X-ray Inspection of Orbital Tube Weld for Detection of Crack-like Flaws
CCP/NESC POD Study

NESC NDE TDT Meeting

April 15, 2021

NASA Project Meeting Participants

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NASA-STD-5009 Standard Radiography Flaw Size for Cracklike Flaw

- Issue: Detection of small cracks by X-ray is NOT supported by NASA-STD-5009. There is uncertainty in reliability of detection of small cracks in Orbital Tube Welds (OTW)
  - Crack opening of small cracks is smaller and cracks with smaller crack opening may have lower POD.

U. S. CUSTOMARY UNITS (inches)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a*	Crack Dimension, c*
Radiographic NDE				
Open Surface	t ≤0.107 t > 0.107	PTC PTC Embedded	0.7t 0.7t 2a=0.7t	0.075 0.7t 0.7t

- Minimum Crack length of 0.150” for the Standard radiography crack size
- Minimum length may be too large for thin wall (t < 0.107”) parts
- Metallic tubing used on spacecraft and launch vehicles generally have thinner wall thickness including in weld areas
- Moreover, original Standard x-ray qualification was performed in single wall configuration
  - NESC Bulletin 19-02 acknowledges that there may be increased risk to meeting 90/95 POD/Conf. for double wall x-ray.
  - This study intends to make progress towards mitigating the risk for OTW x-ray inspection
- CCP program directed CCP M&P/Fracture/NDE to undertake x-ray crack detection POD study to address the issue for orbital tube weld (OTW) inspection for tube specifications used in the CCP program

Objectives

- Determine smallest crack opening (for a/t = 0.7 and a/c = 1) cracks that can be detected reliably using typical X-ray set-up used by NASA
  - Thin wall and thick wall tubing
  - Generate fatigue crack opening and dimension statistics for thin wall and thick wall specimens
  - Down-select x-ray set-up that are likely to be used in production and collect flaw detectability data on these set-ups
- X-ray set-up validation for detection of cracklike flaws
  - Essential input variables total unsharpness, contrast sensitivity, detector response, flaw size (length x depth), crack opening, part thickness, part configuration (double wall), x-ray angle flaw resolution ratio, weld versus parent material
  - Output measurements on calibration flaws and real flaws: CNR, measured indication resolution ratios.
    - Develop transfer between PFIB flaw and fatigue crack
    - Verification of set-up on calibration reference using relevant measurements that relate to POD and POF.
  - Above approach seeks to qualify requirements in addition to NASA-STD-5009 Standard x-ray requirements to provide confidence in Standard x-ray flaw size. This is a challenging task. If Standard x-ray flaw detectability is not demonstrated adequately with additional requirements, those flaws with desired crack openings will be validated as Special x-ray techniques.
- POD Demonstration
  - If adequate number of flaw specimens for target size crack with target size crack opening and corresponding x-ray set-up that can detect these flaws with high reliability is devised than POD demonstration testing will be undertaken
  - Binomial Point estimate POD analysis for hit-miss x-ray flaw detectability data
- Explore other NDE methods for crack cases where X-ray techniques cannot detect cracks of desired crack opening and size.
  - Eddy current testing (LaRC EC scanner can be used for small samples using lab EC scanner
  - Ultrasonic testing ???
    - Currently used for pipe butt weld inspection

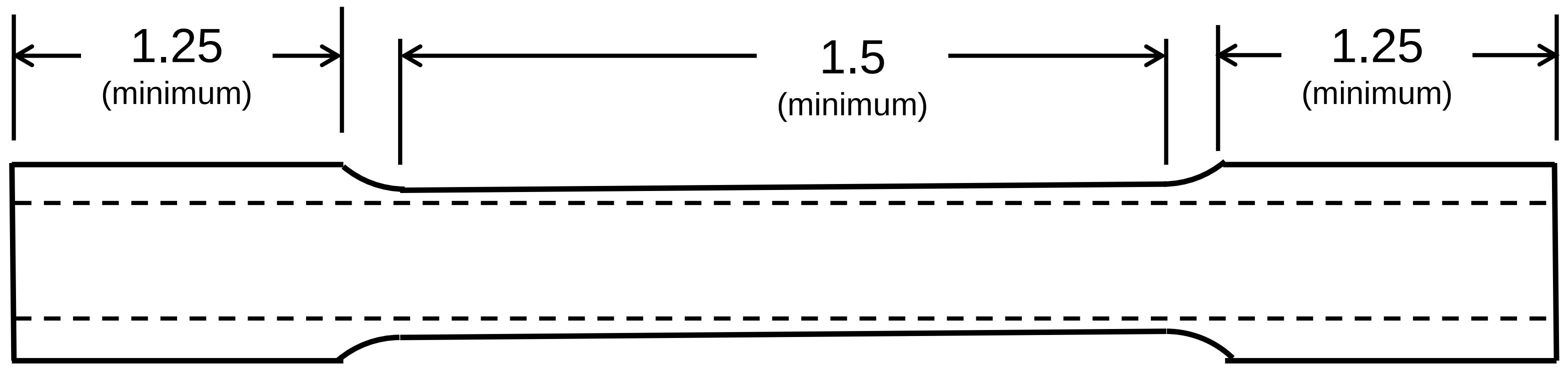
NDE Testing Flaw Specimens and Flaw Specimen Manufacturing

- Fatigue Crack Specimen Manufacturing and Manufacturing NDE/Metrology (NESC, LaRC, GSFC)
  - Target Size Flaw and Materials
    - Fatigue crack was chosen for the specimens as the **“worst case”** for flaw detectability. Fatigue cracks can initiate/grow in service due to cyclic stress in service
    - Target crack: Circumferential-radial crack. Approximate 2:1 aspect ratio that is at most .7t deep in final configuration. Crack opening: As obtained by controlled manufacturing process described below
    - Tube Materials: Ti, Stainless Steel and Inconel. Thin wall ~ 0.028”, Thick wall = 0.060”
    - Crack specimens will be used for NDE primarily but some specimens will be used in destructive fractography testing
  - Tube Necking (NESC LaRC and GSFC)
    - Machine tube specimen to hour-glass (dog-bone) shape for reducing stress concentration at grips and allow crack initiation at Plasma Focused Ion Beam (PFIB) notches where stress concentration is high
    - Machine to a uniform tube thickness (target wall thickness + PFIB notch Depth + margin)
    - Wire EDM is used for necking. Tube spins in the EDM set-up.
  - PFIB Notch Manufacturing/Pre-cracking (NESC LaRC)
    - PFIB notches are used to initiate cracks using uniaxial tension fatigue load
    - Uniaxial fatigue fixture available at LaRC for growing cracks from notches, and can track crack growth on surface with optical microscopy.
  - PFIB Notch Removal, Additional Fatigue Cycles and NDE (NESC LaRC)
    - After crack grows from both ends of the PFIB notch to desired length, PFIB notch is machined away to render tube wall thickness to target size for wall thickness
    - EC NDE is performed. If EC reading is less than expected EC reading, load cycling is continued to selected number of cycles and EC readings are taken to assess flaw size indirectly. Optical microscope is used for crack length measurement while tube specimen is under tension. Also SEM surface measurements are taken to measure crack length and crack opening at many places along crack length
    - Specimens are x-ray CT scanned to image crack profile and measure depth

IN625 Tube Crack Fabrication Process

Technical Lead: Dave Dawicke (AS&M)
NESC Lead: Heather Hickman (NASA NESC)

