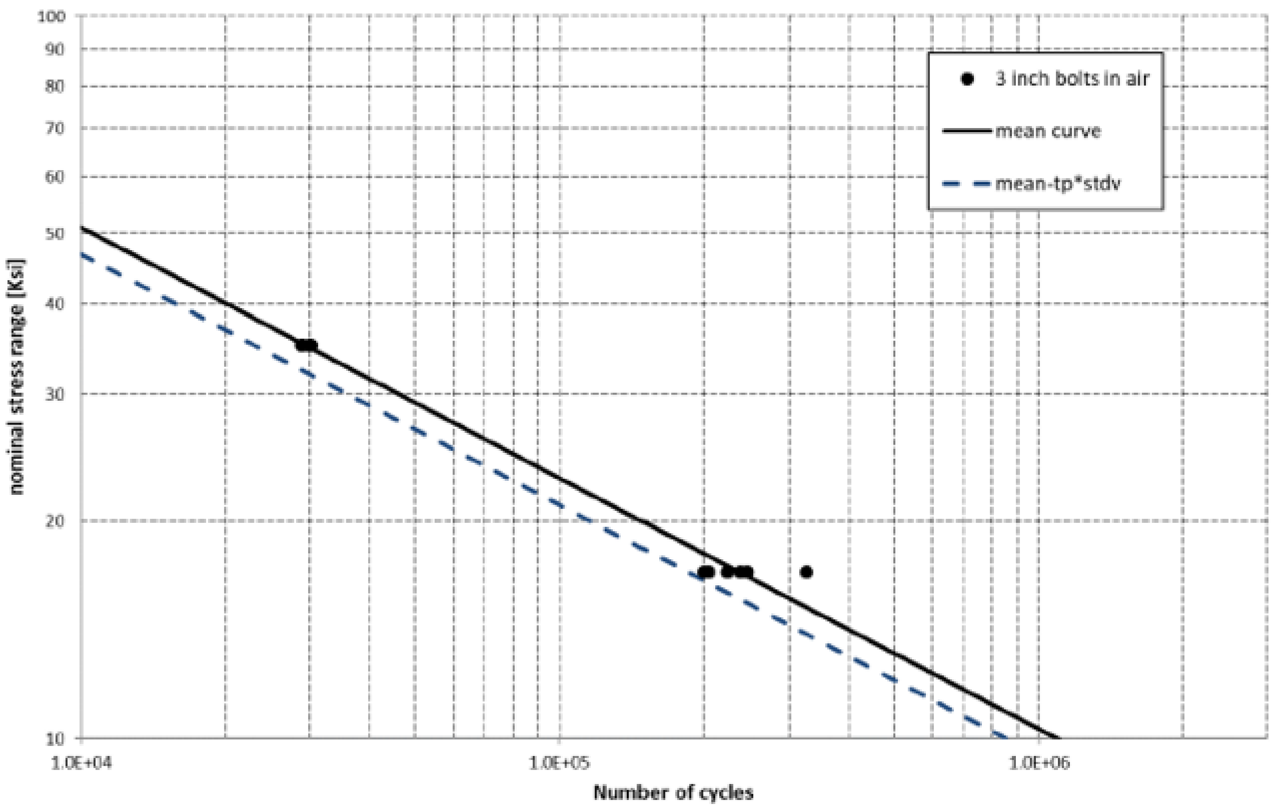

| 1 in. Air S-N Curve Data, Stress in ksi | |
|---|---|
| m = | 3.84 |
| $\log a_1$ (mean) | 10.637 |
| StD ($\log\overline{a_1}$) | 0.103 |
| Tp (13 test data) | 2.201 |
| Mean-Tp*stdv | 10.410 |

**Figure 3—S-N Fatigue Curve for 1-in. Bolts in Air – Phase I**




| 2 in. Air S-N Curve Data, Stress in ksi | |
|---|---|
| m = | 2.923 |
| $\log a_1$ (mean) | 9.088 |
| StD ($\log\overline{a_1}$) | 0.052 |
| Tp (13 test data) | 2.228 |
| Mean-Tp*stdv | 8.973 |

**Figure 4—S-N Fatigue Curve for 2-in. Bolts in Air – Phase I**

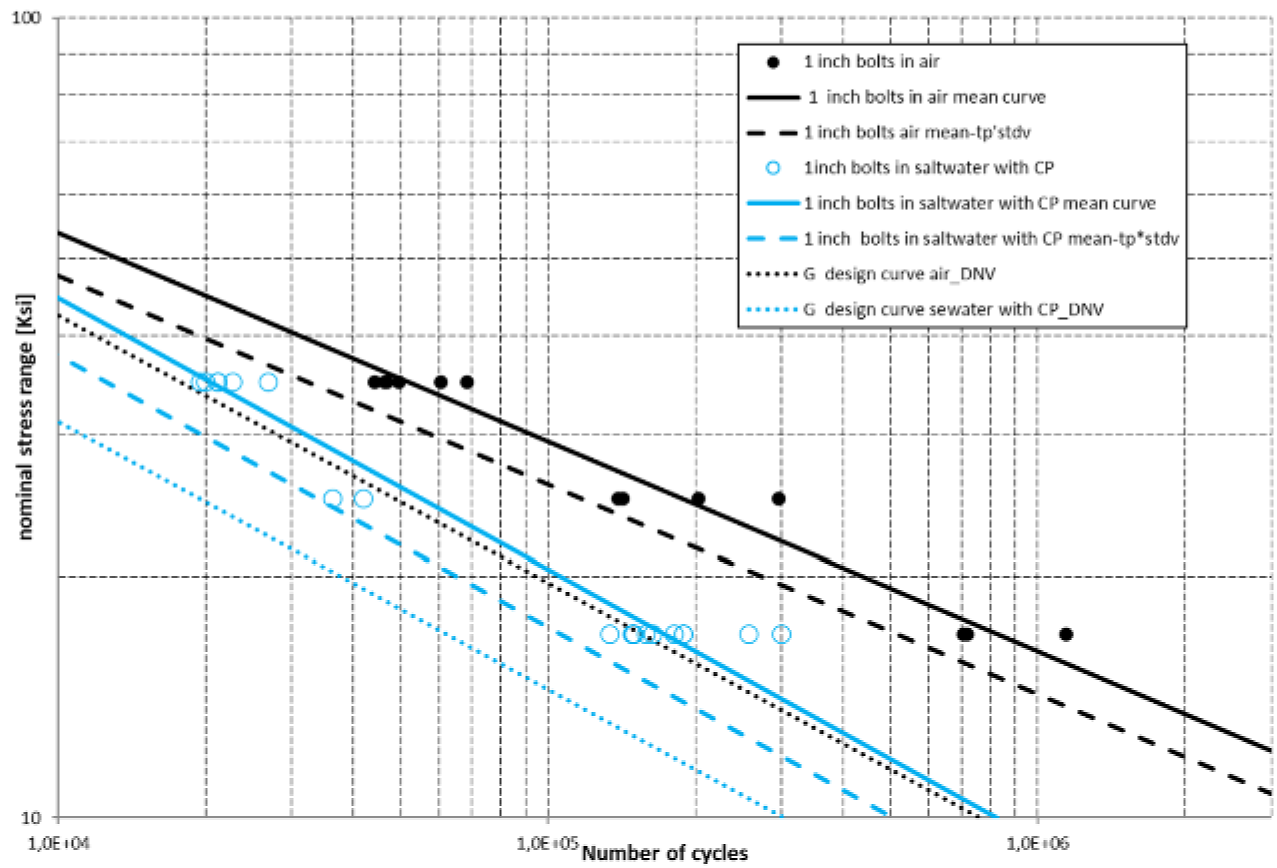



| 3 in. Air S-N Curve Data, Stress in ksi | |
|---|---|
| m = | 2.878 |
| $\log a_1$ (mean) | 8.915 |
| StD ($\log \overline{a_1}$) | 0.053 |
| Tp (13 test data) | 2.228 |
| Mean-Tp*stdv | 8.796 |

**Figure 5—S-N Fatigue Curve for 3-in. Bolts in Air – Phase I**

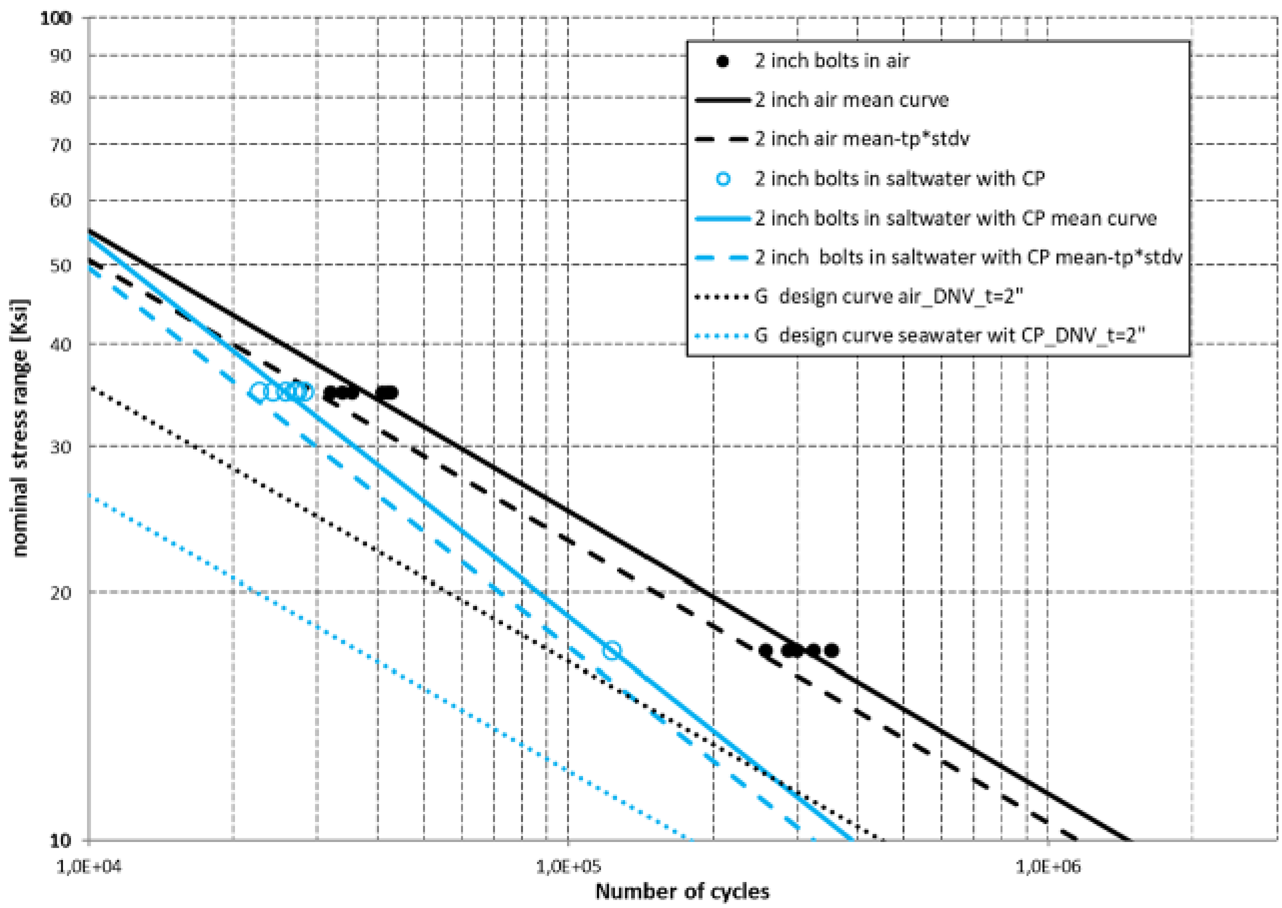
NOTE: The test data for 2 in. and 3 in. bolts in air at LFC is incomplete. Additional testing at LFC is required to develop the more accurate design curves.

Figures 6-8 show and compare the S-N fatigue curves obtained for the 1-in., 2-in., and 3-in. bolts in air and SW+CP, respectively. The plots also show the mean and mean $-t_p$*SD (standard deviation) in both environments. The statistical analysis for the curves in SW+CP were also performed in accordance with requirements of ASTM E739. The figures also contain the regression analysis data for each bolt size in SW+CP at the bottom of each plot.



