CS Tie Plate Structure Materials Characterization Update
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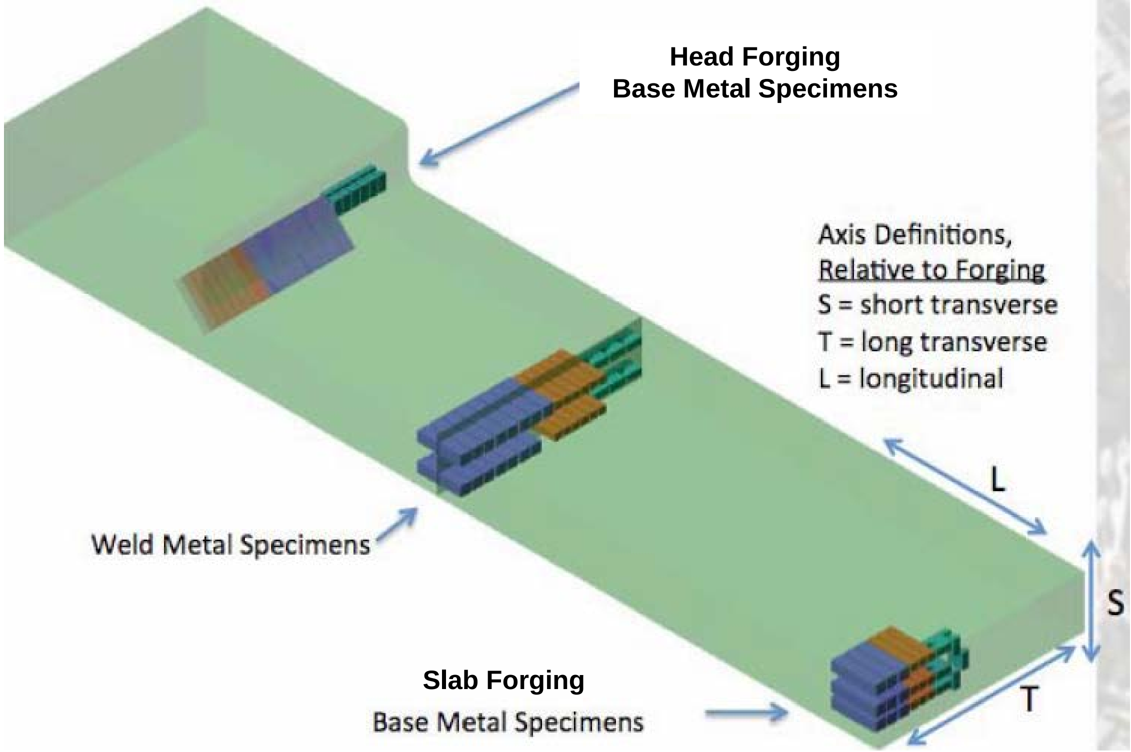
12/6/12



Testing has been performed on;
- Base metal (Nitronic 50 Forging)
&
- Weld metal (316LMN Filler GMAW process)

Types of Tests;
- Tensile 295 K, 77 K, 4 K
- Fracture Toughness, 4 K
- Fatigue Crack Growth Rate, 4 K
- S-n Fatigue Life, 4 K

CS Tie Plate Structural Requirements

The steel must have;

- Good Tensile Properties at 295 K and 4 K ,

YS > 380 MPa.