Step 1: Machine Dogbone Coupons

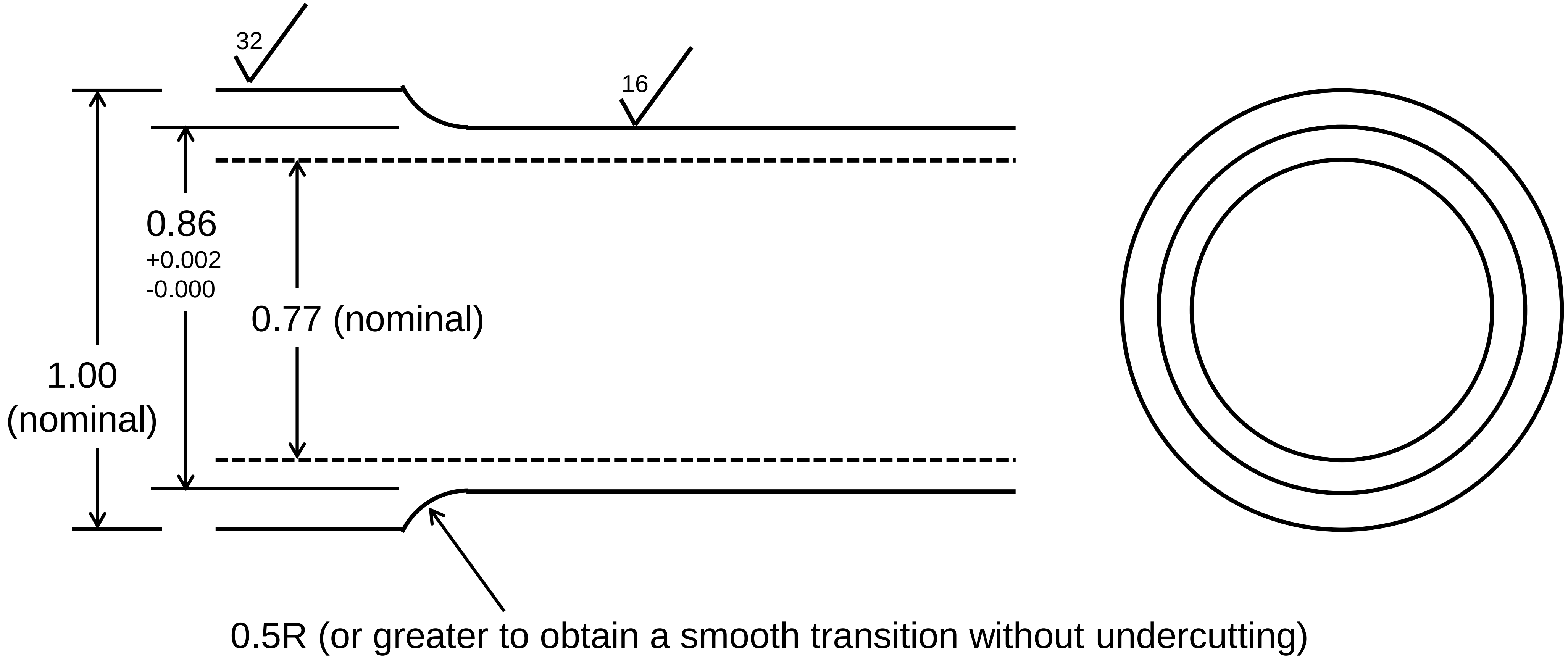


Notes:

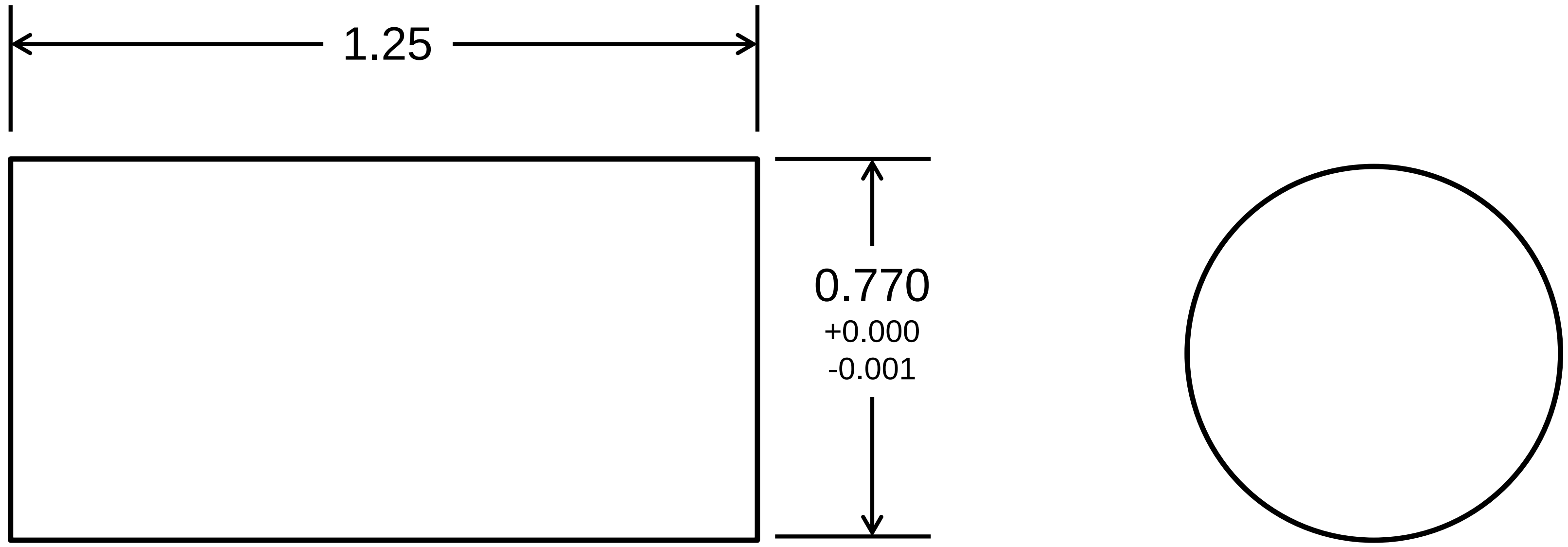
1. Machine 6 coupons
2. Reduce the two 1.25 inch grip sections evenly as needed for the radius region
3. Diameter details on the next page
4. All dimensions in inches

Step 1: Diameter Details

Notes:
1. Machine the gage section and radius from the stock tubing
2. Do not undercut the radius
3. All dimensions in inches



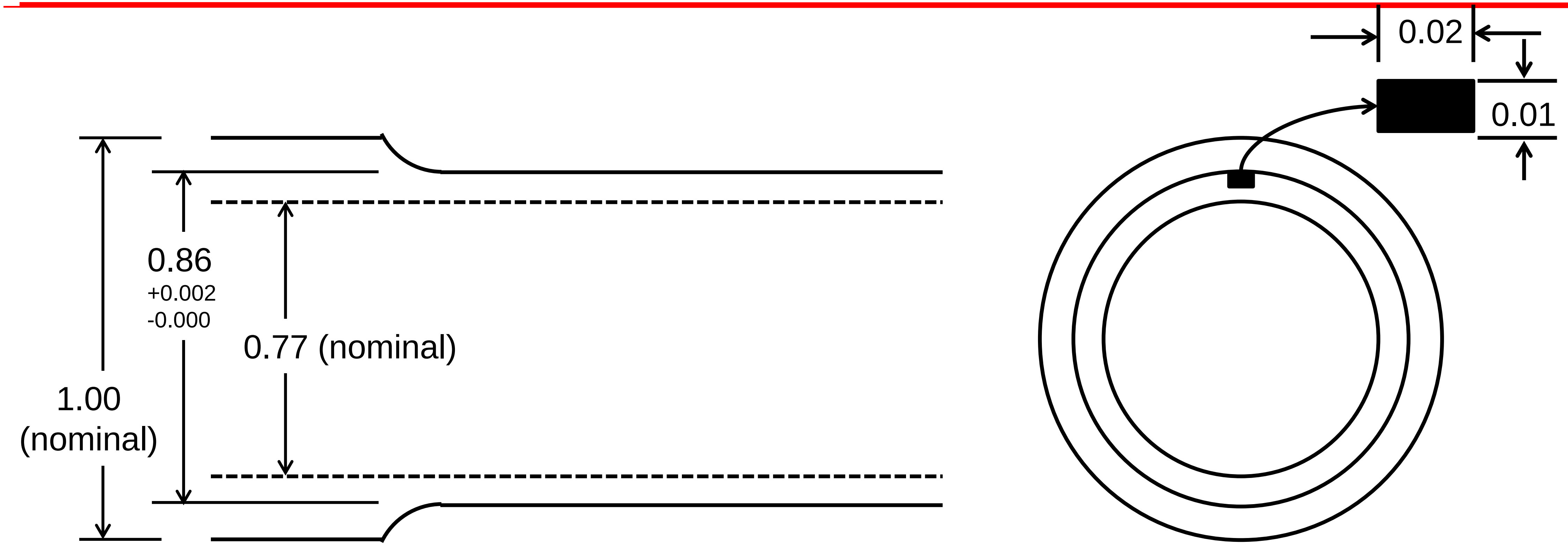
Step 1: End Plugs



Notes:

1. Machine 12 plugs
2. Stock IN625 or similar round is acceptable
3. The plugs must be a tight fit into the ends of each coupon to prevent distortion during gripping of the ends
4. All dimensions in inches

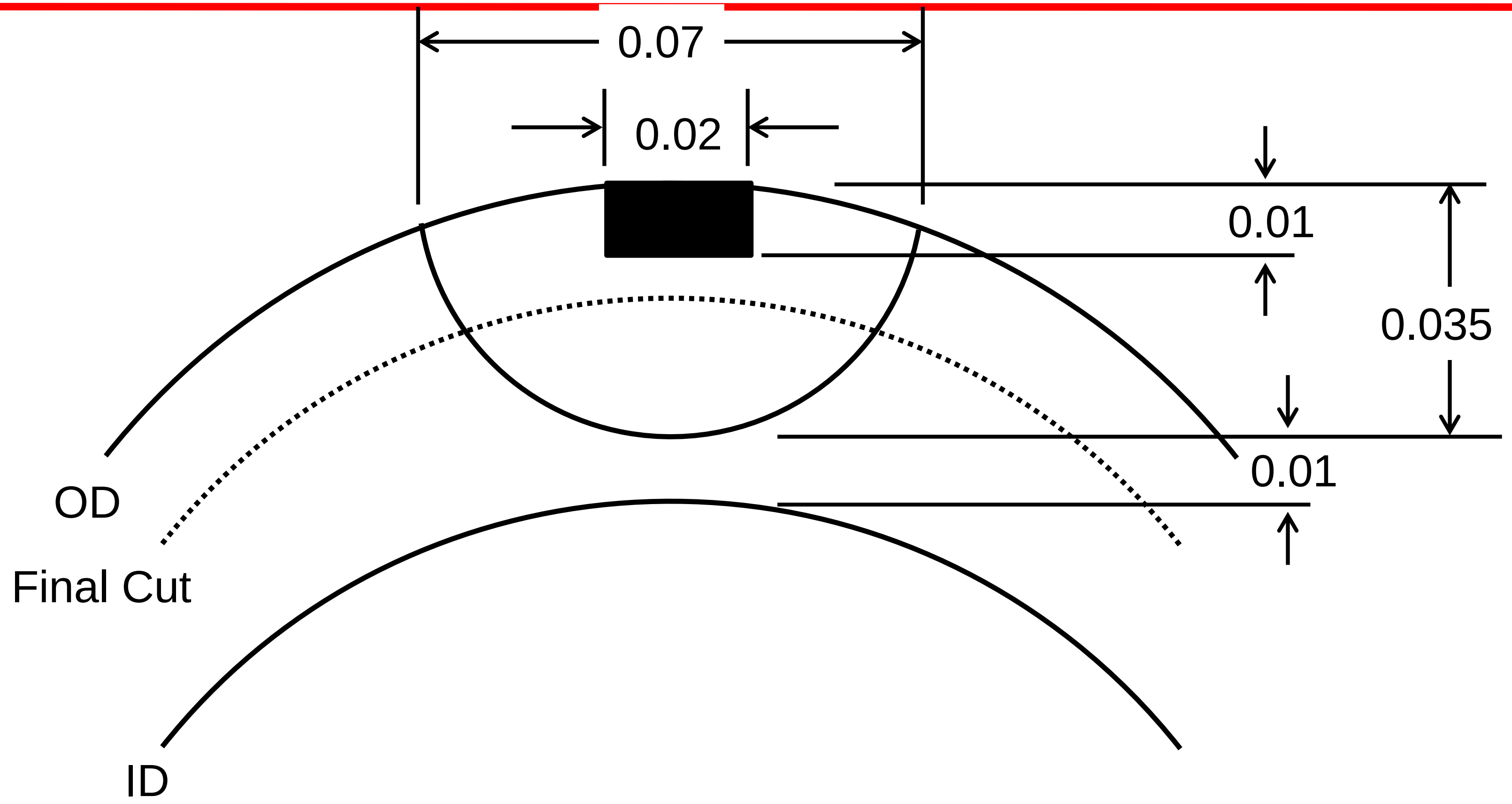
Step 2: Laser Notching



Notes:

1. Add 1 notch to the center of the gage section
2. The length of the notch should be in the circumferential direction
3. All dimensions in inches

Step 3: Precracking

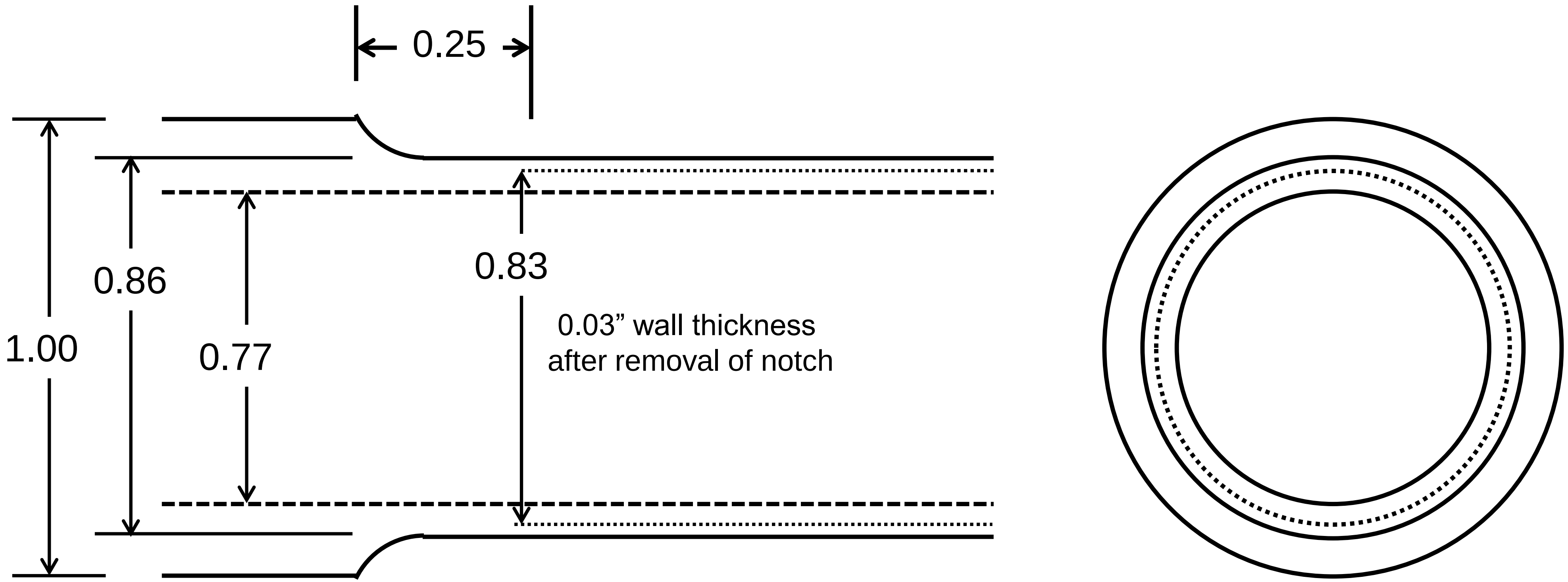


Notes:

1. Precrack the notches at a stress of S = 80,000 psi (<0.8 x Sys)
2. Cycle and optically measure the surface until a length of 2c = 0.07 inches is reached
3. Removing 0.015" of the wall thickness should remove the notch and leave a crack of depth a ~ 0.02" or ~0.7t
4. All dimensions in inches

Second Thickness Reduction

Machine down the wall thickness in the gage section to remove the laser notch and achieve a wall thickness of 0.03”