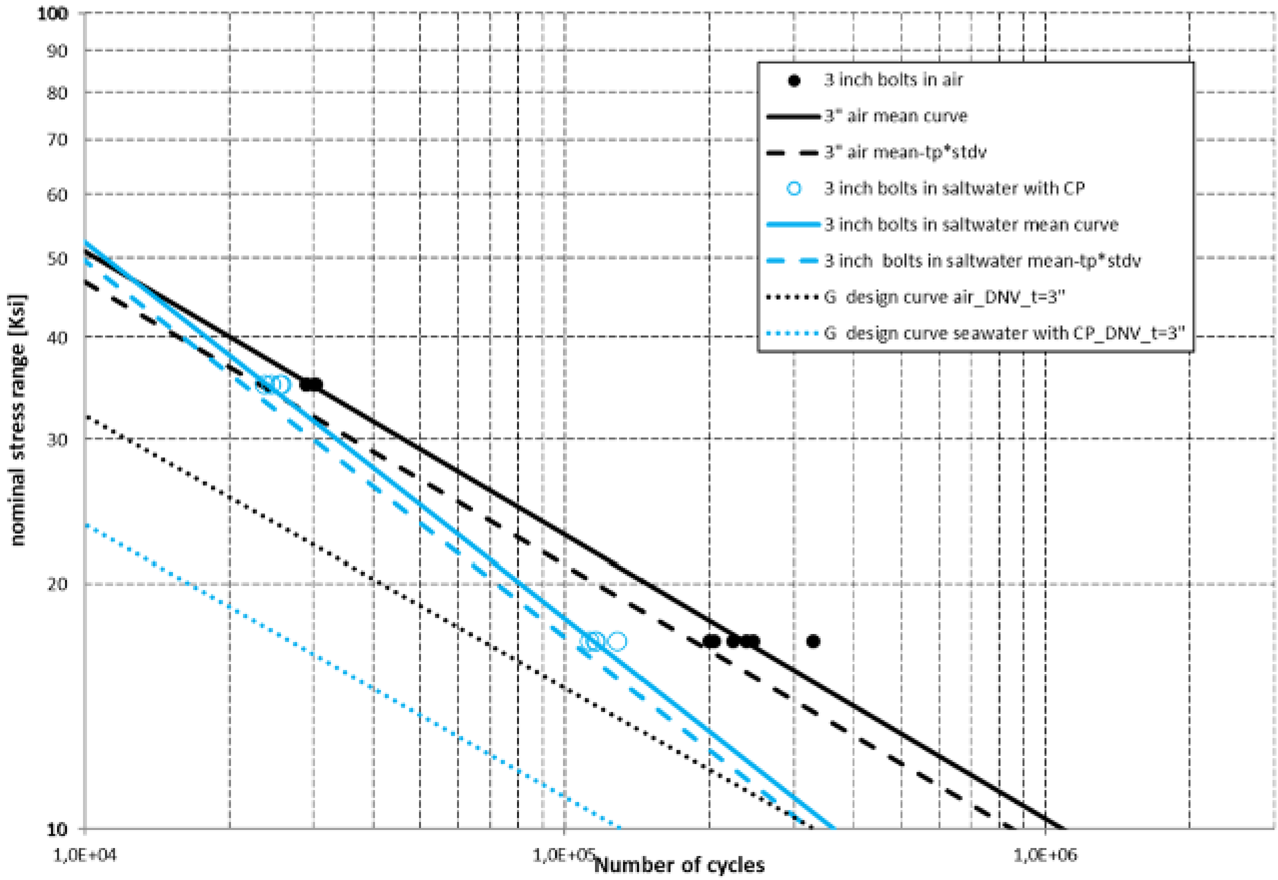

| 1 in. Saltwater with CP S-N Curve Data, Stress in ksi | |
|---|---|
| m = | 2.956 |
| $\log a_1$ (mean) | 8.874 |
| StD ($\log\overline{a_1}$) | 0.101 |
| Tp (13 test data) | 2.110 |
| Mean-Tp*stdv | 8.662 |

**Figure 6—S-N fatigue Curves for 1-in. Bolts in Air and SW+CP – Phase I**




| 2 in. Saltwater with CP S-N Curve Data, Stress in ksi | |
|---|---|
| m = | 2.170 |
| $\log a_1$ (mean) | 7.761 |
| StD ($\log \bar{a}_1$) | 0.031 |
| Tp (13 test data) | 2.571 |
| Mean-Tp*stdv | 7.680 |

**Figure 7—S-N Fatigue Curves for 2-in. Bolts in Air and SW+CP – Phase I**




| 3 in. Saltwater with CP S-N Curve Data, Stress in ksi | |
|---|---|
| m = | 2.160 |
| $\log a_1$ (mean) | 7.730 |
| StD ($\log \overline{a_1}$) | 0.020 |
| Tp (13 test data) | 2.447 |
| Mean-Tp*stdv | 7.681 |

**Figure 8—S-N Fatigue Curves for 3-in. Bolts in Air and SW+CP – Phase I**

The data illustrated in these figures shows that at HFC and for all bolt sizes, the fatigue lives in SW+CP and in air are close whilst at lower-stress ranges and for all bolt sizes, the fatigue lives in SW+CP are lower than the lives in ambient air, resulting in steeper S-N curves. Also, the larger the bolt diameter, the closer the fatigue lives in SW+CP are to the air values at high-stress ranges.

The results illustrate that at HFC, fatigue lives in SW+CP and in air are more influenced by the root radius stress concentration factor. At LFC, fatigue lives in SW+CP are more influenced by the atomic hydrogen adsorption and diffusion to the fracture process zone beneath the surface at the root radius of the bolt, resulting in lower cycles to crack initiation and hence, lower overall fatigue life as compared with air.

Based on the developed S-N fatigue curves for 1-in., 2-in., and 3-in. bolts in air and SW+CP environments, Table 19 provides a "knock-down" factor for different stress levels for different bolt sizes.

**Table 19—Fatigue Test Knock-down Factors for SW+CP/ Air – Phase I**

| Stress Range ksi [MPa] | 1 in. | 2 in. | 3 in. |
|---|---|---|---|
| $\Delta\sigma$ = 35 [241] | 0.42 | 0.68 | 0.85 |
| $\Delta\sigma$ = 25 [174] | 0.20 | — | — |
| $\Delta\sigma$ = 17 [118] | 0.21 | 0.40 | 0.50 |

### 5.2.6 Post S-N Fatigue Test Evaluation - Phase I

#### 5.2.6.1 General

Upon completion of each S-N test, the bolts were evaluated, and pictures of their fracture surfaces were taken and documented on a result sheet along with other information specific to each bolt. A few fractured bolts from each heat were selected to be studied further.

#### 5.2.6.2 Hardness Measurements

Three (3) bolts from each size (in total of 6 bolts) were selected to be evaluated. These bolts are 1-W-L-O-9, 1-W-M-U-6, 1-W-M-O-5, 3-W-L-O-8, 3-W-L-U-7, and 3-W-L-U-9. All the selected bolts for post-test hardness evaluation were S-N fatigue tested in SW+CP condition. The purpose was to determine if any work/strain hardening took place due to the stresses at the first and second engaged threads as well as hydrogen concentration at these locations. Vickers hardness (HV1 and HV10) scale was used, and the measured values were converted to Rockwell C scale per ASTM E140. Figure 9 shows schematically the location of the hardness measurement. Tables 20-25 provide the measured Vickers hardness and the corresponding converted Rockwell C values.

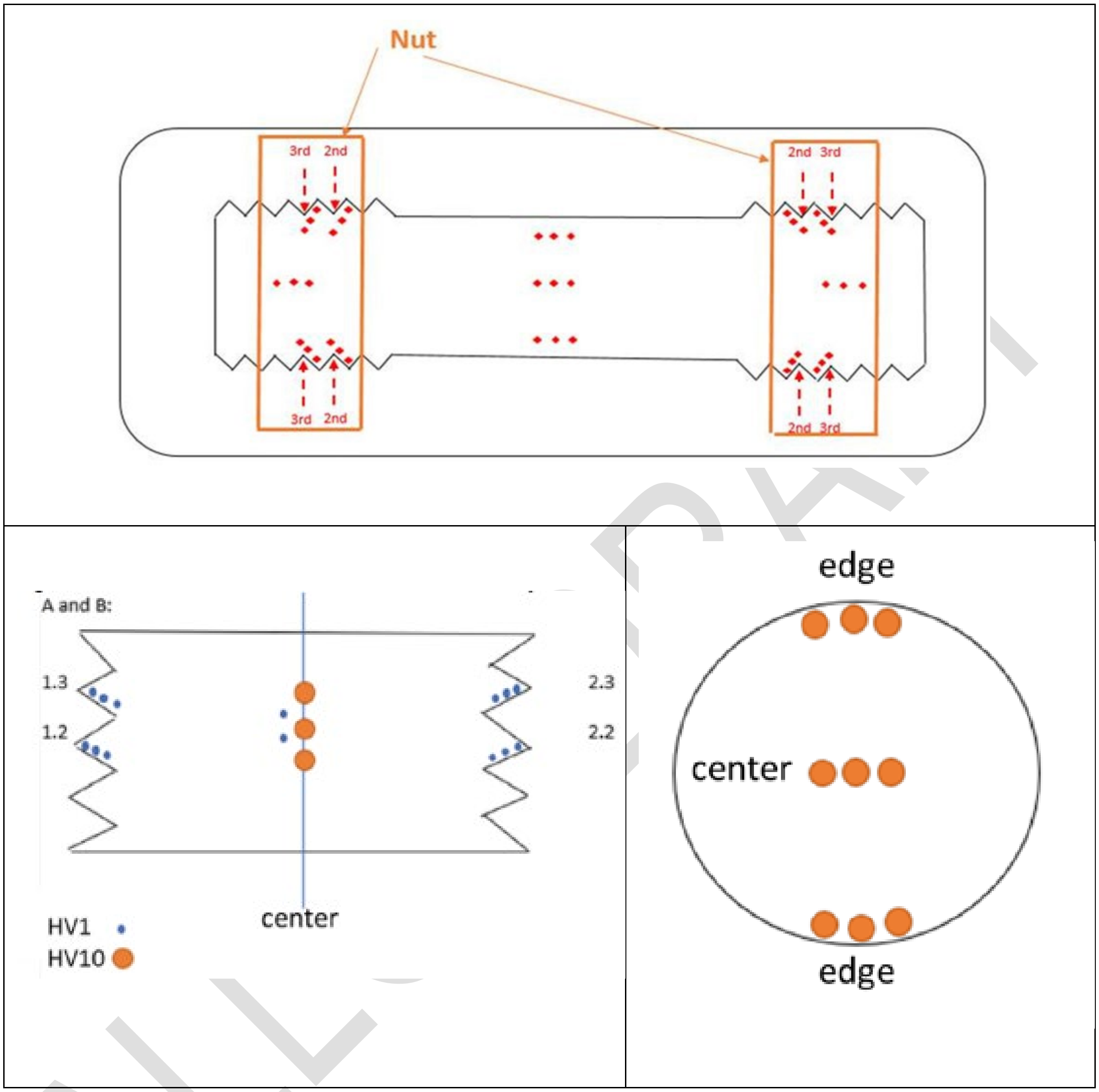



**Figure 9: Schematics of Vickers hardness test locations**

**Table 20: Hardness measurement results for 1 in. bolt from Heat 1 – Phase I**

| Hardness Reading Location | A | | B | | C | | |
|---|---|---|---|---|---|---|---|
| | HV1 | HRC | HV1 | HRC | | HV10 | HRC |
| 1.2 | 282 | 27 | 273 | 28 | Edge 1 | 286 | 28 |
| | 282 | 27 | 282 | 26 | | 284 | 28 |
| | 276 | 26 | 289 | 27 | | 288 | 28 |
| 1.3 | 276 | 26 | 283 | 28 | Edge 2 | 292 | 29 |
| | 280 | 27 | 283 | 27 | | 291 | 29 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 291 | 29 | 288 | 27 | | 291 | 29 |
| 2.2 | 288 | 28 | 280 | 28 | Center | 280 | 27 |
| | 291 | 29 | 272 | 27 | | 282 | 27 |
| | 280 | 27 | 289 | 26 | | 283 | 27 |
| 2.3 | 289 | 28 | 286 | 28 | | | |
| | 291 | 29 | 269 | 28 | | | |
| | 292 | 29 | 285 | 25 | | | |
| Center (HV1) | 280 | 27 | 285 | 28 | | | |
| | 282 | 27 | 285 | 28 | | | |
| | 282 | 27 | 284 | 28 | | | |
| Center (HV10) | 283 | 27 | 278 | 27 | | | |
| | 282 | 27 | 277 | 27 | | | |
| | 282 | 27 | 280 | 27 | | | |

**Table 21: Hardness measurement results for 1 in. bolt from Heat 2 – Phase I**

| Hardness Reading Location | A | | B | | C | | |
|---|---|---|---|---|---|---|---|
| | HV1 | HRC | HV1 | HRC | | HV10 | HRC |
| 1.2 | 298 | 29 | 297 | 29 | Edge 1 | 293 | 29 |
| | 297 | 29 | 298 | 29 | | 293 | 29 |
| | 291 | 29 | 294 | 29 | | 295 | 29 |
| 1.3 | 305 | 30 | 292 | 29 | Edge 2 | 295 | 29 |
| | 298 | 29 | 297 | 29 | | 299 | 30 |
| | 298 | 29 | 293 | 29 | | 300 | 30 |
| 2.2 | 300 | 30 | 304 | 30 | Center | 295 | 29 |
| | 307 | 31 | 291 | 29 | | 297 | 29 |
| | 304 | 30 | 303 | 30 | | 300 | 30 |
| 2.3 | 297 | 29 | 289 | 28 | | | |
| | 292 | 29 | 301 | 30 | | | |
| | 286 | 28 | 289 | 28 | | | |
| Center (HV1) | 276 | 26 | 293 | 29 | | | |
| | 271 | 26 | 290 | 28 | | | |
| | 279 | 27 | 301 | 30 | | | |
| Center (HV10) | 276 | 26 | 280 | 27 | | | |
| | 282 | 27 | 280 | 27 | | | |
| | 286 | 28 | 283 | 27 | | | |