- Good 4 K Fracture Toughness,

Kic > 130 MPa*M^0.5

- **Adequate Fatigue Crack Growth Rate (related to Allowable Flaw Size)**

- **4 K Fatigue Life Requirements;**

  - **In-service Cyclic Stress – 20 x Design Life**

    142 MPa for 1.2 x 10^{-6} cycles

    OR

  - **In-service Design Life – 2 X Cyclic Stress**

    60,000 cycles at 284 MPa

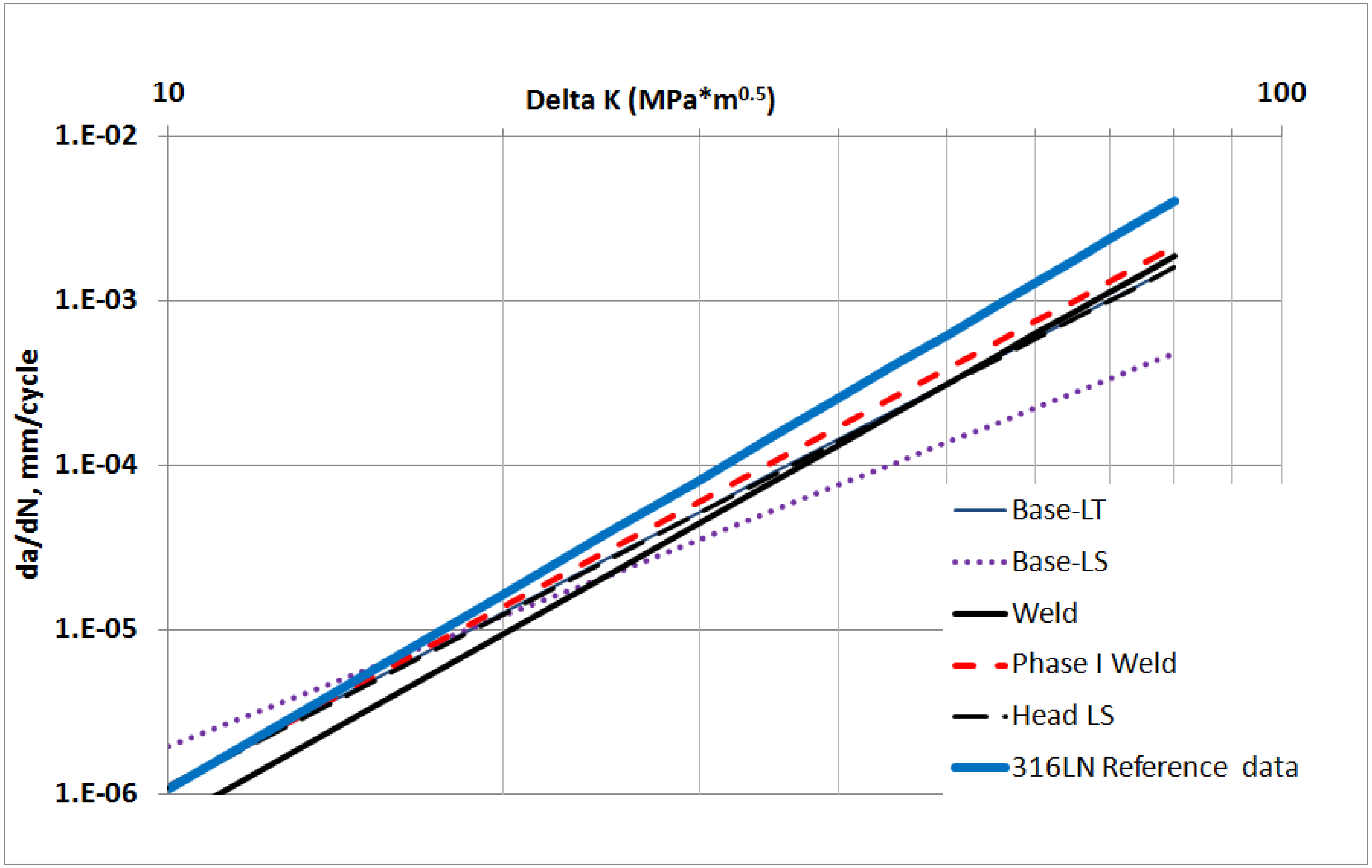
Results: Tensile and Fracture Toughness

Summary of Tensile and Fracture Toughness Test Results					
Property	**Temp.**	**Requirement**	**Head Forging**	**Slab Forging**	**316LMN Weld**
Yield Strength (MPa)	295	380	357	408	463
Yield Strength (MPa)	4	380	1287	1326	1200
Kic (MPa*M^0.5)	4	130	191	167	164

Conclusions: Tensile and Kic

- The 4 K Fracture Toughness and strength requirements are easily met.
-The 295 K yield strength of the Head Forging is below the requirement.
- Possible reasons for the lower YS of the Head vs the Slab
    - Microstructural variability (such as larger grains) in the thicker head forging
    - In Head forging, the tensile specimen axis is oriented at 45° to forge direction (FD), while the Slab forging specimens are parallel to FD. This is simply an observation not a conclusion.
    -More research is necessary to determine the average YS of the Head Forging in the axial or Forging direction

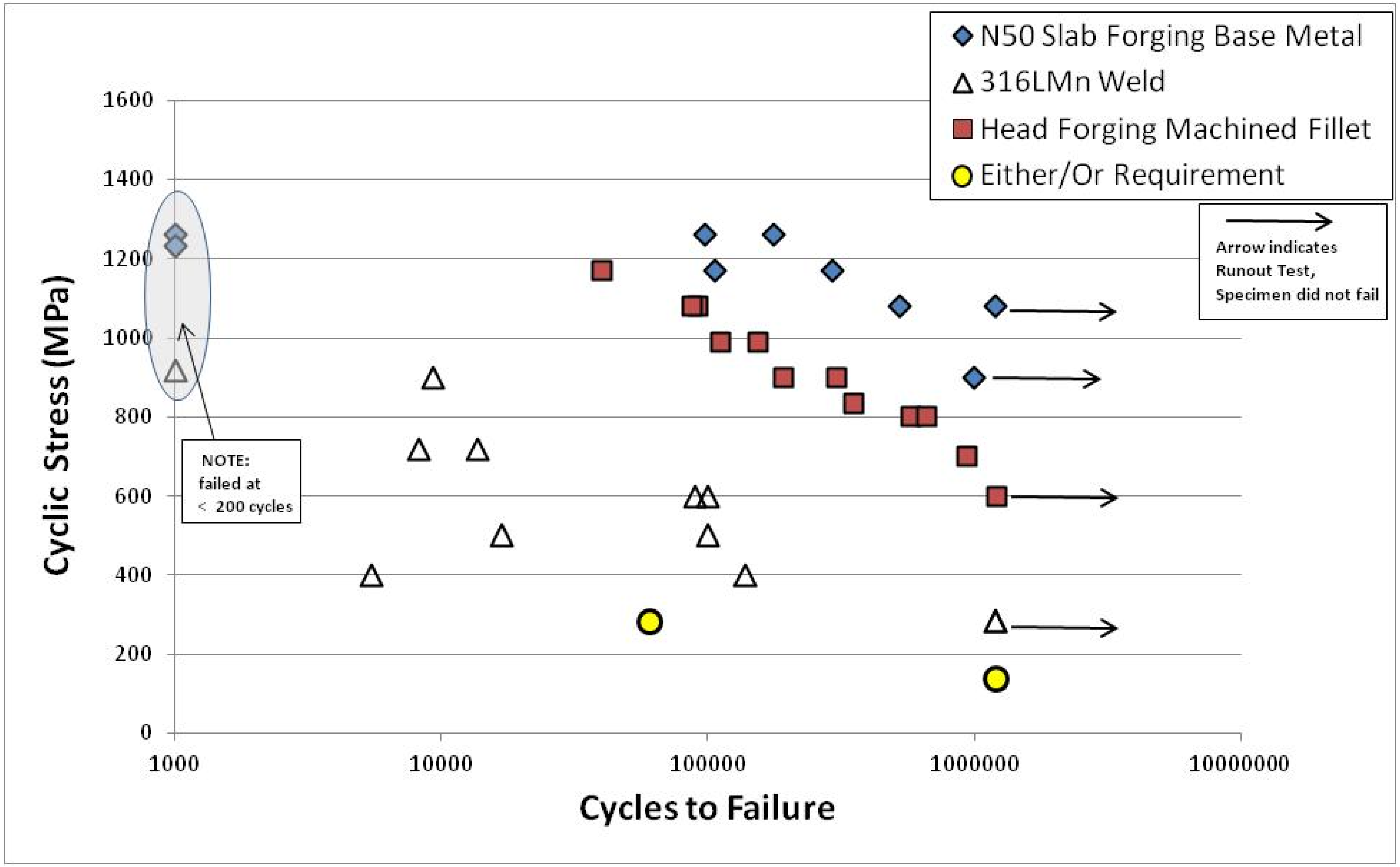
RESULTS: 4 K Fatigue Crack Growth Rate



CONCLUSIONS: FCGR Tests

1. The tie plate base metal and weld metal behave similarly.
2. At a given ΔK = 20 MPa*m$^{0.5}$, the N50 base and 316LMN weld metal have a slightly lower FCGR than an annealed 316LN base reference material.
3. The FCGR data of the base metal and weld can be used in the tie plate design to determine allowable flaw size and non-destructive inspection requirements.

Results: S-n Fatigue Test



CONCLUSIONS: S-n Fatigue Life Tests

1. Base Metal (Head and Slab forgings) data groups nicely and easily satisfies requirement.
2. The head forging fatigue strength is lower than the slab forging, this is consistent with tensile results
3. Weld metal exhibits lots of data scatter and barely satisfies requirement. More testing is recommended.
4. ***The reduced fatigue performance of the weld can be attributed to inhomogenous weld chemistry and microstructure at some of the weld pass surfaces (see following fractographs)***

Discussion: Weld Test Results

The 316LMN weld filler has excellent 4 K
- Tensile Properties
- Fracture Toughness
- Fatigue Crack Growth Rate (FCGR)

The low performance in S-n fatigue tests is surprising !

Fundamental differences in FCGR and S-n Testing

FCGR

-Intentional inclusion of a flaw (the notch)

-Crack growth rate is measured after a true fatigue crack has been initiated.