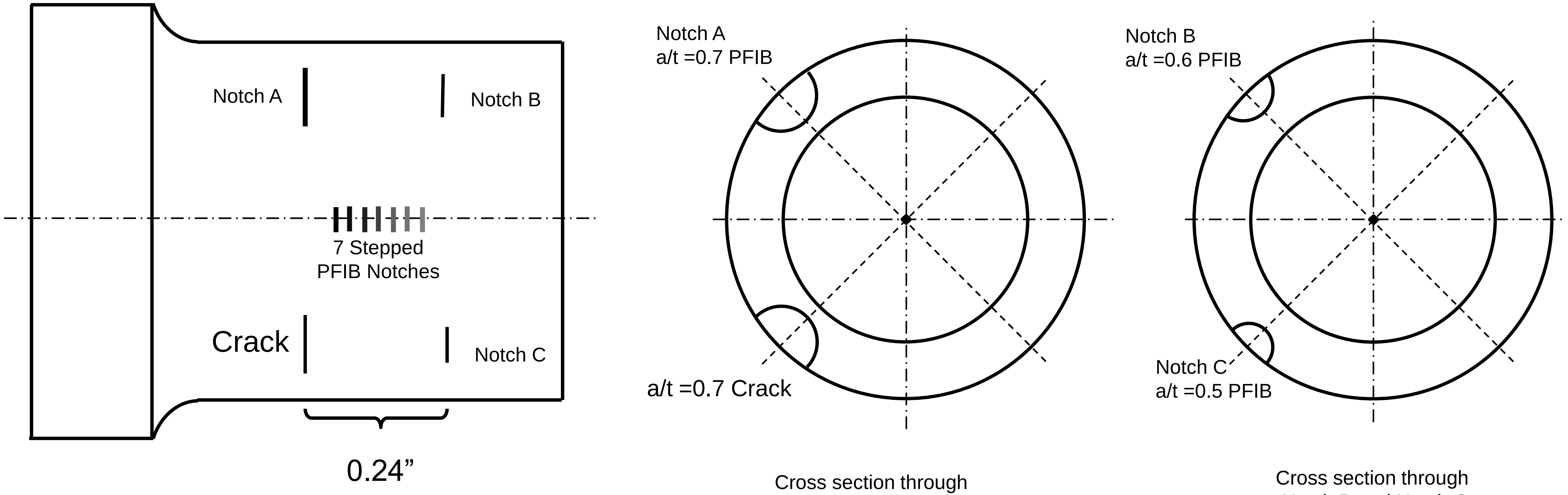


1.00 – nominal outside diameter of tube
0.86 – machined down diameter in the gage section
0.83 – gage section diameter after notch removal
0.77 – nominal inside diameter of tube

Other Test Specimens

1. Specimens selected from fatigue crack specimens for destructive fractography testing to study crack gap morphology in depth direction
2. Calibration Reference Standard
   - Contains a fatigue crack and many PFIB notches (some thumb nail and some in rectangular depth profile)
3. Weld and non-weld flaw/noise response reference standard
   - OTW welded specimen with PFIB notches located in weld and non-weld areas along a chosen axis
4. Welded tube specimen for residual stress measurement
   - OTW welded specimen. As welded.
   - Intended for destructive testing at GSFC