**Table 22: Hardness measurement results for 2 in. bolt from Heat 1 – Phase I**

| Hardness Reading Location | A | | B | | C | | |
|---|---|---|---|---|---|---|---|
| | HV1 | HRC | HV1 | HRC | | HV10 | HRC |
| 1.2 | 304 | 30 | 287 | 28 | Edge 1 | 284 | 28 |
| | 297 | 29 | 298 | 29 | | 273 | 23 |
| | 298 | 29 | 285 | 28 | | 276 | 26 |
| 1.3 | 303 | 30 | 292 | 29 | Edge 2 | 300 | 30 |
| | 295 | 29 | 290 | 28 | | 302 | 30 |
| | 305 | 30 | 293 | 29 | | 296 | 29 |
| 2.2 | 295 | 29 | 294 | 29 | Center | 284 | 28 |
| | 297 | 29 | 305 | 30 | | 273 | 26 |
| | 294 | 29 | 291 | 29 | | 276 | 26 |
| 2.3 | 282 | 27 | 283 | 27 | | | |
| | 285 | 28 | 297 | 29 | | | |
| | 296 | 29 | 288 | 28 | | | |
| Center (HV1) | 292 | 29 | 295 | 29 | | | |
| | 285 | 28 | 294 | 29 | | | |
| | 290 | 28 | 290 | 28 | | | |
| Center (HV10) | 293 | 29 | 284 | 28 | | | |
| | 297 | 29 | 292 | 29 | | | |
| | 294 | 29 | 287 | 28 | | | |

**Table 23: Hardness measurement results for 2 in. bolt from Heat 2 – Phase I**

| Hardness Reading Location | A | | B | | C | | |
|---|---|---|---|---|---|---|---|
| | HV1 | HRC | HV1 | HRC | | HV10 | HRC |
| 1.2 | 303 | 30 | 291 | 29 | Edge 1 | 302 | 30 |
| | 304 | 30 | 311 | 31 | | 302 | 30 |
| | 309 | 31 | 309 | 31 | | 305 | 30 |
| 1.3 | 310 | 31 | 306 | 31 | Edge 2 | 297 | 29 |
| | 314 | 32 | 309 | 31 | | 296 | 29 |
| | 310 | 31 | 308 | 31 | | 298 | 29 |
| 2.2 | 310 | 31 | 313 | 31 | Center | 291 | 29 |
| | 313 | 31 | 298 | 29 | | 282 | 27 |
| | 311 | 31 | 314 | 32 | | 275 | 26 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2.3 | 308 | 31 | 310 | 31 | | | |
| | 301 | 30 | 313 | 31 | | | |
| | 315 | 32 | 318 | 32 | | | |
| Center (HV1) | 300 | 30 | 289 | 28 | | | |
| | 294 | 29 | 293 | 29 | | | |
| | 307 | 31 | 298 | 29 | | | |
| Center (HV10) | 287 | 28 | 319 | 32 | | | |
| | 290 | 28 | 321 | 32 | | | |
| | 292 | 29 | 317 | 32 | | | |

**Table 24: Hardness measurement results for 3 in. bolt from Heat 1 – Phase I**

| Hardness Reading Location | A | | B | | C | | |
|---|---|---|---|---|---|---|---|
| | HV1 | HRC | HV1 | HRC | | HV10 | HRC |
| 1.2 | 306 | 31 | 302 | 30 | Edge 1 | 299 | 30 |
| | 309 | 31 | 304 | 30 | | 298 | 29 |
| | 315 | 32 | 305 | 30 | | 299 | 30 |
| 1.3 | 308 | 31 | 307 | 31 | Edge 2 | 300 | 30 |
| | 311 | 31 | 309 | 31 | | 300 | 30 |
| | 310 | 31 | 308 | 31 | | 299 | 30 |
| 2.2 | 306 | 30 | 307 | 31 | Center | 293 | 29 |
| | 306 | 30 | 315 | 32 | | 290 | 28 |
| | 302 | 30 | 311 | 31 | | 286 | 28 |
| 2.3 | 302 | 30 | 314 | 32 | | | |
| | 303 | 30 | 301 | 30 | | | |
| | 307 | 31 | 308 | 31 | | | |
| Center (HV1) | 303 | 30 | 299 | 30 | | | |
| | 304 | 30 | 305 | 30 | | | |
| | 297 | 29 | 313 | 31 | | | |
| Center (HV10) | 290 | 28 | 299 | 30 | | | |
| | 289 | 28 | 300 | 30 | | | |
| | 291 | 29 | 303 | 30 | | | |

**Table 25: Hardness measurement results for 3 in. bolt from Heat 2 – Phase I**

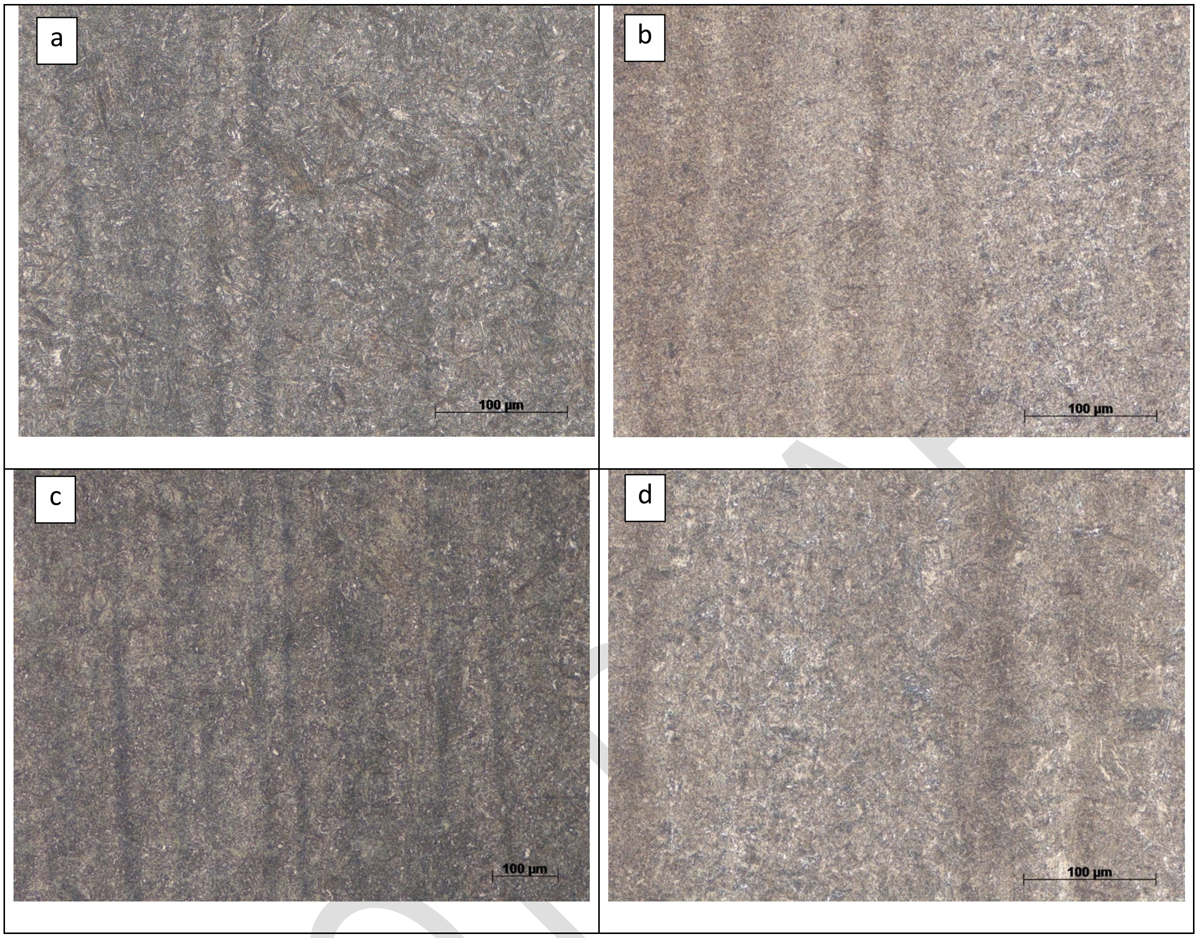
| | A | B | C |
|---|---|---|---|

| Hardness Reading Location | HV1 | HRC | HV1 | HRC | | HV10 | HRC |
|---|---|---|---|---|---|---|---|
| 1.2 | 288 | 28 | 296 | 29 | Edge 1 | 300 | 30 |
| | 310 | 31 | 309 | 31 | | 295 | 29 |
| | 291 | 29 | 302 | 30 | | 298 | 29 |
| 1.3 | 304 | 30 | 295 | 29 | Edge 2 | 297 | 29 |
| | 306 | 31 | 310 | 31 | | 297 | 29 |
| | 311 | 31 | 311 | 31 | | 302 | 30 |
| 2.2 | 292 | 29 | 298 | 29 | Center | 277 | 27 |
| | 298 | 29 | 299 | 30 | | 275 | 26 |
| | 293 | 29 | 294 | 29 | | 283 | 27 |
| 2.3 | 304 | 30 | 297 | 29 | | | |
| | 292 | 29 | 298 | 29 | | | |
| | 305 | 30 | 293 | 29 | | | |
| Center (HV1) | 288 | 28 | 291 | 29 | | | |
| | 288 | 28 | 291 | 29 | | | |
| | 299 | 30 | 294 | 29 | | | |
| Center (HV10) | 287 | 28 | 290 | 28 | | | |
| | 282 | 28 | 291 | 29 | | | |
| | 281 | 27 | 293 | 29 | | | |

### 5.2.6.3 Microstructure Examination

Microstructures of the selected bolts from each heat and each size were studied using optical microscopy. The study revealed that all the bolts contained a temper martensite microstructure. Some degree of banding (inhomogeneity in microstructure due to micro-segregation in chemical composition) and differences in grain size were observed. This phenomenon can lead to slightly different microstructure after quench and temper. Regions rich in alloying elements yield martensite and bainite microstructures, while the areas with lower alloying elements might yield bainite and ferrite types of microstructures.

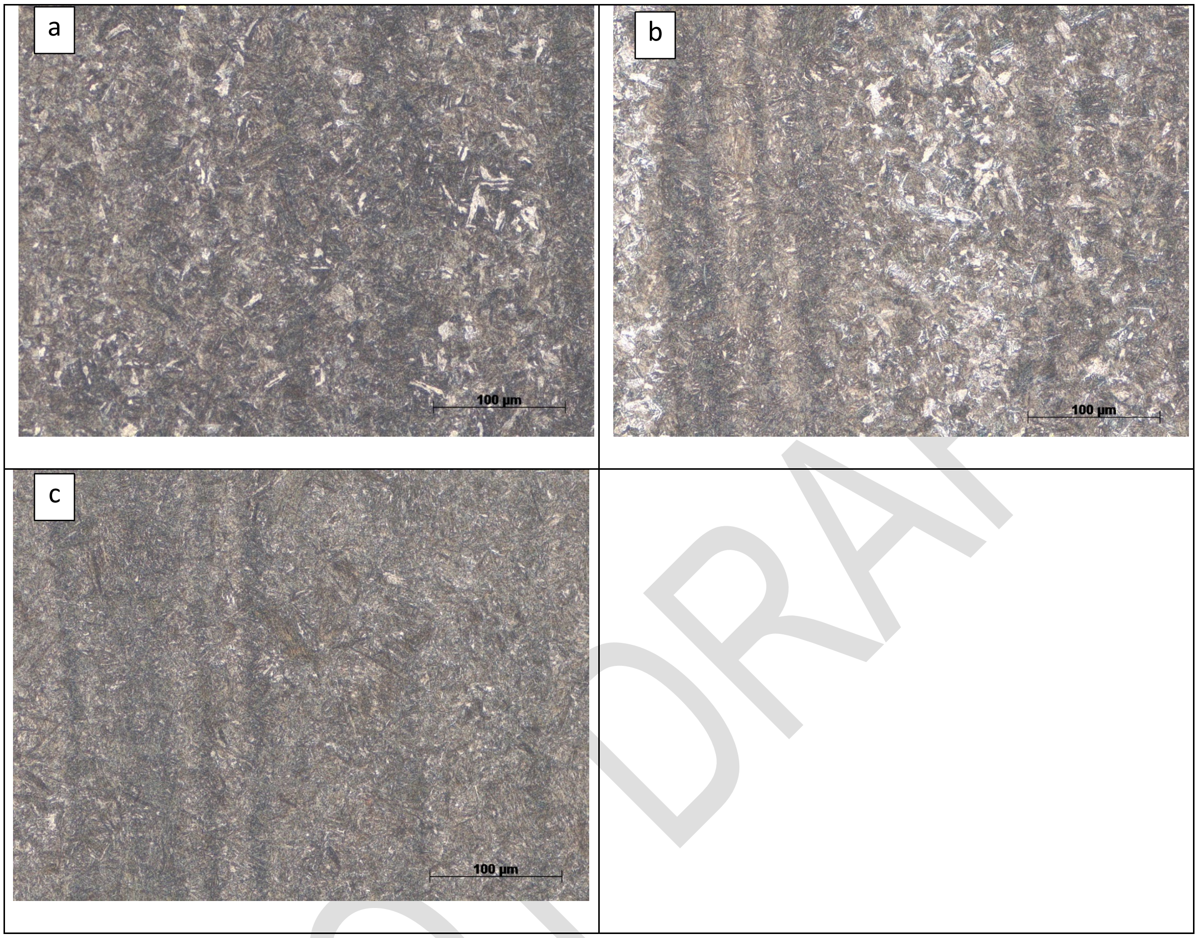
In this study, 1 in. and 3 in. bolts showed similar quenched and tempered and fine-grained microstructure. Areas of banding mainly at the center of the bolts were visible. The 2 in. bolts from the Heat 1 exhibited a more prominent banding than the bolts from the Heat 2. Microstructures of examined bolts, at 200X magnification, from the Heat 1 and Heat 2 at the thread area and at the center for 1 in. bolts are given in Figure 10.