- Cyclic Stress intensity (ΔK) at crack tip is controlled during test (not runaway condition).

- Specimen is designed with long ligament to enable steady state crack growth.

-FCGR specimens were observed to have multiple voids on their fracture surface.

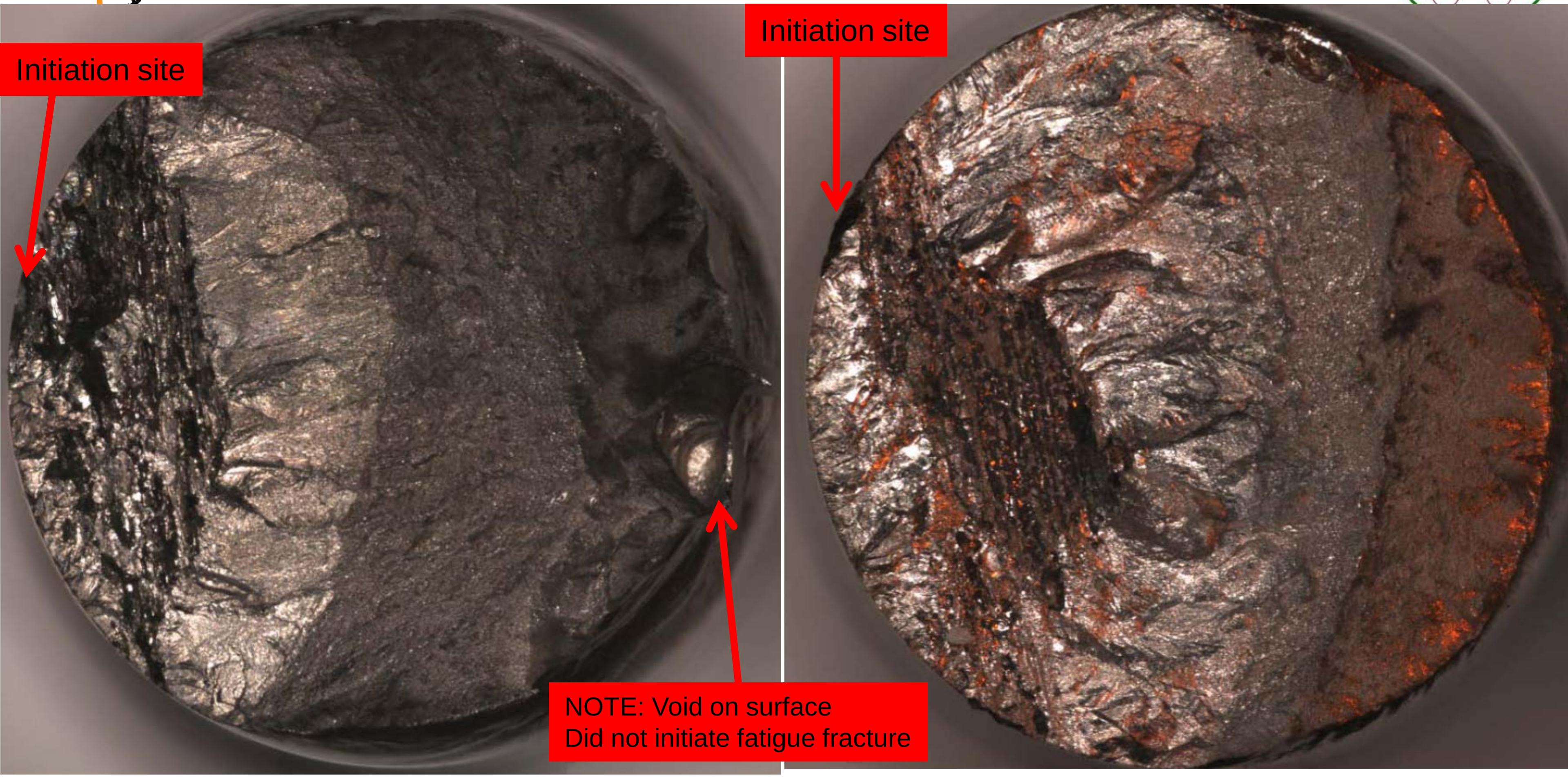
S-n Fatigue

-Gage length is polished to remove machine tool mark stress concentrators.

-Test essentially measures the number of cycles it takes to initiate a crack in the smooth specimen. Once the crack initiates the S-n test is in a runaway condition until failure.

-Three weld S-n specimens were observed to have voids on their gage length surface before testing and were tested anyway. The void appeared to initiate fatigue failure in one case

Results: S-n Fatigue Test



#28, σ = 720 MPa, n = 8216

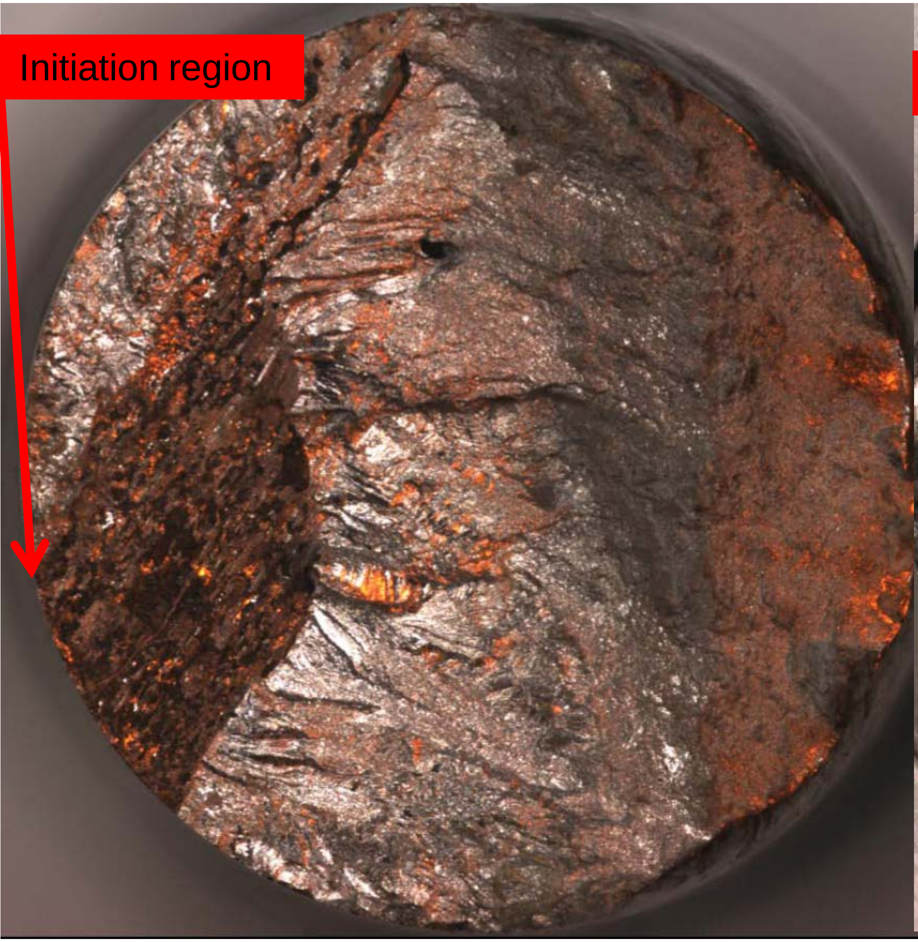
#29, σ = 500 MPa, n = 98,900

Observations:

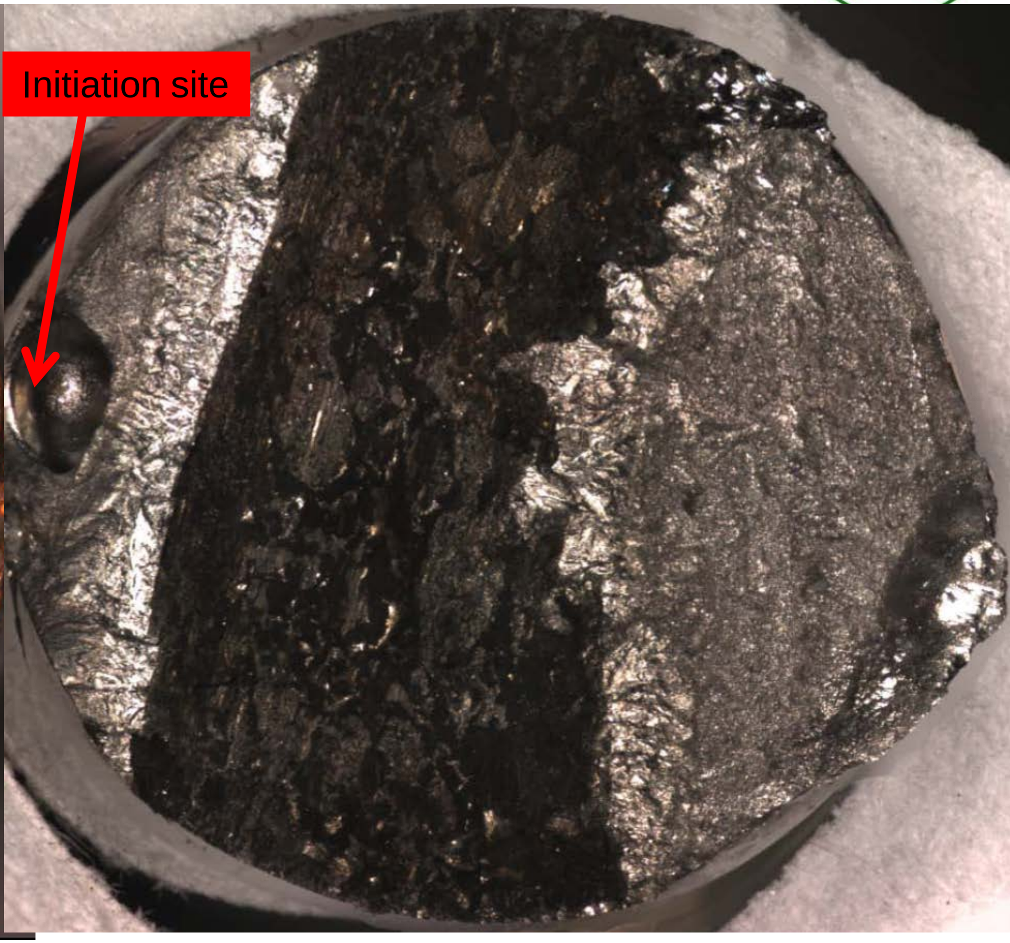
- Fatigue crack initiates on left side of photo and proceeds ~ ½ across before final tensile fracture.

-The fracture surface at initiation site has a dark, coarse, woody-textured appearance .

Results: S-n Fatigue Test



#30 , σ = 500 MPa, n = 16,862



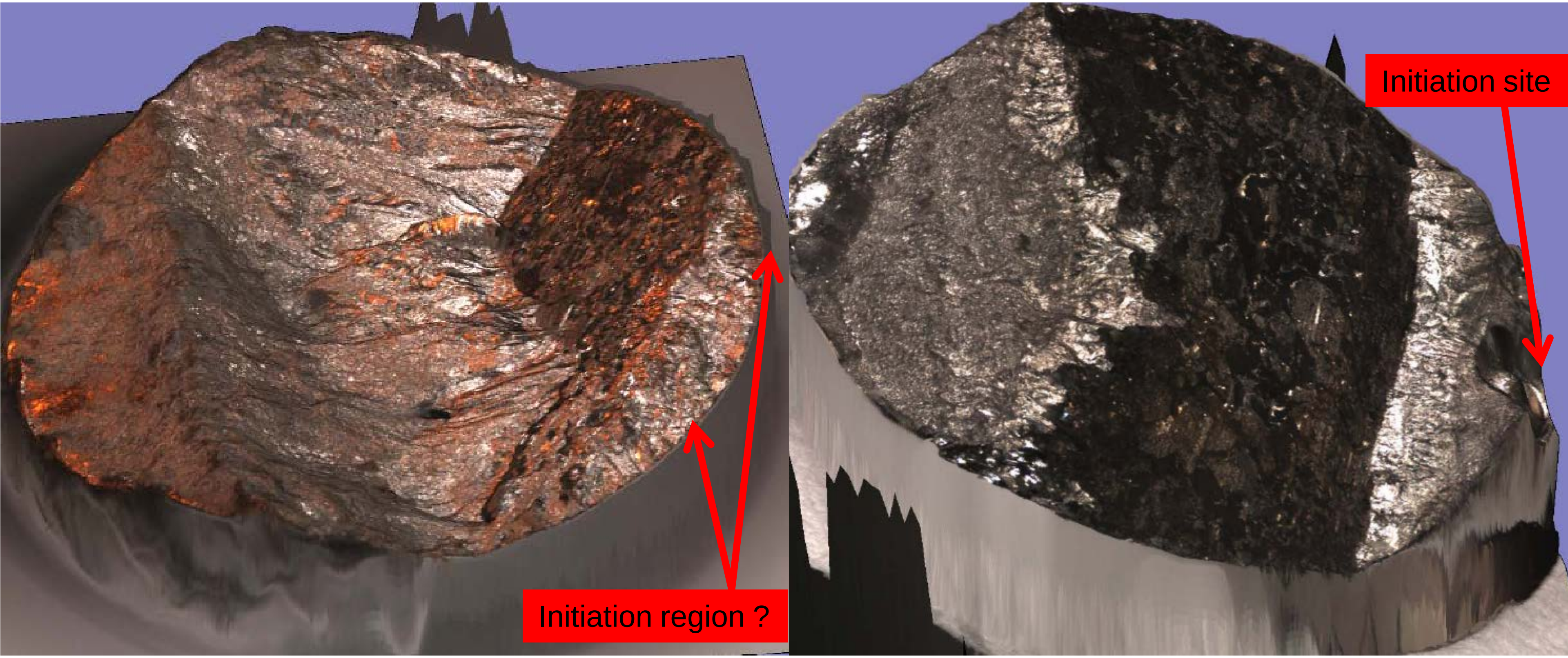
#33 , σ = 400 MPa, n = 5444

Observations:

- Fatigue crack initiates on left side of photo and proceeds ~ 3/4 across before final tensile fracture.
-The fracture surface exhibits regions with a a dark, coarse, woody-textured appearance
- Local compositional analysis (EDS) of the dark regions reveal high O2 and Mn content compared to nominal.