Calibration Specimen with PFIB Notch in-line with Crack

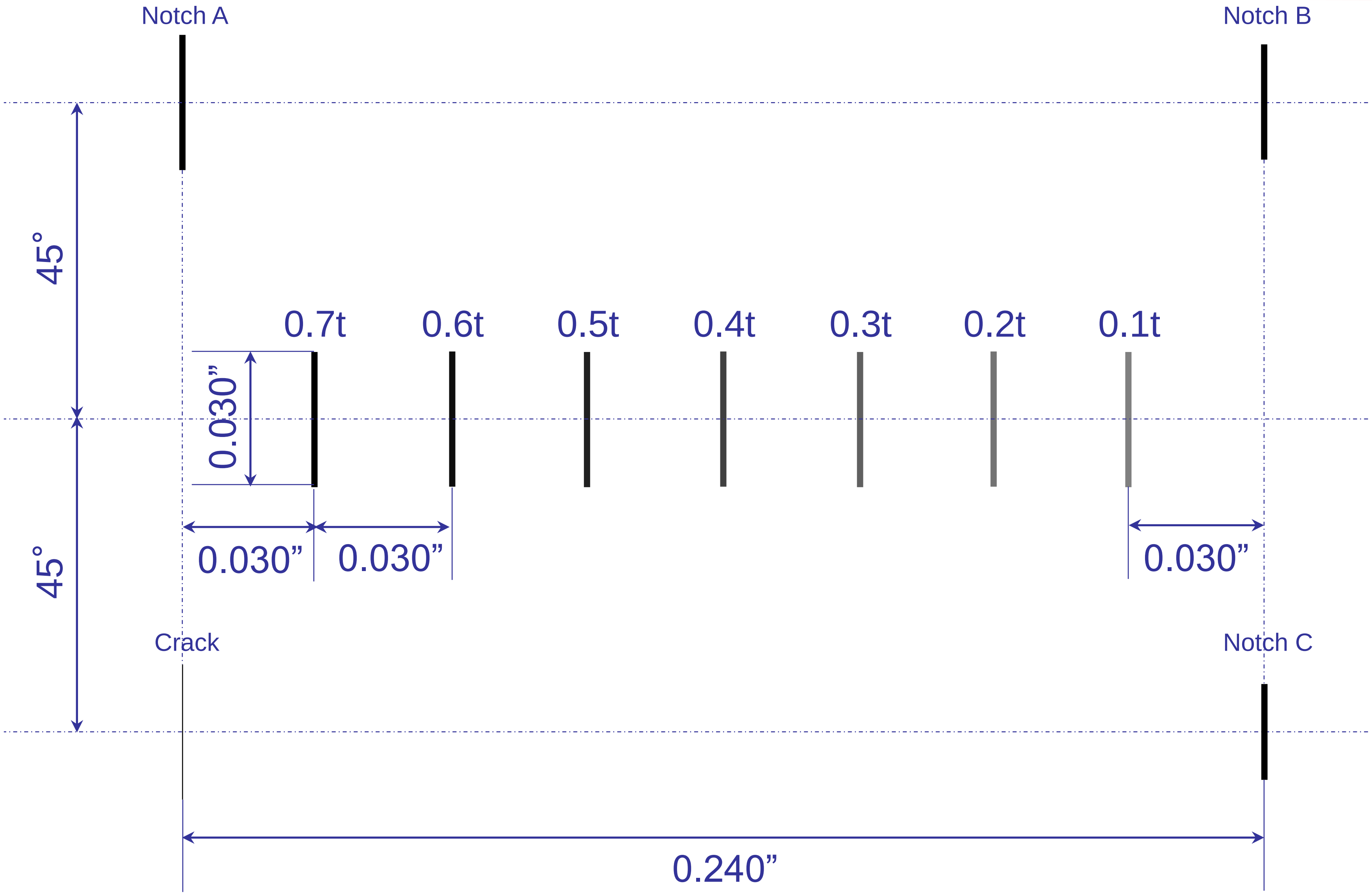


Cross section through Notch A and crack

Cross section through Notch B and Notch C

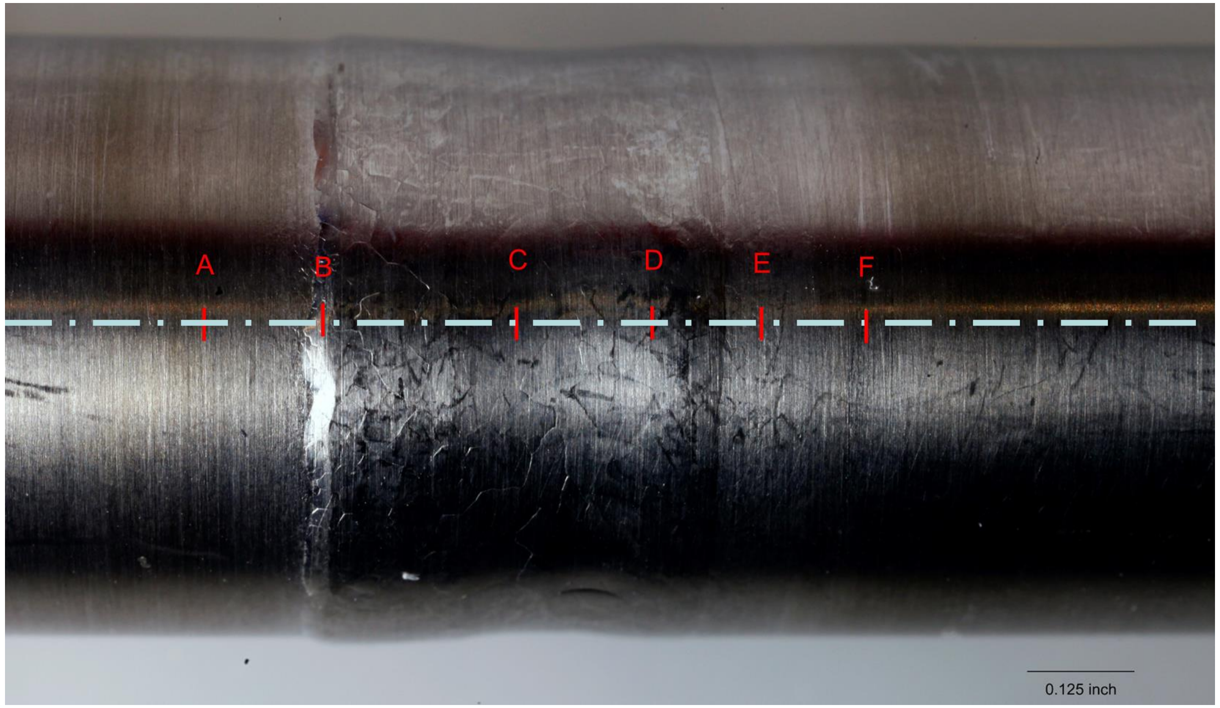
Note: The configuration avoids overlapping of flaw images. All flaws can be imaged in one 45 deg. rotation set-up either in single or in double wall configuration.

7 Stepped PFIB Notches



Notch width for all notches = 0.001"

Welded Tube Notch Specimen

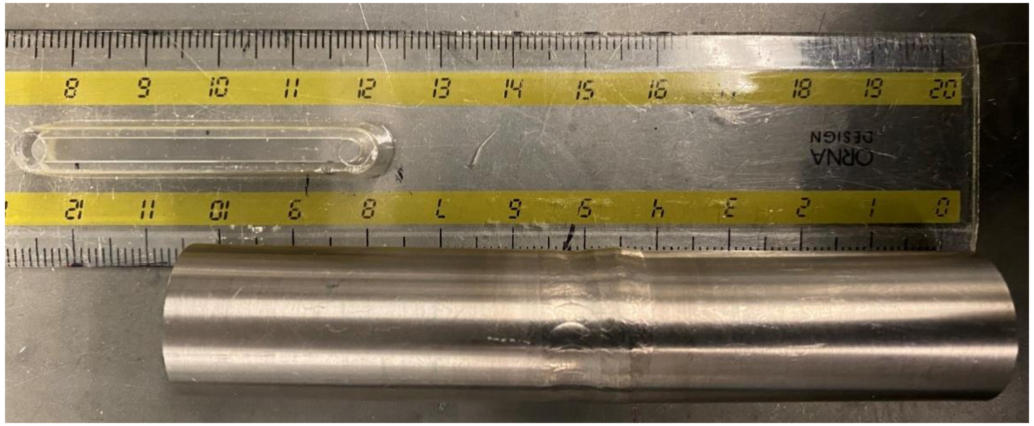


Notch ID	Description
A	Parent material
B	Weld toe
C	Weld center
D	Weld thick region
E	Heat affected zone
F	Parent material

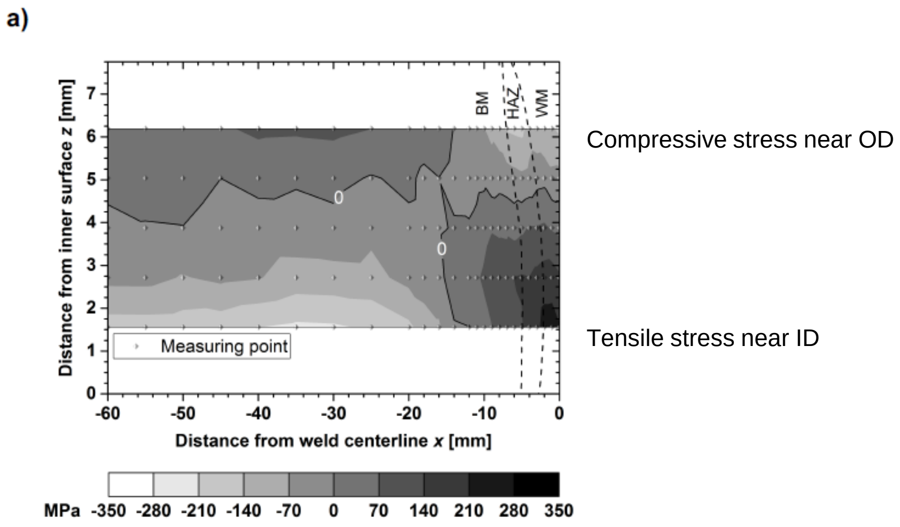
Notes:

1. Same size for all notches. a/t = 0.7. t = wall thickness of parent material. a/c = 1.
2. Notches located on a longitudinal axis.
3. Notches in circumferential direction
4. 1 each for A, B, C, D, E, and F

Welded Tube Residual Stress Specimen



Axial Residual Stress in Pipe Butt Weld



Ref.: Study on the residual stress relaxation in girth-welded steel pipes under bending load using diffraction methods

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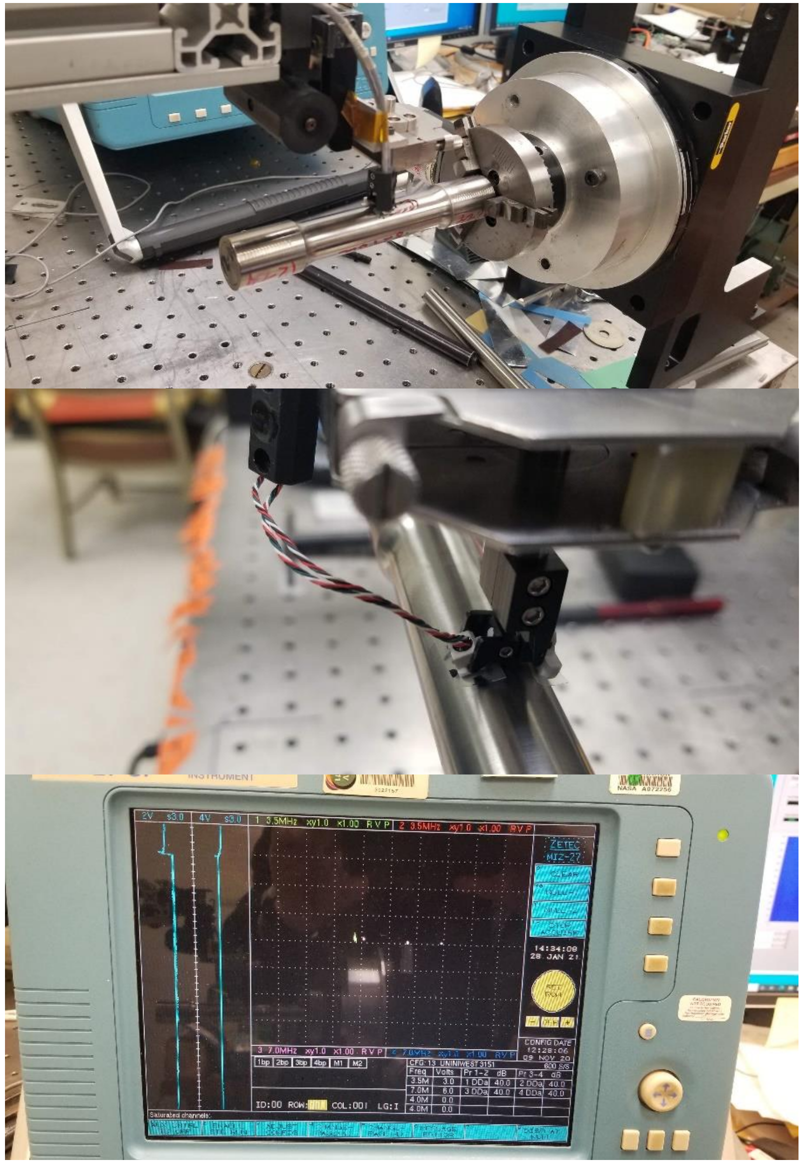
HH/DD/BB

Need to investigate whether residual stress affect detection of cracklike flaws?