Key
a) at the thread area – Heat 1
b) at the center – Heat 1
c) at the thread area – Heat 2
d) at the center – Heat 2

**Figure 10: Optical microscopy microstructure of the 1 in. bolts**

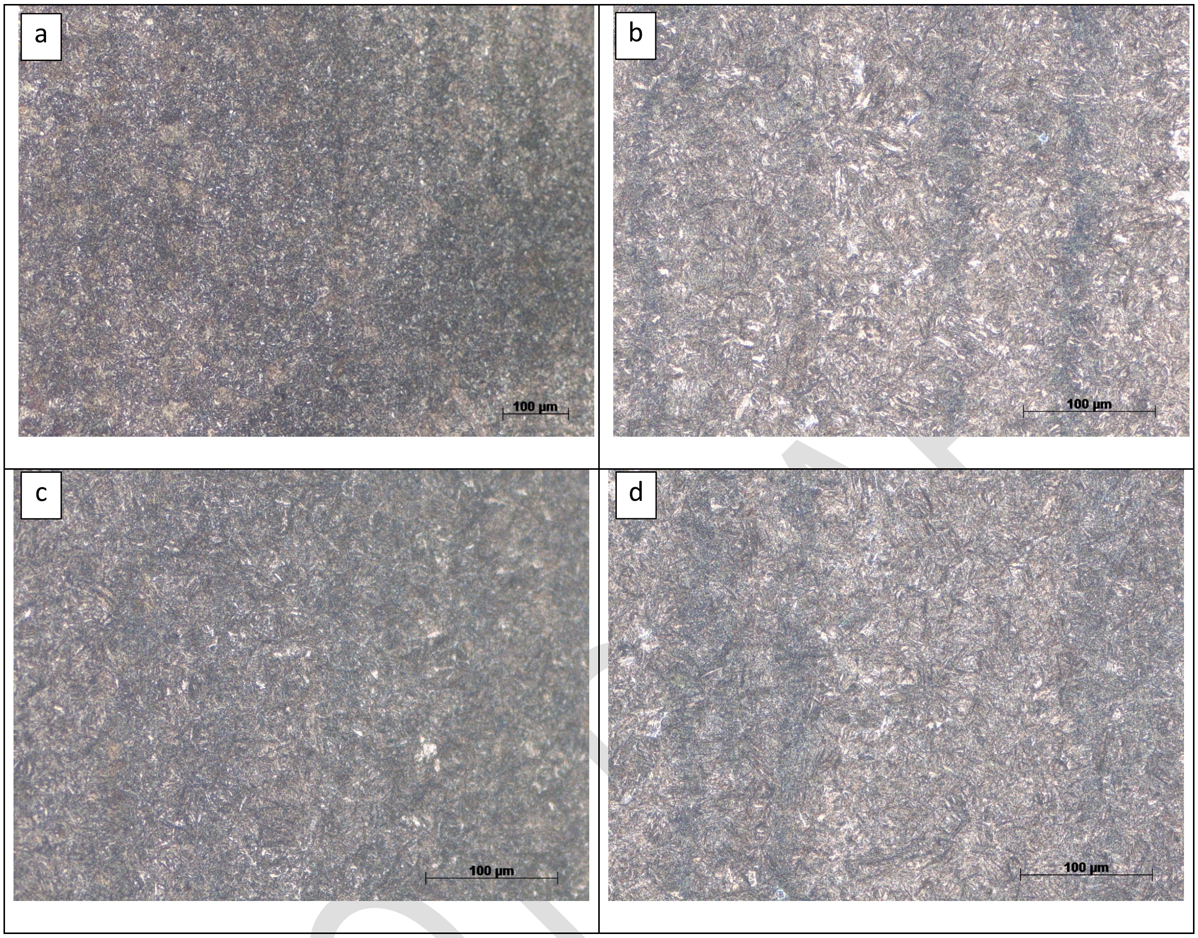
Microstructures of examined bolts, at 200X magnification, from the Heat 1 and Heat 2 at the thread area and at the center for 2 in. bolts are given in Figure 11.




Key
a) at the thread area – Heat 1
b) at the center – Heat 1
c) at the thread area – Heat 2

**Figure 11: Optical microscopy microstructure of the 2 in. bolts**

Microstructures of examined bolts, at 200X magnification, from the Heat 1 and Heat 2 at the thread area and at the center for 3 in. bolts are given in Figures 12.




**Key**
a) at the thread – Heat 1
b) at the center – Heat 1
c) at the thread – Heat 2
d) at the center – Heat 2

**Figure 12: Optical microscopy microstructure of the 3 in. bolts**

### 5.2.7 S-N Fatigue Testing in Air and in SW+CP – Phase II

S-N testing of the bolts in phase II was performed with a defined pre-load of 50% of SMYS and the applied stress ranges and corresponding loads for each bolt size are given in Table 12 in Section 5.2. Tables 26 – 29 show the test results in air and in SW+CP environments for the 1 in. and 3 in. bolts respectively.

**Table 26—S-N Fatigue Test Results for 1-in. Bolts in Air – Phase II**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 1-D-H-U-1 | 1 | 52.6 (363) | 17,959 | — |
| 1-D-H-U-2 | 1 | 52.6 (363) | 17,940 | — |
| 1-D-M-U-3 | 1 | 34.7 (239) | 63,221 | — |
| 1-D-M-U-4 | 1 | 34.7 (239) | 59,773 | — |
| 1-D-L-U-5 | 1 | 24.9 (172) | 246,744 | LFC + 10% |
| 1-D-L-U-6 | 1 | 21.5 (148) | 2,977,599 | Runout LFC + 5% |
| 1-D-L-U-7 | 1 | 22.9 (158) | 493,574 | LFC + 7.5% |
| 1-D-H-O-1 | 2 | 52.6 (363) | 17,628 | — |
| 1-D-H-O-2 | 2 | 52.6 (363) | 16,672 | — |
| 1-D-M-O-3 | 2 | 34.7 (239) | 95,905 | — |
| 1-D-M-O-4 | 2 | 34.7 (239) | 92,145 | — |
| 1-D-L-O-5 | 2 | 17.9 (123) | 3,383,336 | runout |
| 1-D-L-O-6 | 2 | 21.5 (148) | 7,899,730 | Run out LFC + 5% |
| 1-D-L-O-7 | 2 | 24.9 (172) | 369,586 | LFC + 10% |
| 1-D-L-O-8 | 2 | 22.9 (158) | 641,584 | LFC + 7.5% |

**Table 27—S-N Fatigue Test Results for 1-in. Bolts in SW+CP– Phase II**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 1-W-H-O-1 | 2 | 52.6 (363) | 11,752 | — |
| 1-W-H-O-2 | 2 | 52.6 (363) | 12,418 | — |
| 1-W-H-O-3 | 2 | 52.6 (363) | 12,850 | — |
| 1-W-M-O-4 | 2 | 34.7 (239) | 37,008 | — |
| 1-W-M-O-5 | 2 | 34.7 (239) | 25,283 | — |
| 1-W-M-O-6 | 2 | 34.7 (239) | 34,613 | — |
| 1-W-L-O-7 | 2 | 17.9/20.7 (123/143) | 414,607 | Increased to LFC + 4% after 381,298 cycles |
| 1-W-L-O-8 | 2 | 17.9/21.5 (123/148) | 618,490 | Increased to LFC + 5% after 567,405 cycles, stopped without fracture |
| 1-W-L-O-9 | 2 | 21.5 (148) | 128,960 | LFC + 5% |
| 1-W-L-O-10 | 2 | 21.5 (148) | 164,318 | LFC + 5% |
| 1-W-L-O-11 | 2 | 22.5 (155) | 132,907 | Wrong max. and min. load, discarded result |
| 1-W-L-O-12 | 2 | 20.7 (143) | 719,682 | LFC + 4%, stopped without fracture |
| 1-W-H-U-1 | 1 | 52.6 (363) | 13,996 | — |
| 1-W-H-U-2 | 1 | 52.6 (363) | 13,240 | — |
| 1-W-H-U-3 | 1 | 52.6 (363) | 12,422 | — |
| 1-W-M-U-4 | 1 | 34.7 (239) | 33,575 | — |
| 1-W-M-U-5 | 1 | 34.7 (239) | 29,435 | — |
| 1-W-M-U-6 | 1 | 34.7 (239) | 25,395 | — |
| 1-W-L-U-7 | 1 | 21.5 (148) | 266,357 | LFC + 5% |

| | | | | |
|---|---|---|---|---|
| **1-W-L-U-8** | 1 | **21.5 (148)** | **154,412** | **LFC + 5%** |
| **1-W-L-U-9** | 1 | **21.5 (148)** | **504,542** | **LFC + 5%** |

**Table 28—S-N Fatigue Test Results for 3-in. Bolts in Air – Phase II.**

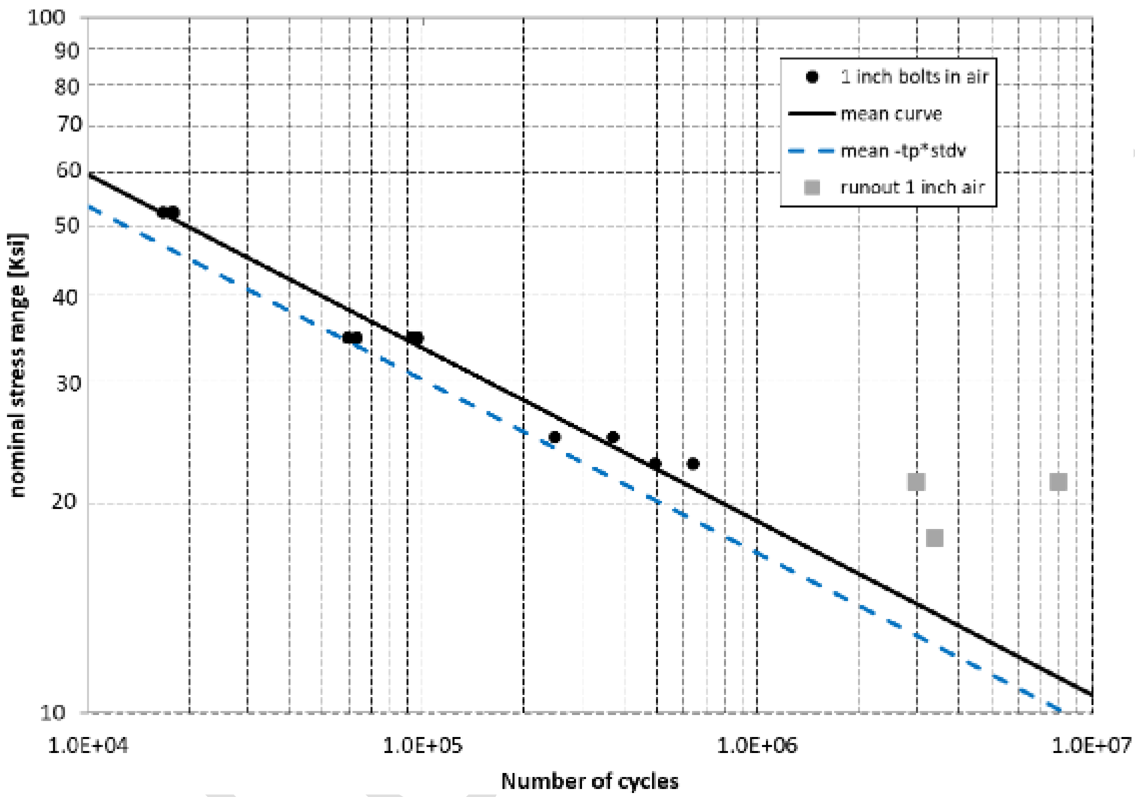
| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 3-D-H-U-1 | 1 | 52.6 (363) | 11,445 | — |
| 3-D-H-U-2 | 1 | 52.6 (363) | 11,370 | — |
| 3-D-M-U-3 | 1 | 34.7 (239) | 34,172 | — |
| 3-D-M-U-4 | 1 | 34.7 (239) | 35,877 | — |
| 3-D-L-U-5 | 1 | 17.9 (172) | 460,566 | — |
| 3-D-L-U-6 | 1 | 17.9 (172) | 720,260 | — |
| 3-D-L-U-7 | 1 | 17.9 (172) | 479,181 | — |
| 3-D-H-O-1 | 2 | 52.6 (363) | 10,017 | — |
| 3-D-H-O-2 | 2 | 52.6 (363) | 10,638 | — |
| 3-D-M-O-3 | 2 | 34.7 (239) | 33,264 | — |
| 3-D-M-O-4 | 2 | 34.7 (239) | 33,712 | — |
| 3-D-L-O-5 | 2 | 17.9 (123) | 225,637 | — |
| 3-D-L-O-6 | 2 | 17.9 (123) | 212,144 | — |
| 3-D-L-O-7 | 2 | 17.9 (123) | 252,474 | — |