Results: S-n Fatigue Test

3-D Photos of fracture surface

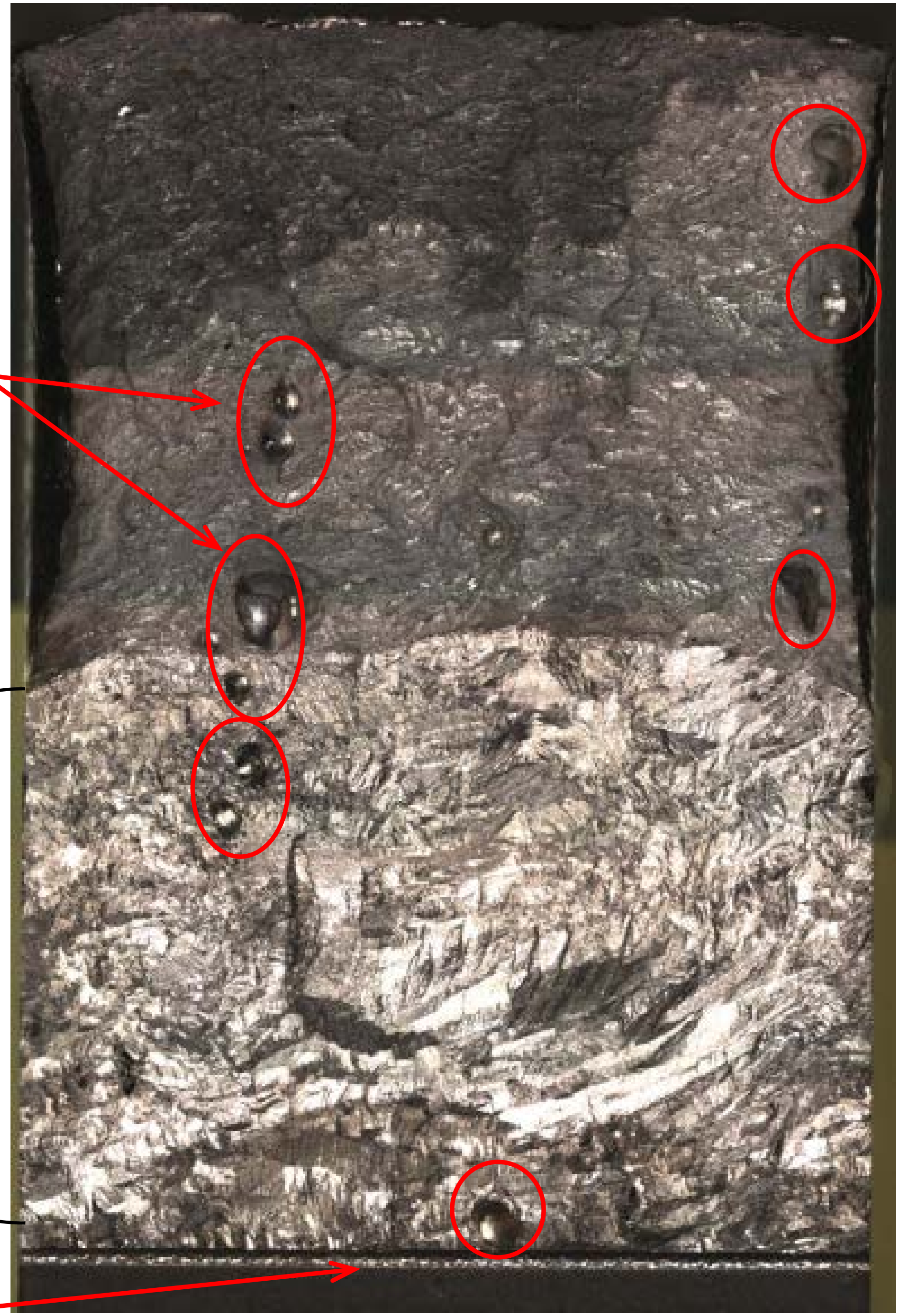


#30

#33

Notes;
- Orientation of these photos is ~180° to preceding photos of #30 and #33.
- Crack initiates on right hand side of photo and proceeds
~ ¾ across specimen before final tensile fracture

Dual purpose FCGR and Jic test Specimen #55 The CT specimen is cracked open to reveal a fracture surface that exhibits multiple voids



FCGR Region

Machined Notch Tip

Crack Direction

Discussion: Weld Test Results

Observations:

- The fracture plane of both specimens is parallel to the weld pass direction.
- Of (6) Weld CT specimens tested, only (**1**) ***exhibited*** regions of the dark colored, woody-textured oxidation on the fracture surface (Spec.#53) .
- Of (12) S-n Fatigue specimens tested, only (**1**) specimen ***did not exhibit*** the dark colored, woody-textured oxidation on the fracture surface

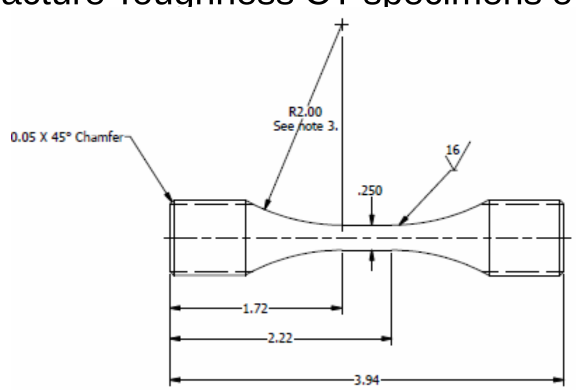
Possible explanation

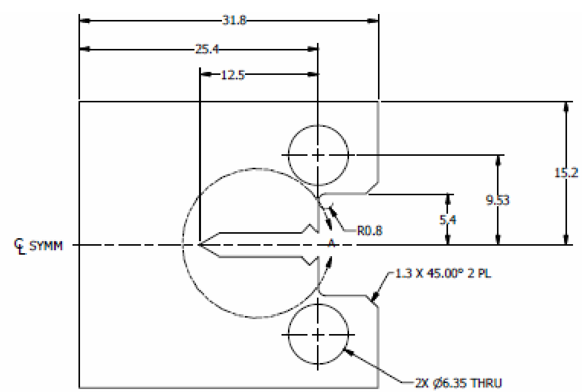
-The CT fracture plane is defined by the notch location. Therefore we evaluate of a slice of material on a predetermined plane that may or may not include a weld pass interface surface.