Actions and Activities

- LaRC to provide all metrology (Optical microscope and SEM), NDE (EC, x-ray CT) measurements
- LaRC to provide additional data on crack morphology on the destructive testing specimens
- X-ray (film, CR and DR) flaw detectability data, set-up data and flaw indication measurement data for all specimens provided
- KSC provides CCP Program briefings, CCP funding, seeks CCP program directive, data analysis, weekly meeting minutes and general support
- JSC is providing weekly meeting organization, data analysis, NDE technique validation, and general support
- MSFC NDE providing support to weekly meetings

Eddy Current Technique at NASA LaRC

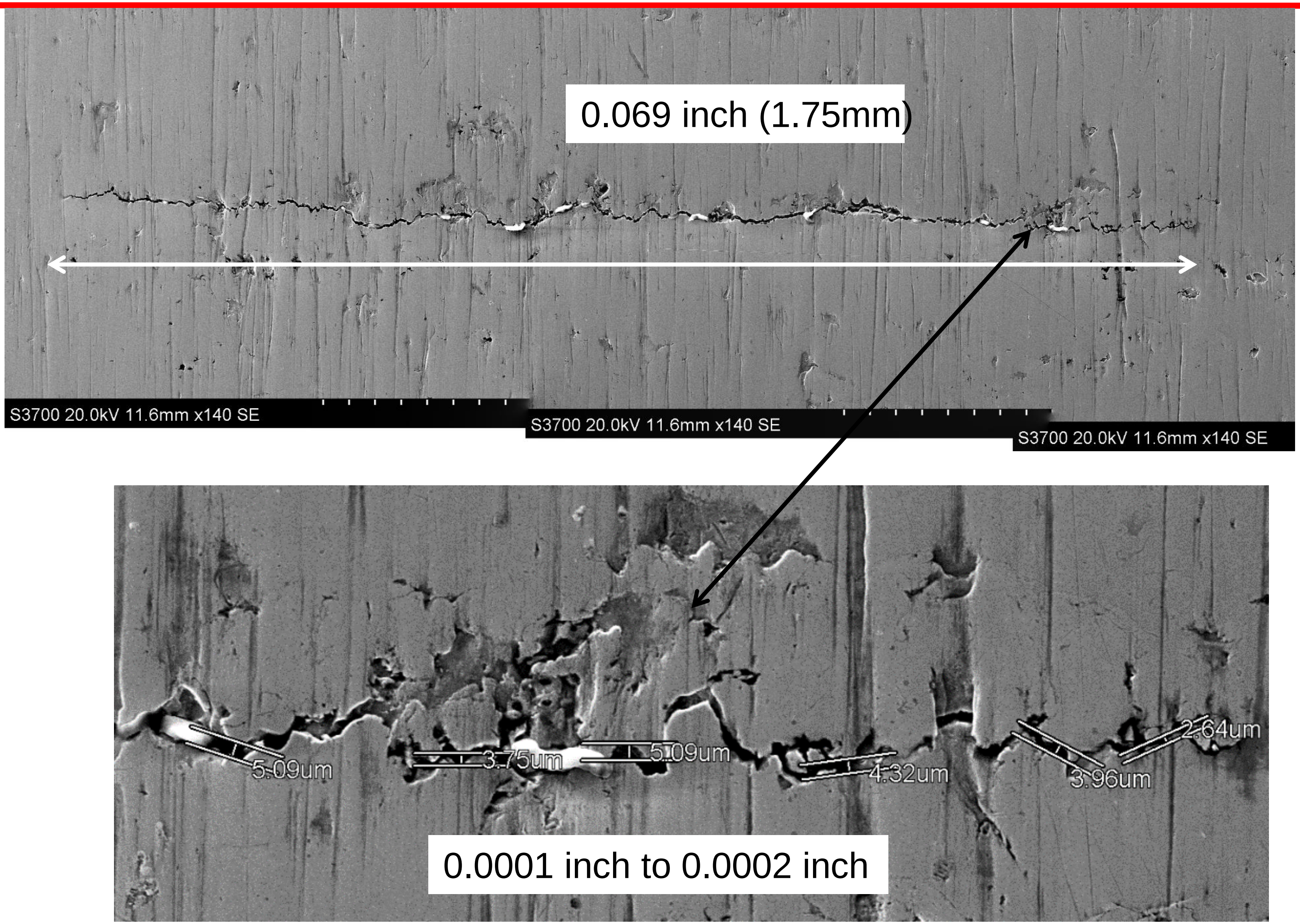


- 3.5 MHz inspection with Uniwest 3151 Driver/Differential Pickup Eddy Current Coil and MIZ-27 Eddy Current instrument.
- Automated stepper motor controlled scanning with 0.005” step size in circumferential and axial directions.
- Data processing and using MATLAB ECgui routine incudes phase rotation, convolution filter based upon probe response to point defect, automated crack detection, crack response calculated as sum of 18 (3x3 matrix at each crack tip) peak measurements across flaw.

Selected Data on IN625 0.028" Wall Tube Cracks

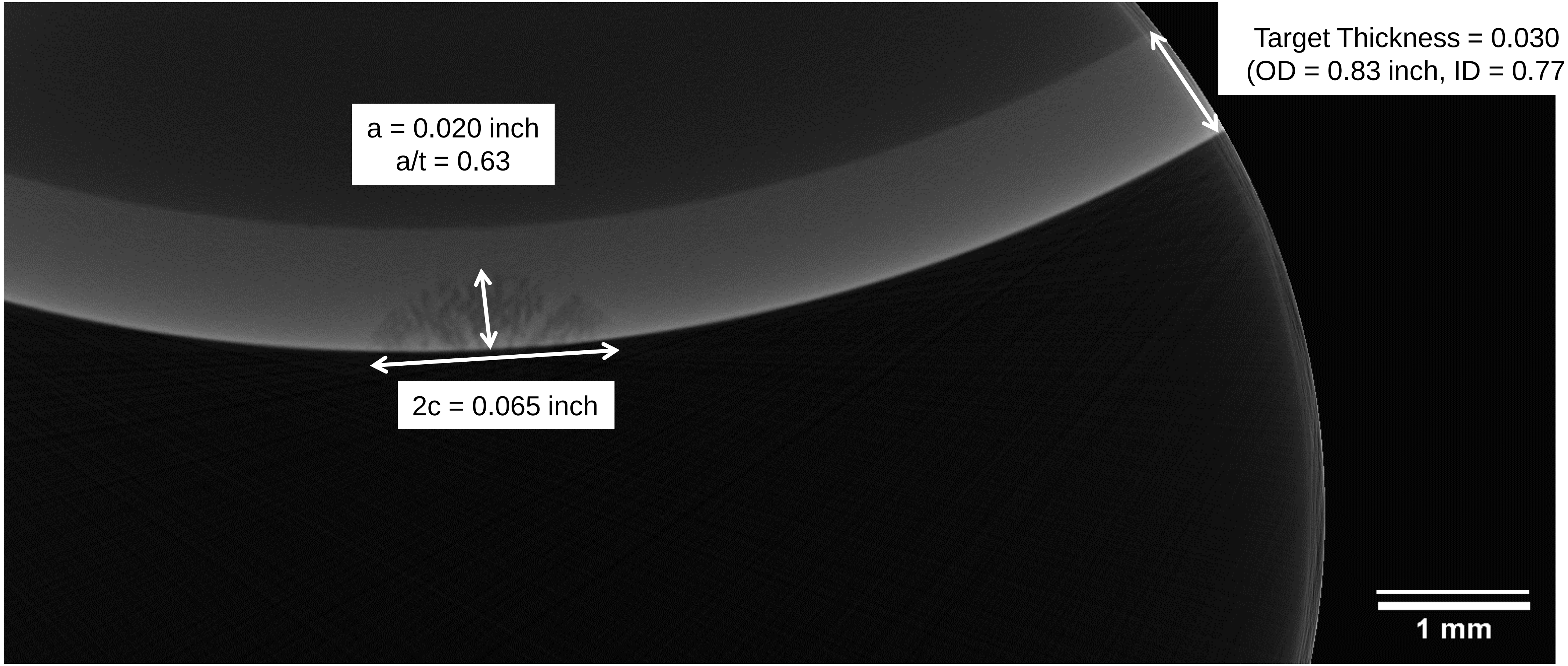
Technical Lead: Dave Dawicke (AS&M)
NDE: Russell Wincheski, Eric Burke (NASA LaRC)
Will Sommer (AMA)
NESC Lead: Heather Hickman (NASA NESC)