**Table 29—S-N Fatigue Test Results for 3-in. Bolts in SW+CP– Phase II**

| Specimen ID | Heat | Stress Range, Δσ, ksi (MPa) | Cycles to Failure | Comments |
|---|---|---|---|---|
| 3-W-H-U-1 | 1 | 52.6 (363) | 10,248 | — |
| 3-W-H-U-2 | 1 | 52.6 (363) | 10,822 | — |
| 3-W-H-U-3 | 1 | 52.6 (363) | 11,015 | — |
| 3-W-M-U-4 | 1 | 34.7 (239) | 28,626 | — |
| 3-W-M-U-5 | 1 | 34.7 (239) | 28,038 | — |
| 3-W-M-U-6 | 1 | 34.7 (239) | 30,828 | — |
| 3-W-L-U-7 | 1 | 17.9 (123) | 748,367 | stopped without fracture, runout |
| 3-W-L-U-8 | 1 | 17.9 (123) | 0 | Stopped due to technical issues with the test frame |
| 3-W-L-U-9 | 1 | 17.9 (123) | 136,365 | — |
| 3-W-L-U-10 | 1 | 17.9 (123) | 367,342 | — |
| 3-W-H-O-1 | 2 | 52.6 (363) | 10,322 | — |
| 3-W-H-O-2 | 2 | 52.6 (363) | 10,428 | — |
| 3-W-H-O-3 | 2 | 52.6 (363) | 10,623 | — |
| 3-W-M-O-4 | 2 | 34.7 (239) | 27,838 | — |
| 3-W-M-O-5 | 2 | 34.7 (239) | 27,621 | — |
| 3-W-M-O-6 | 2 | 34.7 (239) | 27,275 | — |
| 3-W-L-O-7 | 2 | 17.9 (123) | 109,373 | — |
| 3-W-L-O-8 | 2 | 17.9 (123) | 107,181 | — |
| 3-W-L-O-9 | 2 | 17.9 (123) | 125,140 | — |

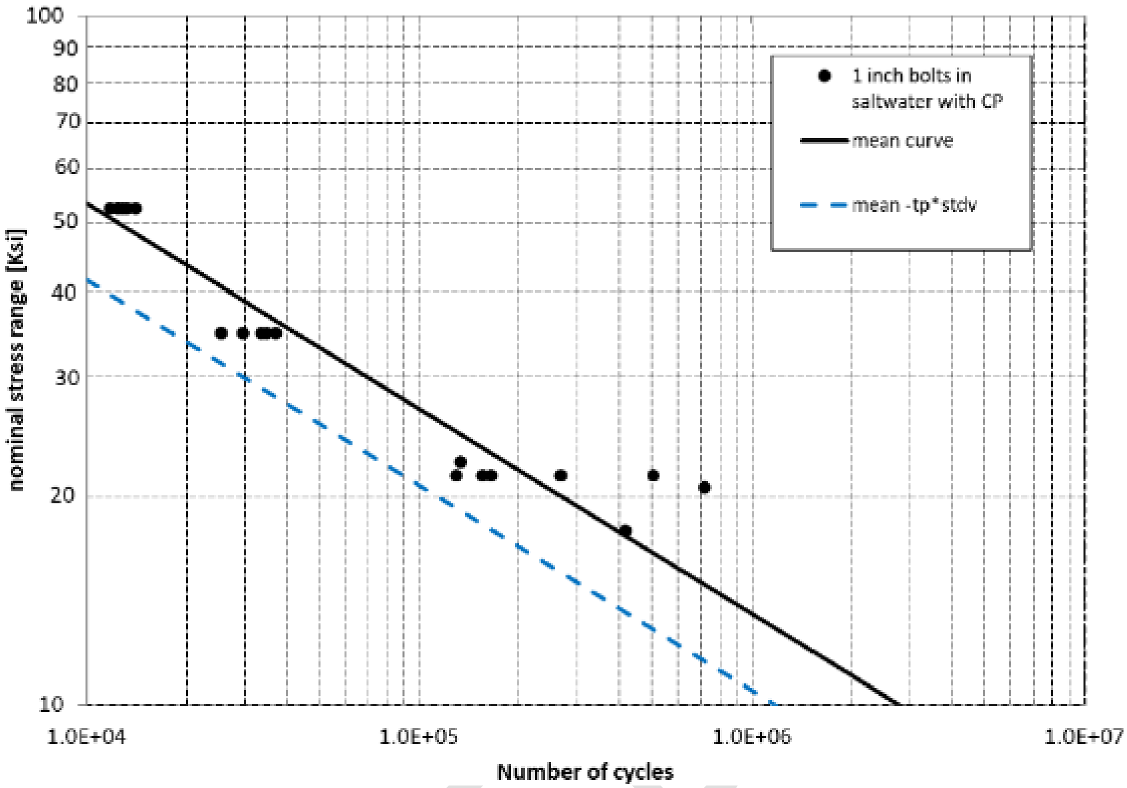
### 5.2.8 S-N Fatigue Curves in Air and in SW+CP Environments – Phase II

Figures 13 and 14 show the S-N fatigue curves obtained for the 1-in. bolts in air and in SW+CP environment. The plots also show the mean and mean $-t_p$*SD. Following the same approach of Phase I, the statistical analysis was performed in accordance with requirements of ASTM E739. The test results that showed run-outs were excluded in the regression analysis.




| 1" air data | DNV (phase II) disregarding runouts |
|---|---|
| | Free regression |
| m | 4.01 |
| $log a_1$ (mean) | 11.110 |
| StD ($log\overline{a_1}$) | 0.091 |
| Tp (12 test data) | 2.201 |
| Mean-tp*stdv | 10.910 |

**Figure 13 – S-N Fatigue Curve for 1 in. Bolts in Air – Phase II**




| 1" SW+CP data | DNV (phase II) disregarding runouts |
|---|---|
| | Free regression |
| m | 3.20 |
| $loga_1$ (mean) | 9.541 |
| StD ($\overline{loga_1}$) | 0.155 |
| Tp (18 test data) | 2.120 |
| Mean-tp*stdv | 9.214 |

**Figure 14 – S-N Fatigue Curve for 1 in. Bolts in SW+CP Environment – Phase II**

Figure 15 compares the test results for the 1 in. bolts in air and in SW+CP. The effect of hydrogen uptake on the 1 in. bolts is illustrated by the lower fatigue life in SW+CP as compared to in air at the same stress ranges. The hydrogen charging effects in fatigue life are more pronounced at LFC, which led to a steeper slope of the SW+CP fatigue curve.

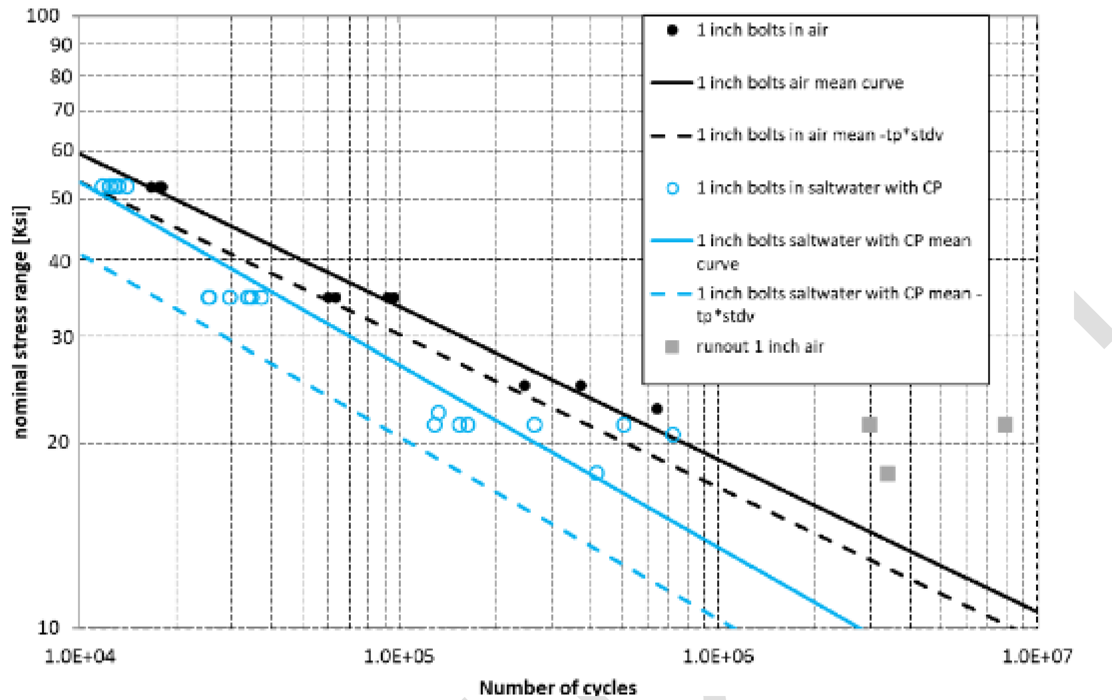
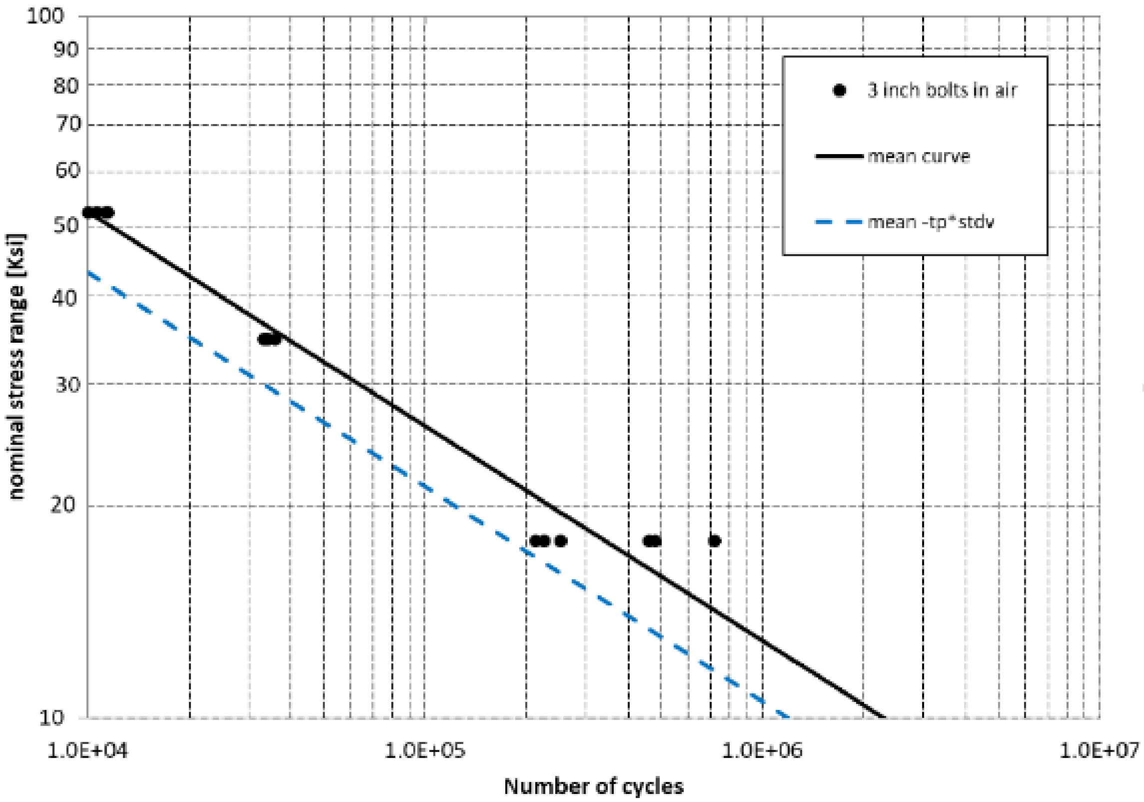