-The S-n Fatigue specimens has a 13 mm long gage length along which the fracture plane can preferentially initiate. The 13 mm length likely contains a weld pass interface surface.

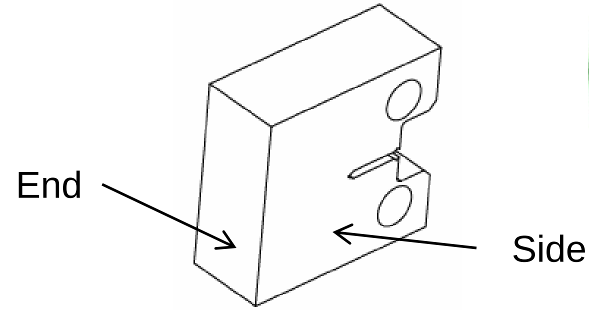
-Comparing the relative volume of material evaluated in the 2 different test a 1 mm thickness is assigned to the CT fracture surface plane.

-The (12) S-n fatigue tests evaluate approximately 5 X the volume of material that the (6) Fracture Toughness CT specimens evaluate.





Weld Metallography -½ of CT Specimen # 53 is polished and etched to reveal weld microstructure



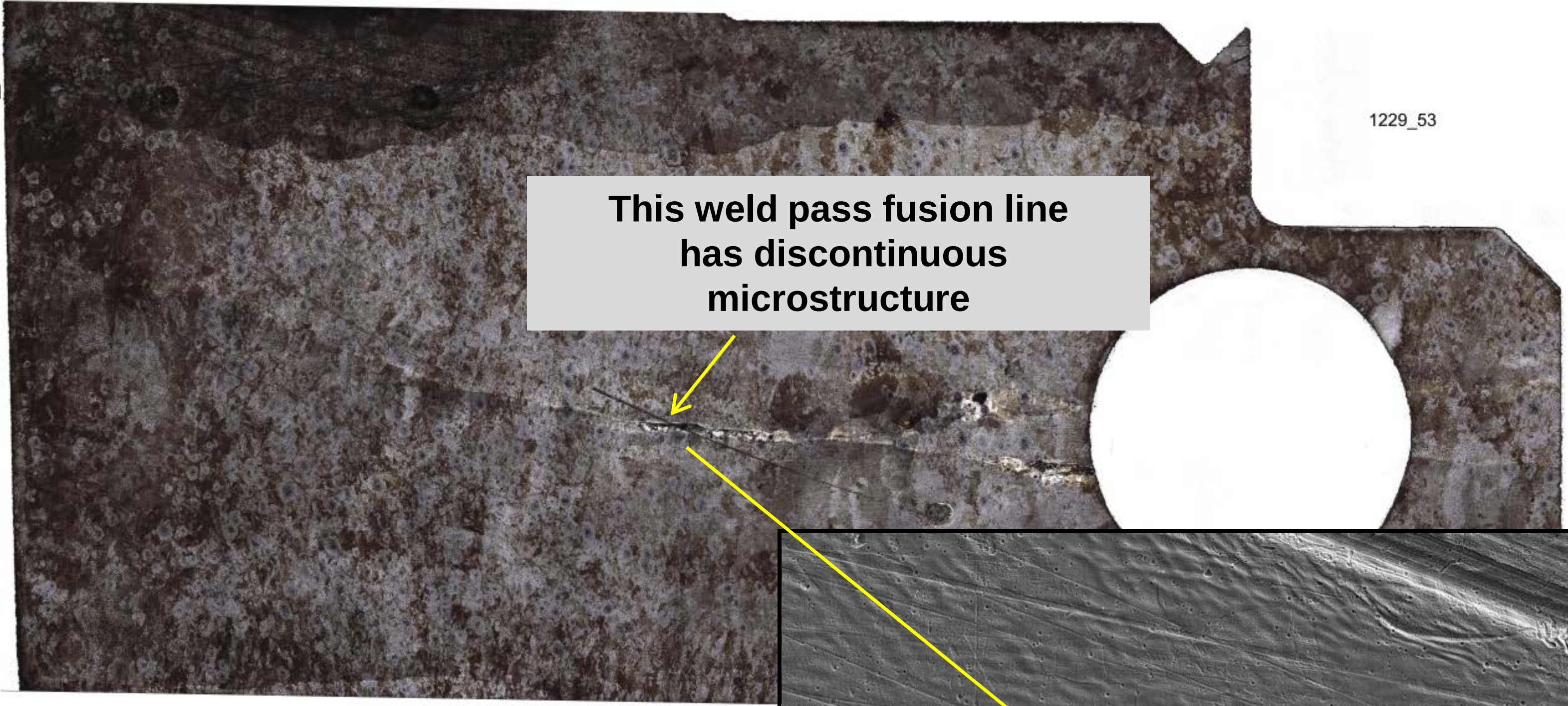