Example of SEM Measurements: T-01



Nominal crack opening ~ 5 μm

Example of CT Measurements: T-01



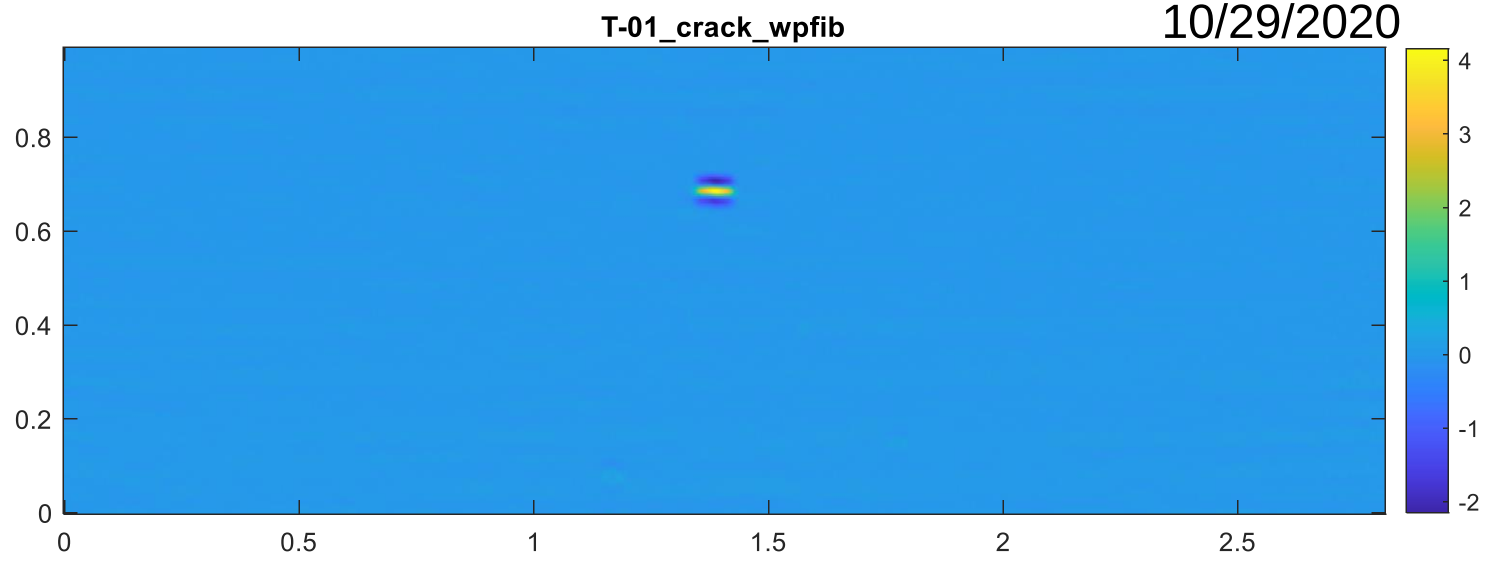
Measured Thickness = 0.032 inch

Target Thickness = 0.030 inch
(OD = 0.83 inch, ID = 0.77 inch)

EB/BW

Example of Eddy Current Measurements – T01

10/29/2020



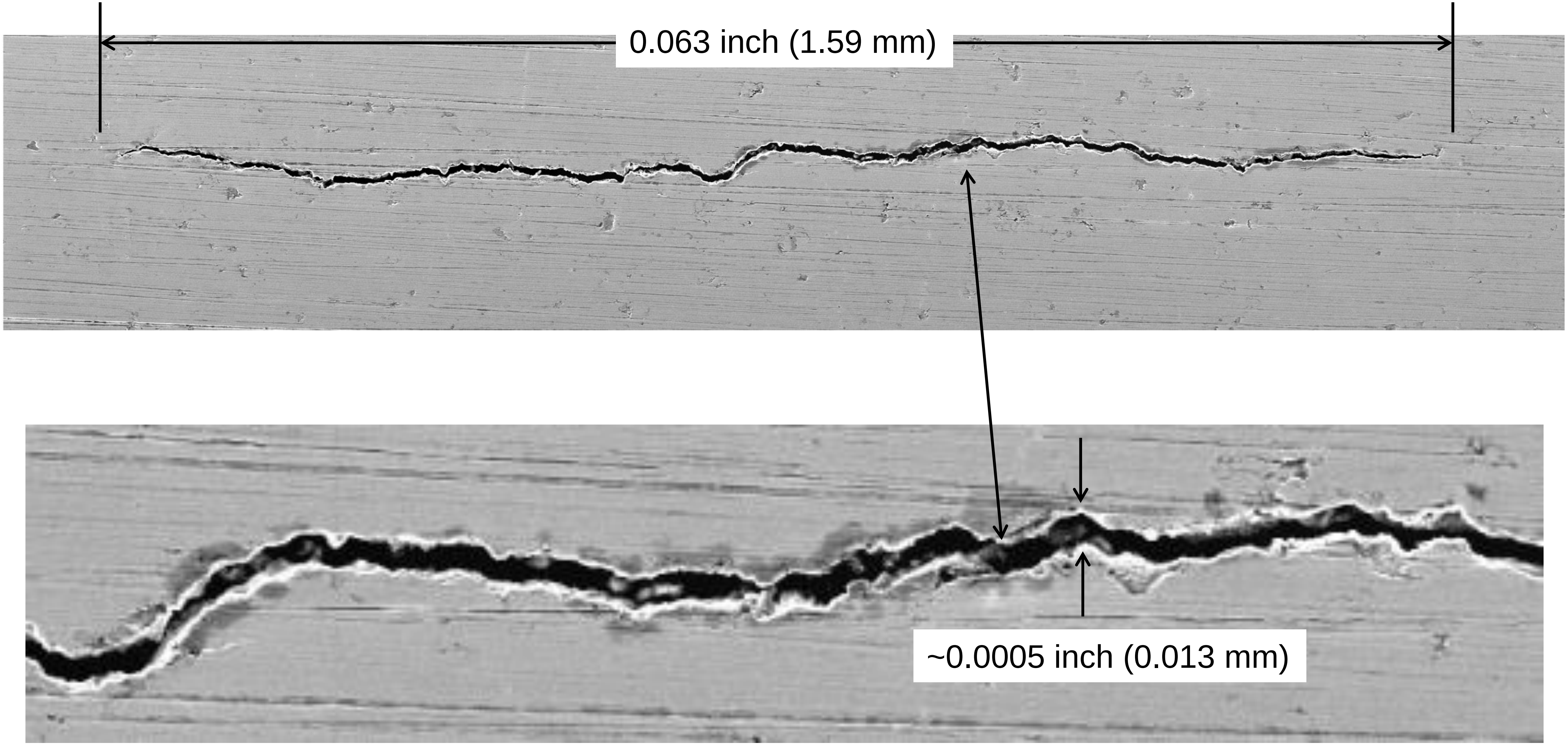
Axial Distance (in)

Circumferential Distance (in)