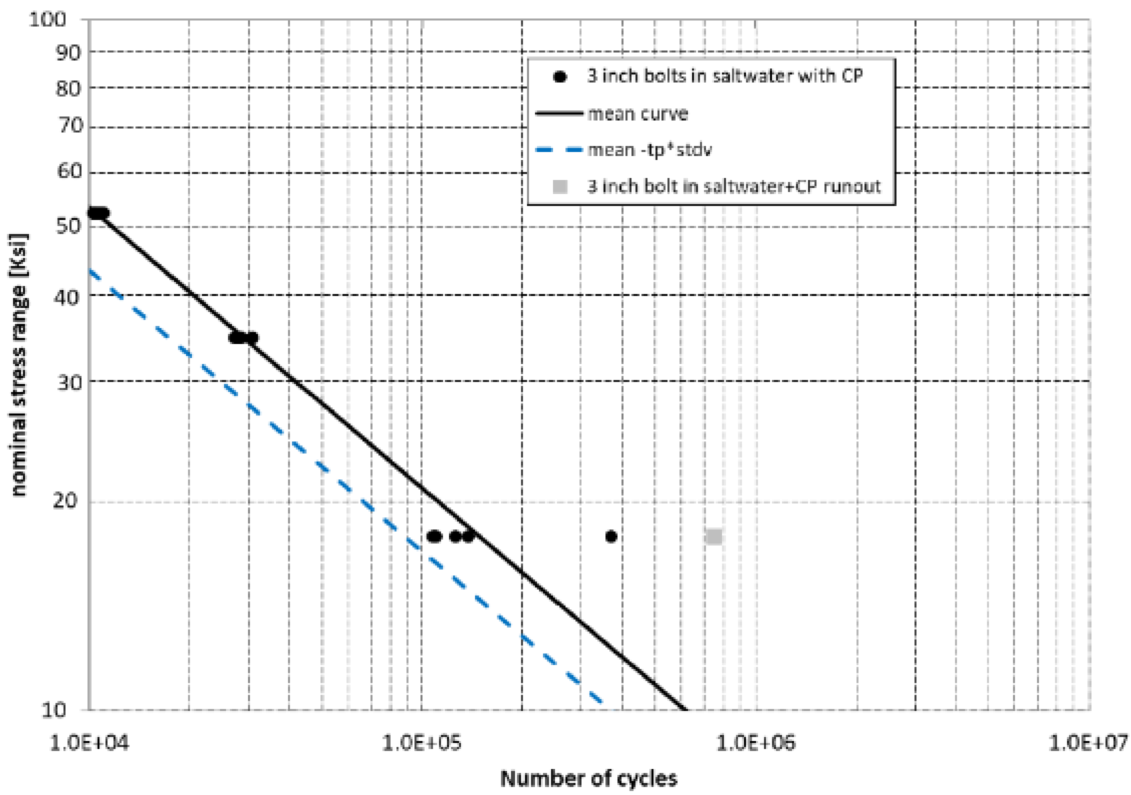

**Figure 15 – S-N Fatigue Test Results for 1 in. Bolts in air and SW+CP – Phase II**

Figures 16 and 17 show the S-N fatigue curves for the 3 in. bolts in air and in SW+CP environment, respectively.




| 3” air data | DNV (phase II) disregarding runouts |
|---|---|
| | Free regression |
| m | 3.27 |
| $log a_1$ (mean) | 9.629 |
| StD ($log\overline{a_1}$) | 0.140 |
| Tp (14 test data) | 2.179 |
| Mean-tp*stdv | 9.323 |

**Figure 16 – S-N Fatigue Curve for 3 in. Bolts in Air – Phase II**




| 3” SW+CP data | DNV (phase II) disregarding runouts |
|---|---|
| | Free regression |
| m | 2.46 |
| $loga_1$ (mean) | 8.244 |
| StD $(log\overline{a_1})$ | 0.113 |
| Tp (17 test data) | 2.132 |
| Mean-tp*stdv | 8.008 |

**Figure 17 – S-N Fatigue Curve for 3 in. Bolts in SW+CP environment – Phase II**

Figure 18 compares the test results for the 3 in. bolts in air and in SW+CP environment. At HFC the difference in fatigue lives in air and SW+CP environments are insignificant indicating that at HFC, the fatigue life of 3 in. bolts in SW+CP environment is dominated by bolt stiffness and stress concentration factor at the thread root of the bolting rather than hydrogen uptake. In addition, hydrogen uptake and transport in the material is a time dependent phenomenon and hence lesser effect of hydrogen embrittlement due to duration of the test at HFC and MFC.

At LFC, the difference between air and SW+CP is more pronounced with SW+CP environment showing lower overall fatigue lives due to availability of time for hydrogen uptake and transport to the fracture process zone at or beneath the thread roots. At LFC, the scatter of the test results in air and SW+CP environment is higher than MFC and HFC, but overall fatigue lives in SW+CP appears to be lower due to hydrogen uptake and embrittlement. In general, the 3 in. bolts mean curve in SW+CP environment exhibits a steeper slope.

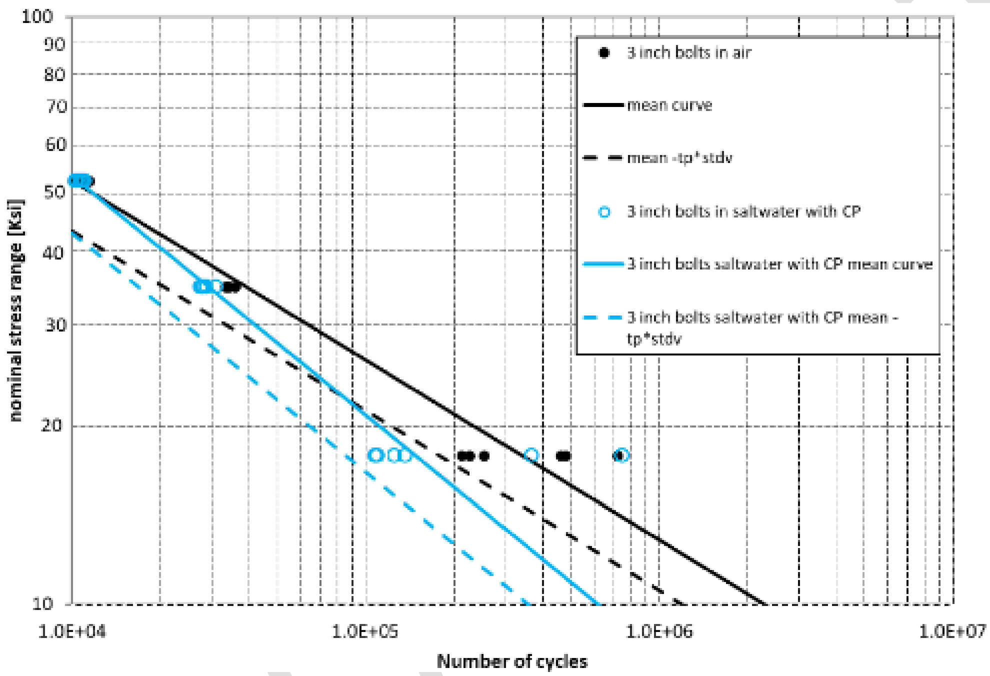



**Figure 18 – S-N Fatigue Test Results for 3 in. Bolts in air and SW+CP – Phase II**

Figures 19 and 20 compare the S-N fatigue design curves for the 1 in. and 3 in. bolts in air and in SW+CP environment, respectively. Figure 19 shows that in air, the 3 in. bolt exhibits a lower fatigue capacity at each stress range and steeper slope as compared to the 1 in. bolts. This is attributed to the higher stiffness and stress concentration factor at the thread roots of the 3 in. bolts.

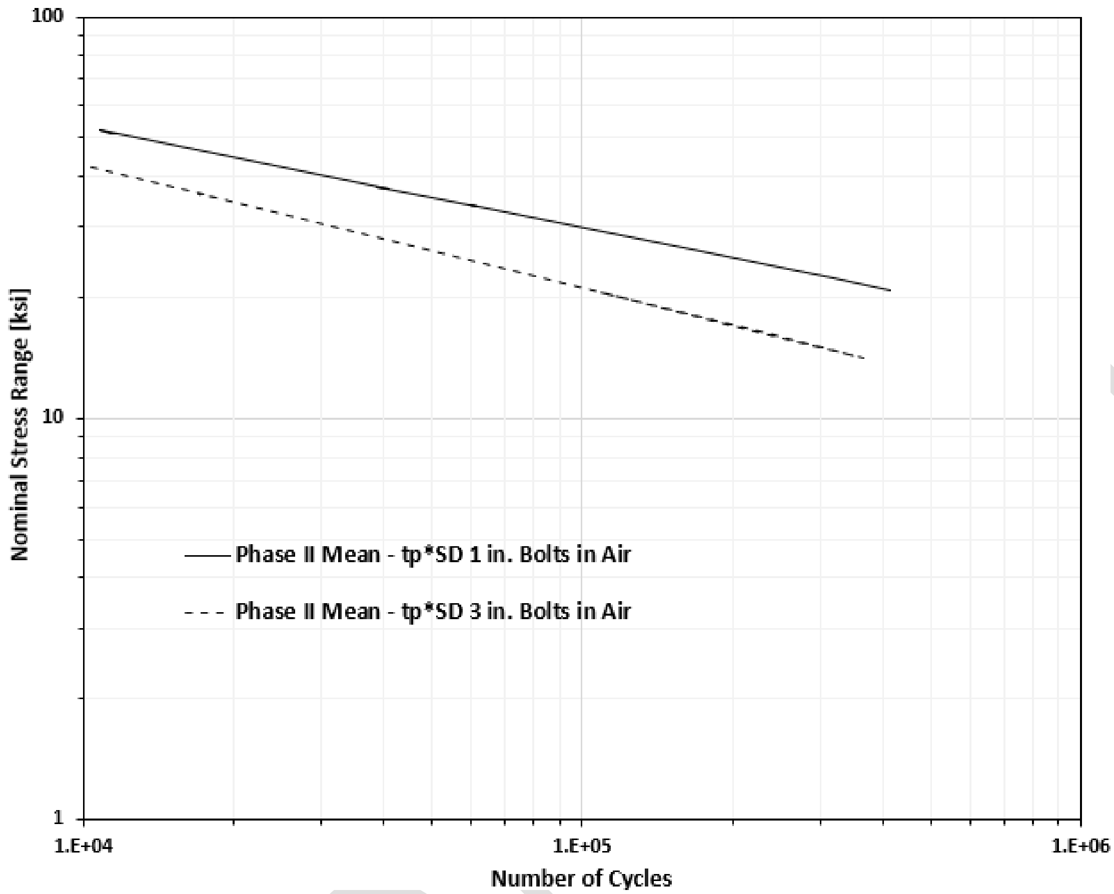



**Figure 19 – Comparison of the 1 in. and 3 in. Bolt S-N Fatigue Curves in Air – Phase II**

Similar trend is observed in Figure 20 for the 1 in. and 3 in. bolts tested in SW+CP environment except at HFC, the difference in fatigue lives appear to be minimal. Besides stiffness and stress concentration effects discussed for in air fatigue curves comparison, hydrogen uptake and embrittlement also plays a role in SW+CP environment. The hydrogen embrittlement effect on 1 in. bolts are more pronounced shifting the curve toward the 3 in. bolts curve.

This indicates that at the HFC, the difference in fatigue lives (if any) between the 1 in. and 3 in. bolts in SW+CP are dominated by the bolt stiffness and stress concentration factors at the thread roots. At LFC, fatigue lives seem to be dominated by atomic hydrogen diffusion and transport to the fracture process zone at or beneath the thread roots. The results show that this process is more prevalent as the thickness of the bolt increases leading to lower fatigue lives and hence, steeper design fatigue curves at the same nominal applied stress range.