End View

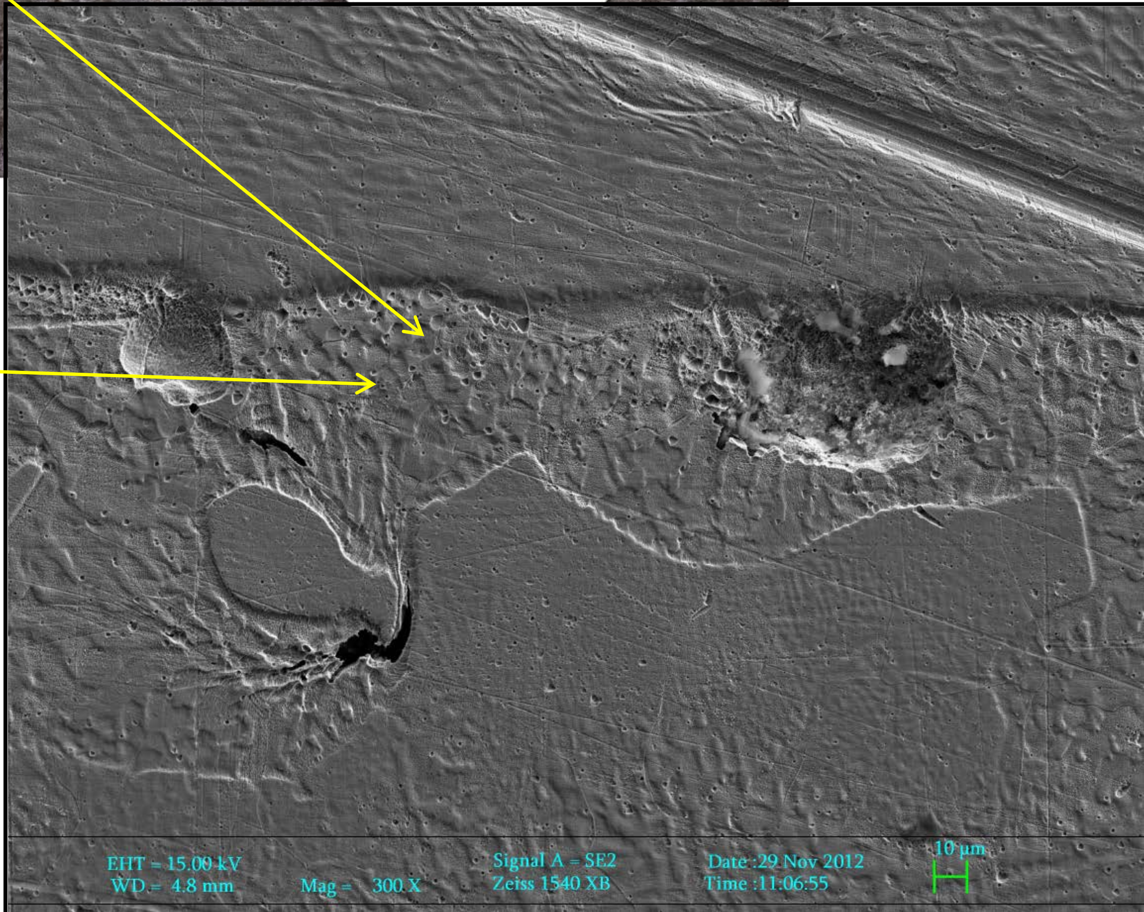
Side View

Weld Pass Direction

Weld pass Interface Fusion Lines

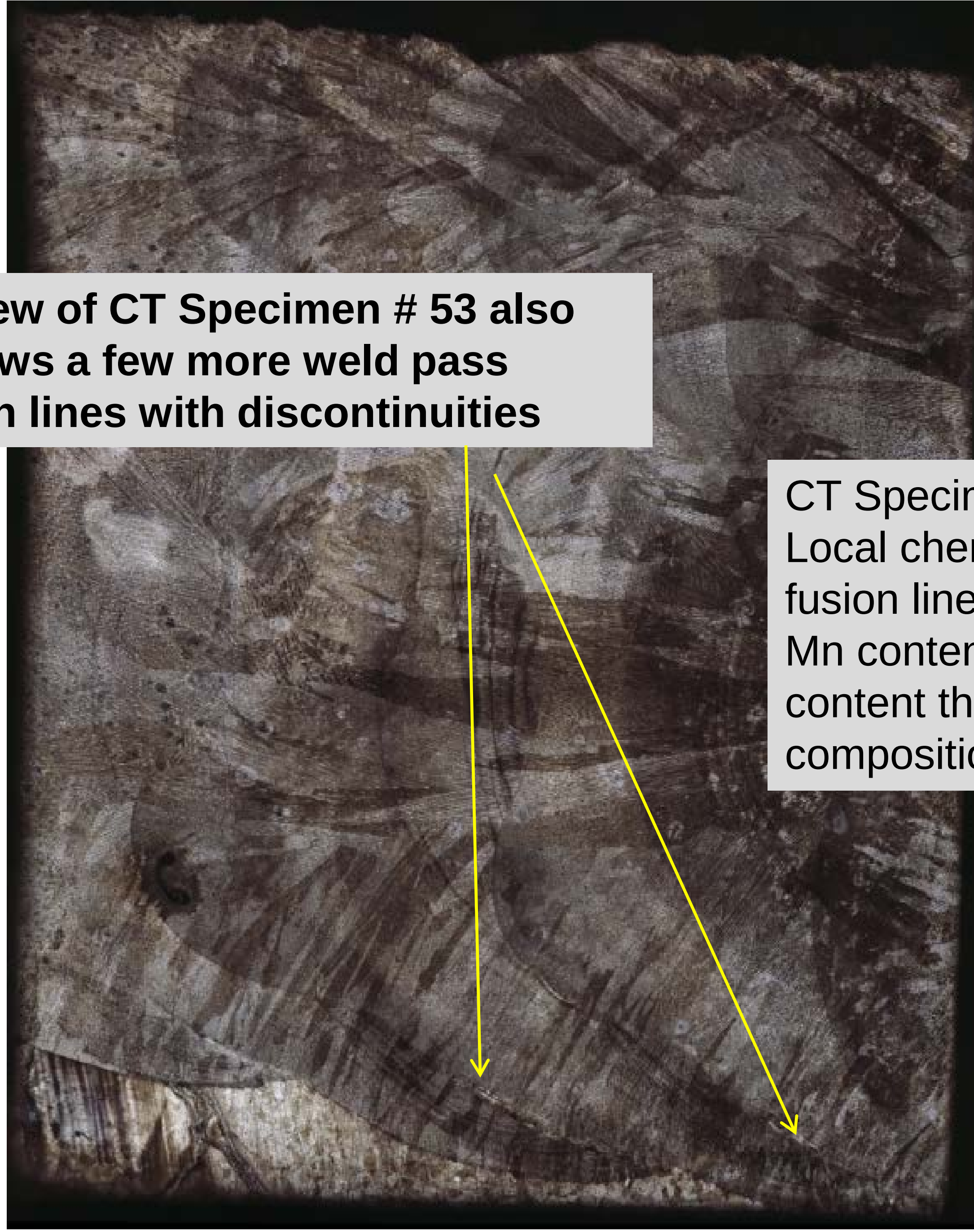
This weld pass fusion line has discontinuous microstructure





CT Specimen #53
Local chemistry mapping indicates the fusion line is higher in Mn content and lower in Fe content compared to the nominal weld composition.

End View of CT Specimen # 53 also shows a few more weld pass fusion lines with discontinuities



CT Specimen #53 end view
Local chemistry mapping of the fusion line indicates its higher in Mn content and lower in Fe content than the nominal weld composition.