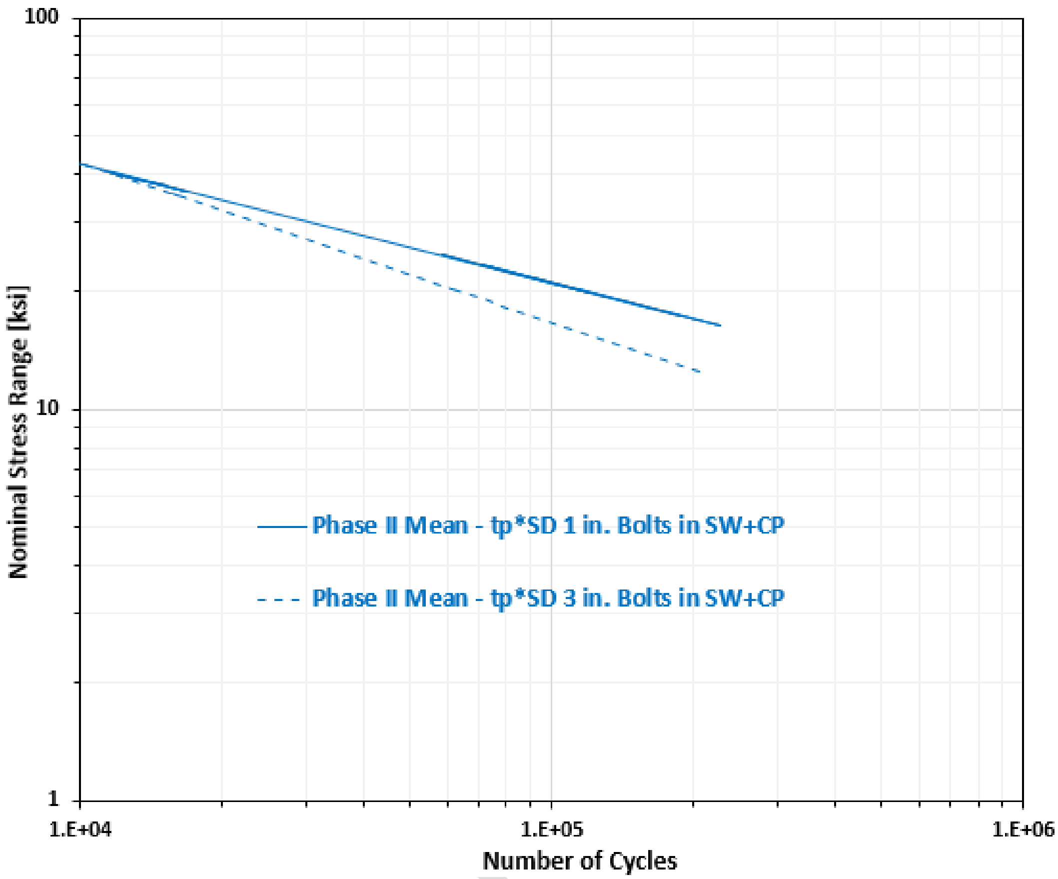



**Figure 20 – Comparison of the 1 in. and 3 in. Bolt S-N Fatigue Curves in SW+CP – Phase II**

Based on the Phase II S-N fatigue curves for the 1 in. and 3 in. bolts in air and SW+CP environment, Table 30 provides a knock-down factor at different stress ranges for the two bolt sizes.

**Table 30: Knock-Down Factors for SW+CP/Air Environments at three applied stress ranges – Phase II**

| Stress Range Ksi [MPa] | 1 in. | 3 in. |
|---|---|---|
| Δσ = 52.6 [362.4] | 0.73 | 0.97 |
| Δσ = 34.7 [239.1] | 0.40 | 0.83 |
| Δσ = 21.5 [148.1] | 0.06* | - |
| Δσ = 17.9 [123.3] | - | 0.43 |

* No ambient air failures

### 5.2.9 Post-Test Evaluation – Phase II

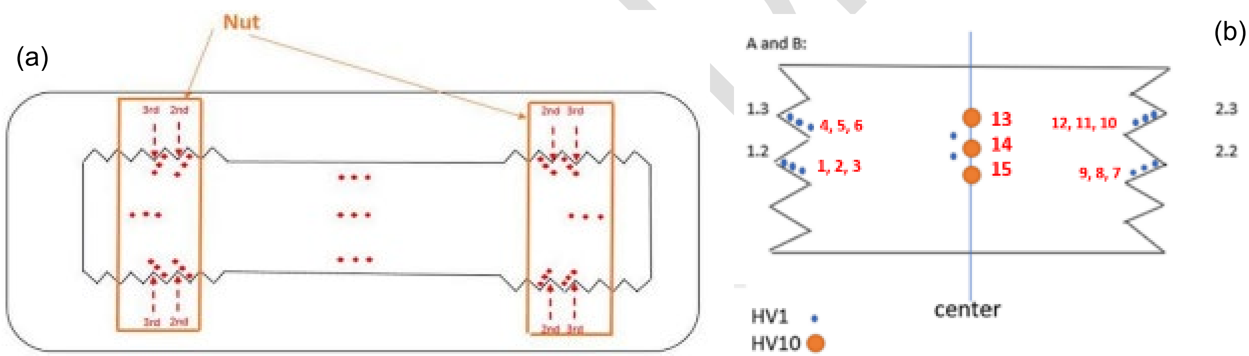
#### 5.2.9.1 General

Upon completion of each S-N test, the bolts were evaluated, and pictures of their fracture surfaces were taken and documented on a result sheet along with other information specific to each bolt. A few fractured bolts from each heat and size were selected to be studied further.

#### 5.2.9.2 Hardness Measurements

After completion of the S-N tests, six (6) bolts were selected for hardness measurement. This included three (3) 1 in. bolts (1-W-L-O-9, 1-W-M-U-6, 1-W-M-O-5) and three (3) 3 in. bolts (3-W-L-O-8, 3-W-L-U-7, 3-W-L-U-9). All the selected bolts were fatigue tested in SW+CP environment. The purpose was to determine if any work/strain hardening took place due to the stresses at the first and second engaged threads as well as hydrogen concentration at these locations.

Hardness measurements were conducted using the Vickers (HV1, and VH10) Scale. Measured Vickers hardnesses were then converted to Rockwell C (HRC) per ASTM E140 Table 1. Figure 21 shows the location of hardness measurements, (a), and the indent number allocated to each hardness reading, (b), for both bolt sizes.




Key
a) Vickers Hardness Testing Location
b) Indent Number Allocated to Each Hardness Reading

**Figure 21 – Schematics of hardness test locations – Phase II**

Tables 31 and 32 show both the HV1 and HV10 hardness measurements as well as the converted HRC values for the 1 in. and 3 in. Bolts – Phase II.

**Table 31: Measured HV1 and HV10 hardness and converted HRC values for the 1 in. Bolts – Phase II**

| 1 in. | Indent number | 1-W-L-O-9 1st thread | | 1-W-L-O-9 2nd thread | | 1-W-M-U-6 1st thread | | 1-W-M-U-6 2nd thread | | 1-W-M-O-5 1st thread | | 1-W-M-O-5 2nd thread | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HV1 | HRC | HV1 | HRC | HV1 | HRC | HV1 | HRC | HV1 | HRC | HV1 | HRC |
| 1.2 (A) | 1 | 271 | 26 | 269 | 26 | 285 | 28 | 292 | 29 | 276 | 26 | 268 | 25 |
| | 2 | 273 | 26 | 274 | 26 | 285 | 28 | 298 | 30 | 271 | 26 | 276 | 27 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 273 | 26 | 269 | 26 | 293 | 29 | 284 | 28 | 281 | 27 | 268 | 25 |
| 1.3 (A) | 4 | 271 | 26 | 272 | 26 | 285 | 28 | 292 | 29 | 275 | 26 | 275 | 26 |
| | 5 | 273 | 26 | 276 | 26 | 290 | 29 | 279 | 27 | 272 | 26 | 277 | 27 |
| | 6 | 273 | 26 | 273 | 26 | 301 | 30 | 292 | 29 | 277 | 27 | 274 | 26 |
| 2.2 (B) | 7 | 279 | 27 | 277 | 27 | 289 | 28 | 295 | 29 | 272 | 26 | 271 | 26 |
| | 8 | 279 | 27 | 275 | 26 | 292 | 29 | 290 | 29 | 280 | 27 | 277 | 27 |
| | 9 | 279 | 27 | 271 | 26 | 289 | 28 | 285 | 28 | 276 | 26 | 275 | 26 |
| 2.3 (B) | 10 | 269 | 25 | 271 | 26 | 287 | 28 | 291 | 29 | 273 | 26 | 268 | 25 |
| | 11 | 276 | 26 | 275 | 26 | 291 | 29 | 278 | 27 | 275 | 26 | 275 | 26 |
| | 12 | 276 | 26 | 272 | 26 | 289 | 28 | 282 | 27 | 273 | 26 | 274 | 26 |
| **AVG** | | **274** | **26** | **273** | **26** | **290** | **29** | **289** | **29** | **275** | **26** | **273** | **26** |
| Center HV10 | | HV | HRC | HV | HRC | HV | HRC | HV | HRC | HV | HRC | HV | HRC |
| | 13 | 271 | 26 | 263 | 25 | 287 | 28 | 275 | 26 | 267 | 26 | 266 | 25 |
| | 14 | 271 | 26 | 263 | 25 | 284 | 28 | 278 | 27 | 270 | 26 | 269 | 26 |
| | 15 | 270 | 26 | 262 | 25 | 287 | 28 | 281 | 27 | 271 | 26 | 270 | 26 |
| **AVG** | | **271** | **26** | **263** | **25** | **286** | **28** | **278** | **27** | **269** | **26** | **268** | **26** |

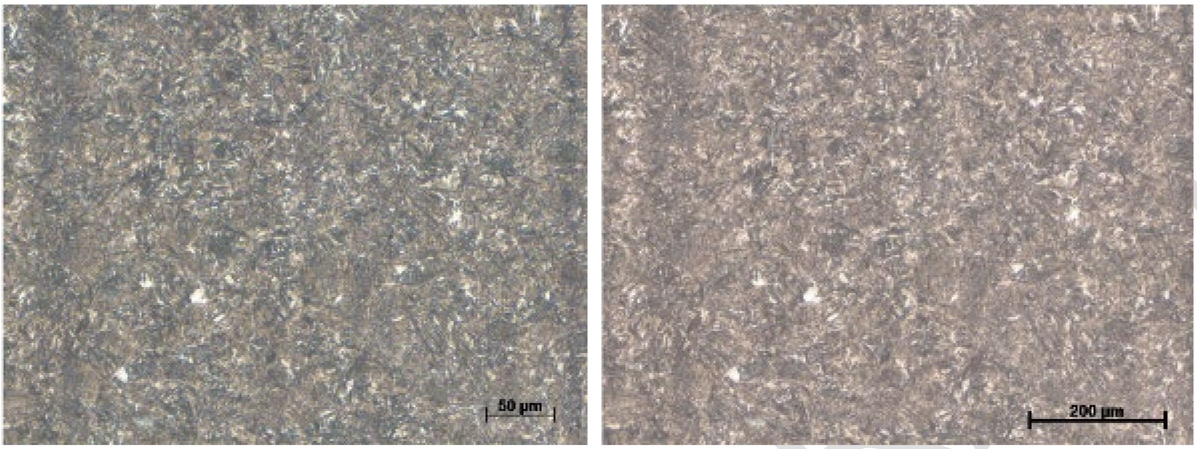
**Table 32: Measured HV1 and HV10 hardness and converted HRC values for the 3 in. Bolts – Phase II**

| 1 in. | Indent number | 3-W-L-O-8 1st thread | | 3-W-L-O-8 2nd thread | | 3-W-L-U-9 1st thread | | 3-W-L-U-9 2nd thread | | 3-W-L-U-7 1st thread | | 3-W-L-U-7 2nd thread | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HV1 | HRC | HV1 | HRC | HV1 | HRC | HV1 | HRC | HV1 | HRC | HV1 | HRC |
| 1.2 (A) | 1 | 284 | 27 | 312 | 31 | 289 | 28 | 302 | 30 | 284 | 27 | 294 | 29 |
| | 2 | 283 | 27 | 291 | 28 | 290 | 28 | 280 | 27 | 304 | 30 | 291 | 28 |
| | 3 | 277 | 26 | 293 | 28 | 281 | 27 | 298 | 29 | 279 | 27 | 306 | 30 |
| 1.3 (A) | 4 | 290 | 28 | 301 | 29 | 277 | 26 | 307 | 30 | 315 | 31 | 288 | 29 |
| | 5 | 272 | 26 | 288 | 28 | 286 | 28 | 295 | 29 | 285 | 27 | 302 | 30 |
| | 6 | 276 | 26 | 293 | 28 | 285 | 27 | 296 | 29 | 280 | 27 | 295 | 29 |
| 2.2 (B) | 7 | 281 | 27 | 309 | 30 | 278 | 26 | 296 | 29 | 284 | 27 | 292 | 28 |
| | 8 | 285 | 27 | 295 | 29 | 289 | 28 | 285 | 27 | 277 | 26 | 292 | 28 |
| | 9 | 280 | 27 | 291 | 28 | 285 | 27 | 292 | 28 | 275 | 26 | 290 | 28 |
| 2.3 (B) | 10 | 276 | 26 | 305 | 30 | 277 | 26 | 312 | 31 | 278 | 26 | 278 | 26 |
| | 11 | 279 | 27 | 292 | 28 | 282 | 27 | 300 | 29 | 290 | 28 | 287 | 28 |
| | 12 | 285 | 27 | 298 | 29 | 285 | 27 | 303 | 30 | 286 | 27 | 276 | 26 |
| **AVG** | | **281** | **27** | **297** | **29** | **284** | **27** | **297** | **29** | **286** | **28** | **291** | **28** |
| Center HV10 | | HV | HRC | HV | HRC | HV | HRC | HV | HRC | HV | HRC | HV | HRC |
| | 13 | 285 | 27 | 284 | 27 | 283 | 27 | 288 | 28 | 284 | 27 | 284 | 27 |
| | 14 | 289 | 28 | 282 | 27 | 286 | 28 | 285 | 27 | 284 | 27 | 281 | 27 |
| | 15 | 288 | 28 | 274 | 26 | 285 | 27 | 282 | 27 | 280 | 27 | 278 | 26 |
| **AVG** | | **287** | **28** | **280** | **27** | **285** | **27** | **285** | **27** | **283** | **27** | **281** | **27** |

### 5.2.9.3 Microstructure Evaluation

For microstructural examination, the same 1 in. and 3 in. bolts for hardness measurements were used. Cross sectional samples were cut from each bolt, polished, and etched to reveal the microstructure. The microstructures were examined with an Optical Microscope and photomicrographs were taken at various magnifications.

Figure 22 shows the microstructure at the center and the thread of bolt sample 1-W-M-U-6 at 200X. The microstructure at the center of the bolt is primarily tempered martensite with some banding. The tempered martensite with some banding was observed from both the center and the thread areas for all 1 in. bolts examined.




(a) (b)

Key

a) Center
b) thread

**Figure 22 – Optical Microscope Photomicrograph – Phase II**

The microstructure of the 3 in. bolts also included tempered martensite with some banding, but it also included some retained austenite. Figure 23 shows the microstructure of the 3 in. bolt identified as 3-W-L-O-8 at 200X. The light colored phase at the center of Figure 23 was identified as retained austenite.

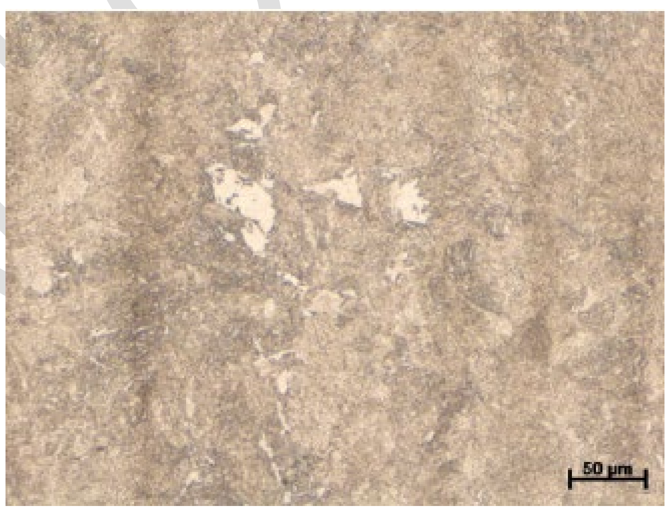



**Figure 23 – Optical Microscope Photomicrograph – Phase II**

The retained austenite was identified using SEM and Energy-Dispersive X-ray Spectroscopy (EDS) mapping. The result of mapping for different elements are shown in Figure 24.

The elemental mapping shows that the elements are randomly distributed in the light-colored phase and surrounding area which was mostly tempered martensite. This suggests the light colored phase is retained austenite which did not transform to martensite during quenching.

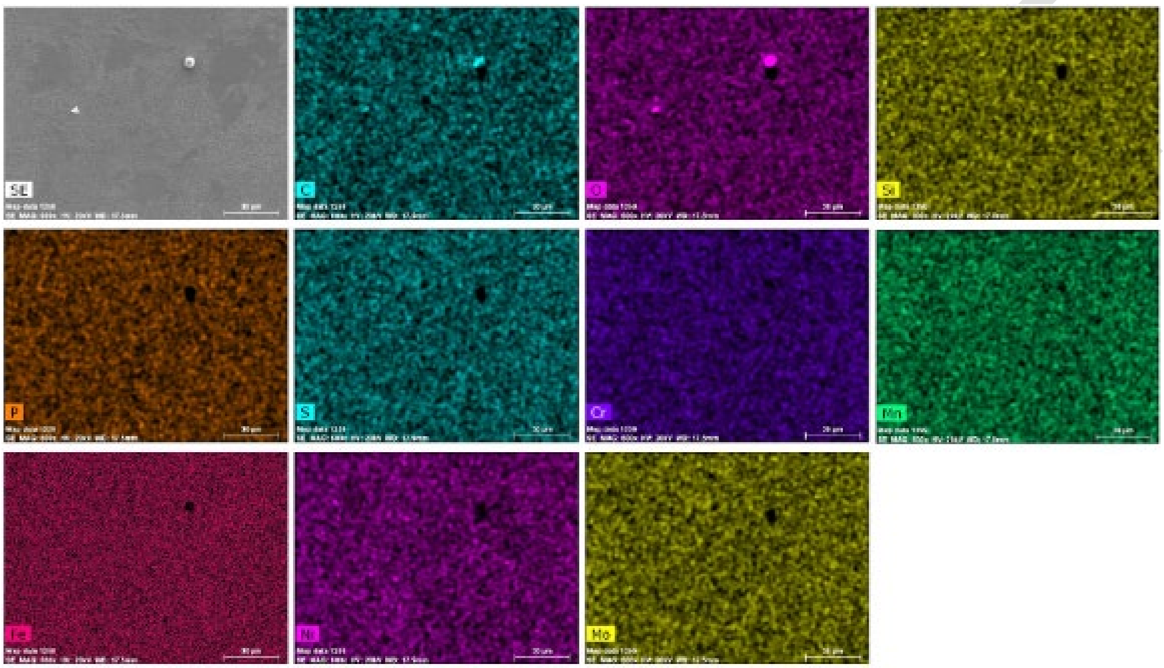
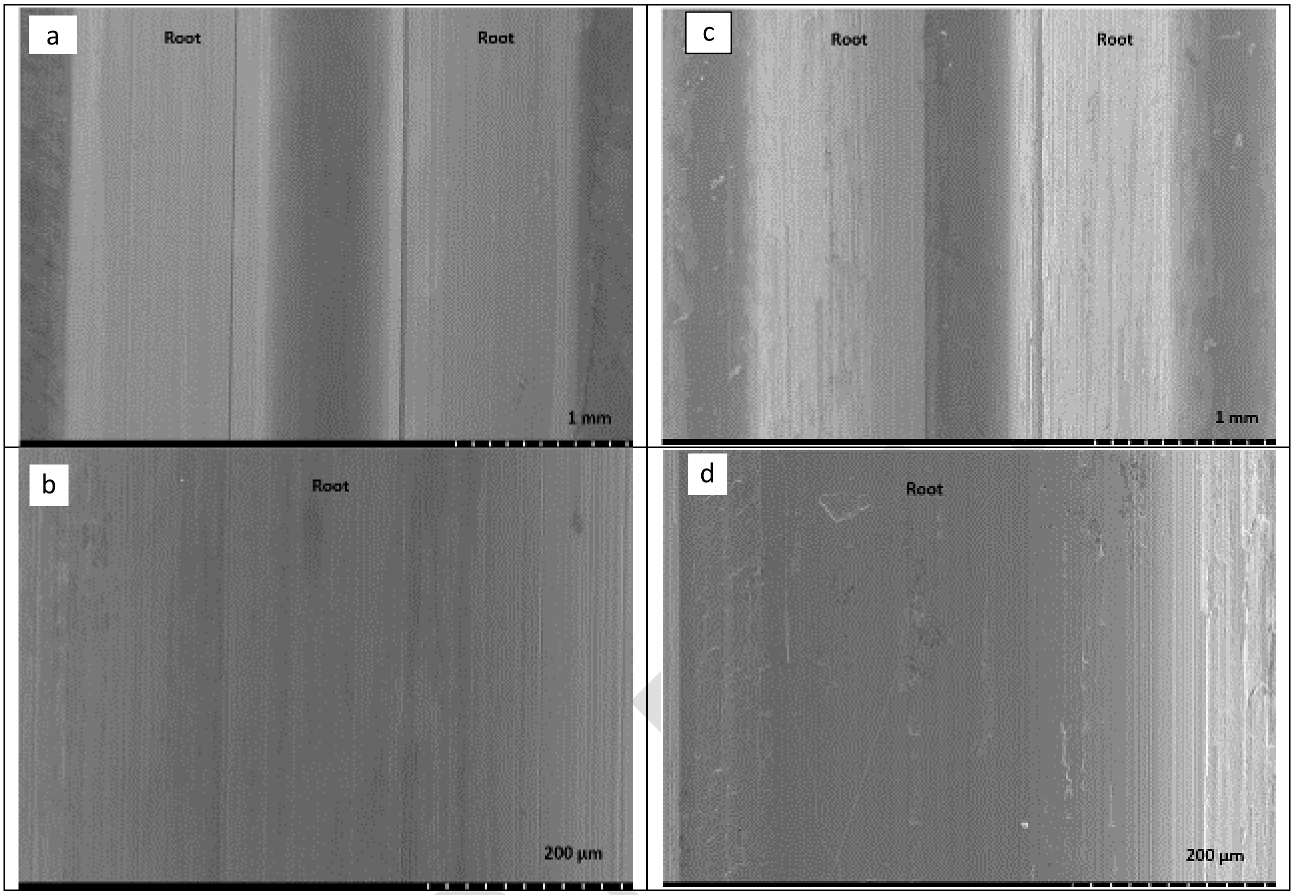



**Figure 24 – EDS Mapping of the Light-Colored Phase observed (or described) in Figure 23**

### 5.2.9.4 Thread Root Roughness Profile

As shown by the S-N fatigue curves in air and in SW+CP developed in Phase II, large scatter in fatigue lives were observed at the lowest applied nominal stress range (LFC) for both 1 in. and 3 in. bolts. Additionally, the 3 in. bolts supplied by one of the suppliers consistently showed higher fatigue lives at LFC as compared to the second bolting supplier. As a result, the thread root surface conditions of several 3 in. bolts from both suppliers tested at LFC in air were evaluated by SEM. For this objective, 10-15 cm (4-6 in.) samples from the intact thread regions of tested bolts in air were cut to ensure that the threads were not altered due to mechanical contact with the nut threads.

Figure 25 compares the thread root surface conditions of the 3 in. bolts from the two heats tested in air at LFC ($\Delta\sigma$ = 17.9 ksi). The bolts were identified as 3-D-L-O-6 ($N_f$ = 212,144 Cycles), and 3-D-L-U-6 ($N_f$ = 720,260 Cycles), respectively. These SEM photomicrographs show that the thread root surface roughness of the bolts from the two heats varies from one heat to the other.




Key
a,b) Thread Root Roughness – Heat 1
c,d) Thread Root Roughness – Heat 2

**Figure 25 – SEM Photomicrograph taken at Low Magnification For 3 in. bolts**

The S-N test results from the 3 in. bolts in air illustrate that even though both Heat 1 and Heat 2 were supplied in accordance with API 20E BSL-3 requirements, thread root surface roughness has made a difference in fatigue lives at LFC.

# 7 Conclusions

Full scale S-N fatigue testing of low alloy steel bolting of 1 in., 2 in., and 3 in. in Phase I and 1 in. and 3 in. in Phase II in air and saltwater with CP conditions provided valuable data that can be used for the applicable designs. The main conclusions are the following.

1) The bolting fatigue life decreases with increasing the bolt size. This is due to increased stiffness and increased root radius stress concentration factor with increasing bolt size.

2) 1 in. fatigue test series performed in ambient air in both Phases had several runouts at the lower alternating nominal stress range which indicates that the 1 in. bolt size is approaching a fatigue

threshold limit for constant amplitude loading. It is believed that without surface discontinuities identified, the fatigue life indicates an endurance limit for alternating stress of approximately 17 ksi in Phase I and approximately, 20ksi in Phase II.

3) Fatigue testing of 1 in. bolts in air and at the low stress range exhibited runouts in both phases indicating an endurance limit that varies with mean stress. The endurance limit in air seems to be near 17 ksi and 20 ksi for Phase I and Phase II respectively.

4) The fatigue reduction factor for saltwater with CP is affected by both bolt size and stress ranges. The higher the alternating stress and the larger the bolt, the less the reduction factor in environment. This is attributed to atomic hydrogen diffusion and transport being more dominant at the lower alternating stress levels.

5) The log- log plot of the slope for the fatigue curves for the saltwater with CP tests is steeper than the slope of the curve for the ambient air tests. This again is due to the influence of the atomic hydrogen diffusion and transport at lower alternating stress ranges.

6) Phase II testing results showed that the knock down factor due to saltwater under cathodic protection influence is less for the 3 in. bolts than for the 1 in. bolts.

7) Both 1 in. and 3 in. bolts show a mean stress dependency in both environments. In Phase II, higher fatigue lives were obtained due to lower mean stress than in Phase I where the mean stress was higher.

8) All bolts demonstrated no susceptibility to shear failure of the threads from testing and post test evaluation. All the bolt failures observed were due to crack initiation at the first engaged thread root in bolt thread, which propagated radially through the cross section of the bolt (tensile type failure).

9) Although bolting for Phase I and Phase II were conforming with API 20E BSL-3 requirements, differences in bolting thread root roughness appeared to contribute to a wider scatter in fatigue lives at the lowest applied nominal stress range in air.

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