Analysis of S-n Fatigue Spec. #25's fracture surface, A dark woody textured region of the fracture surface is viewed at higher magnifications

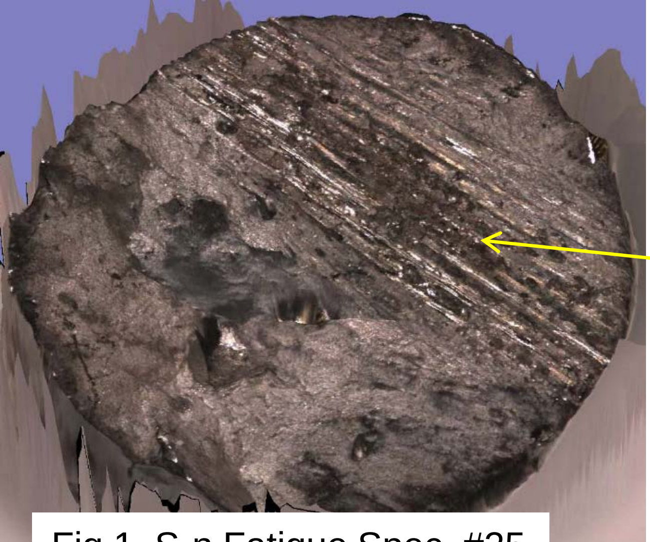


Fig 1. S-n Fatigue Spec. #25
Macro of fracture surface

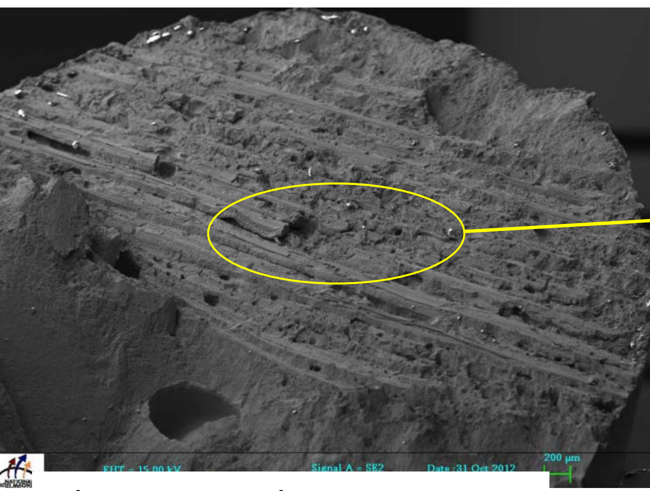


Fig 2. S-n Fatigue Spec. #25
SEM of fracture surface

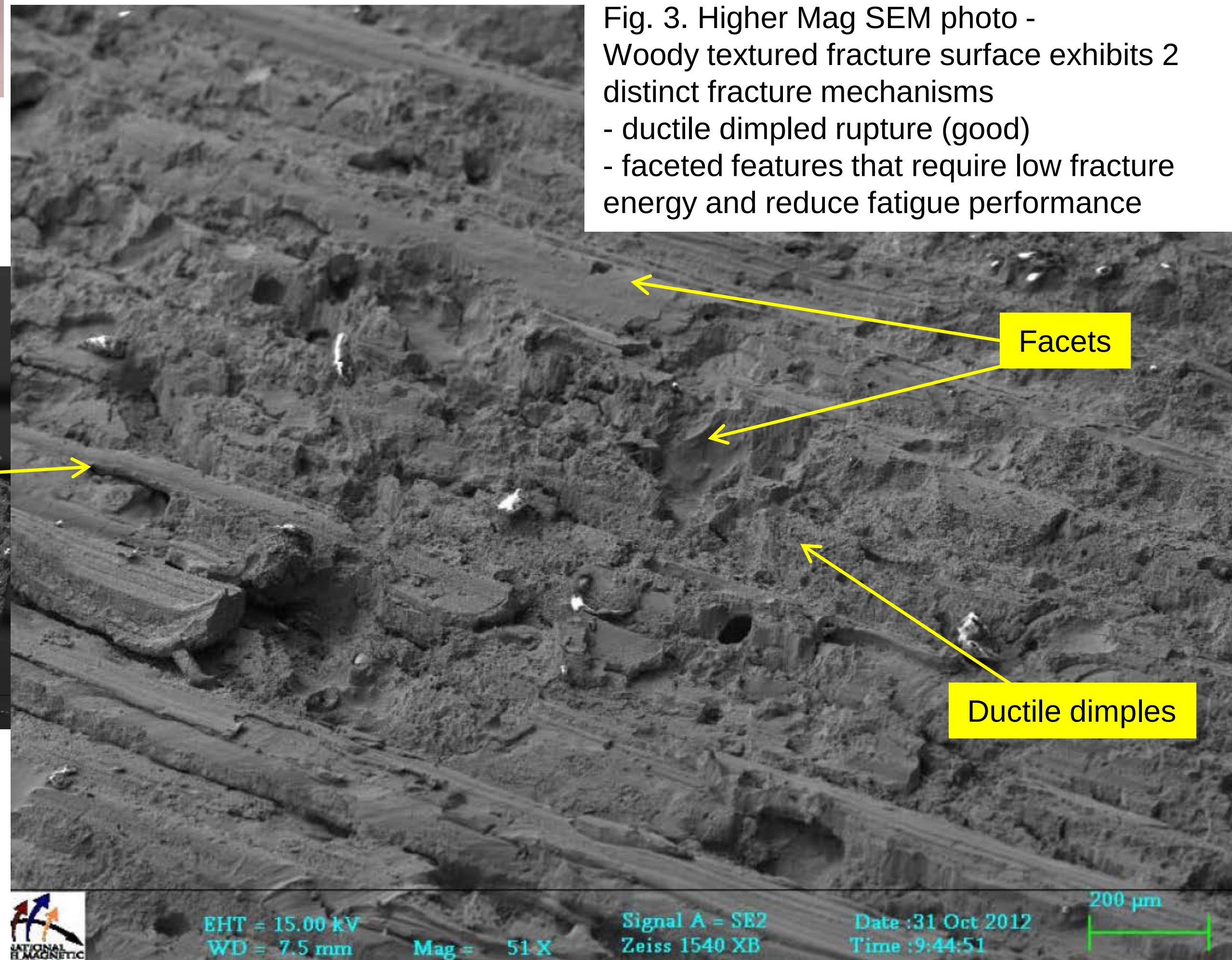


Fig. 3. Higher Mag SEM photo -
Woody textured fracture surface exhibits 2 distinct fracture mechanisms
- ductile dimpled rupture (good)
- faceted features that require low fracture energy and reduce fatigue performance

CONCLUSIONS

1. The N50 forging base metal exceeds the mechanical property requirements for the CS Tie Plate application with one exception. The room temperature yield strength of the head forging (357 MPa) is slightly below the 295 K yield strength requirement of 380 MPa.

2. Although the 316LMN weld filler metal meets all the mechanical property requirements for the application, there appears to be an issue with weld quality.

   a) Metallographic evaluation of the weld microstructure reveals inconsistent microstructural appearance and chemistry at various fusion lines between weld passes. This observation may be related to the localized coarse fracture surface regions observed on S-n fatigue specimens.
   b) Additionally the weld metal appears to have a significant void density , a quality issue that may not be covered in the quality control specifications. The concern is that although the void size (1 to 2 mm dia) is well below the allowable flaw size, too many of them may link up to act as one larger than acceptable void.

3. Speculation- ***if*** CT specimens were machined such that the notch tip and subsequent fracture plane were coincident with a low quality weld pass interface, ***then*** the FCGR and Kic would probably be inferior (and maybe unacceptable) compared to the data generated in the study thus far.