4.160 Peak, 60.568 peak sum 18 points, Length at 0.5V threshold = 0.091” (- ~0.02)

BW

Example of SEM Measurements, T-02

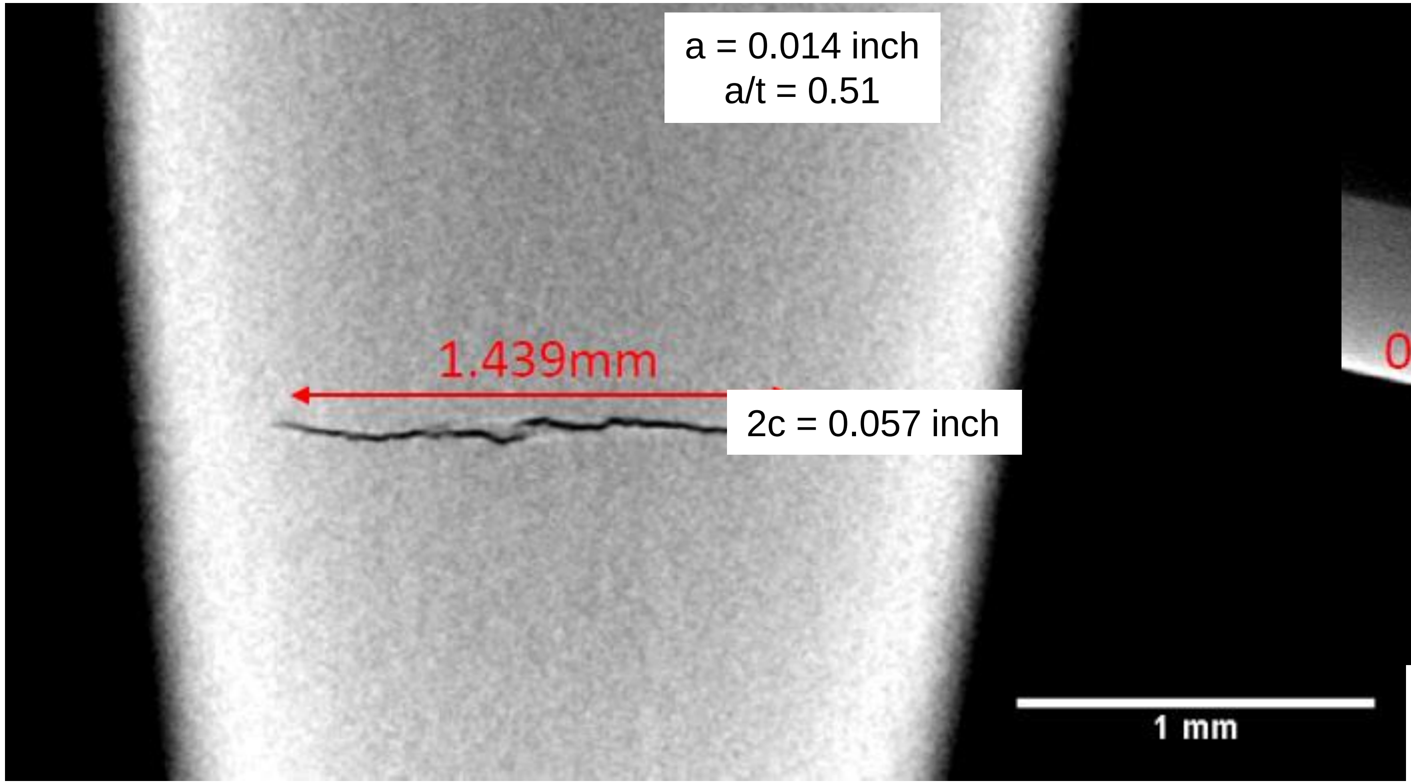


BW

Example of CT Measurements, T-02

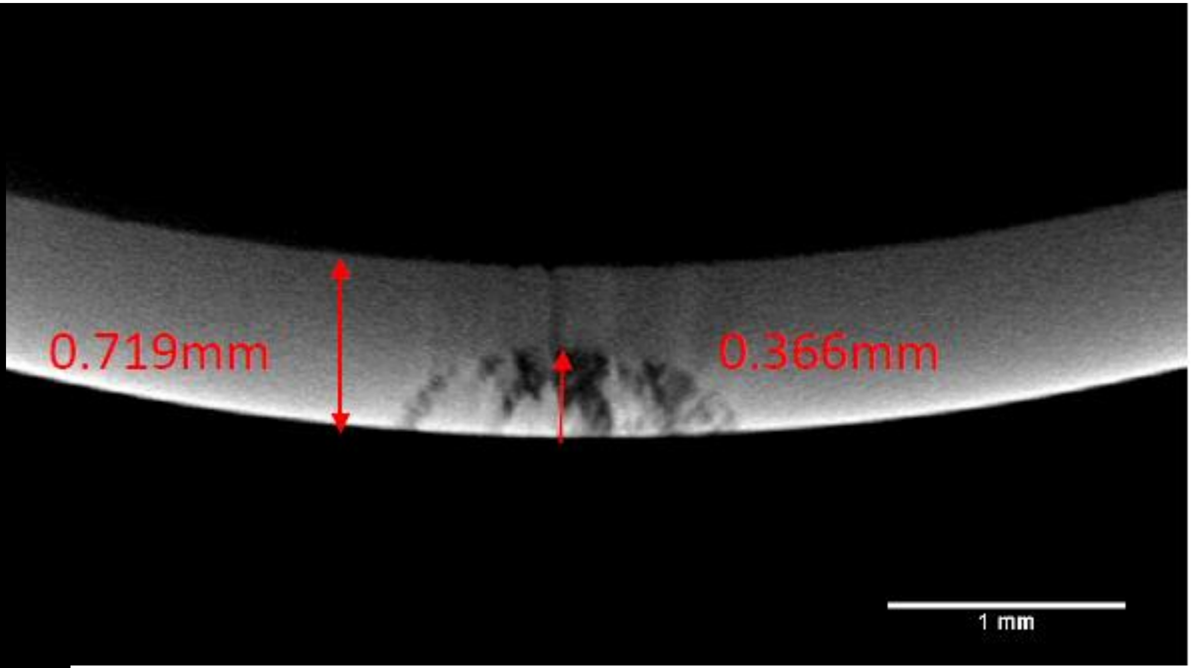
Measured Thickness = 0.028 inch

Target Thickness = 0.030 inch
(OD = 0.83 inch, ID = 0.77 inch)



a = 0.014 inch
a/t = 0.51

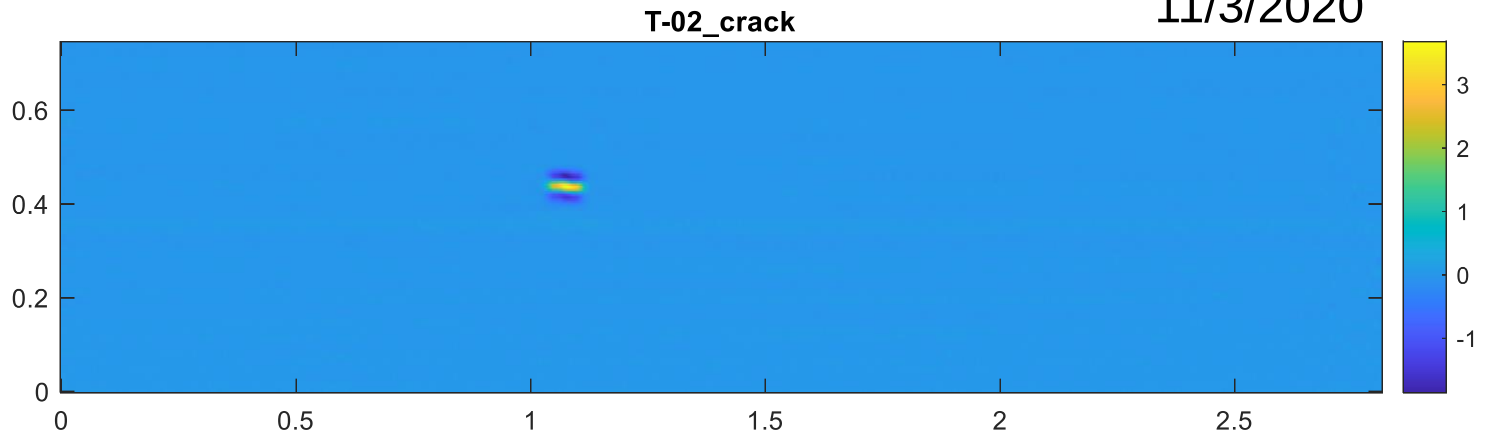
2c = 0.057 inch



EB/BW

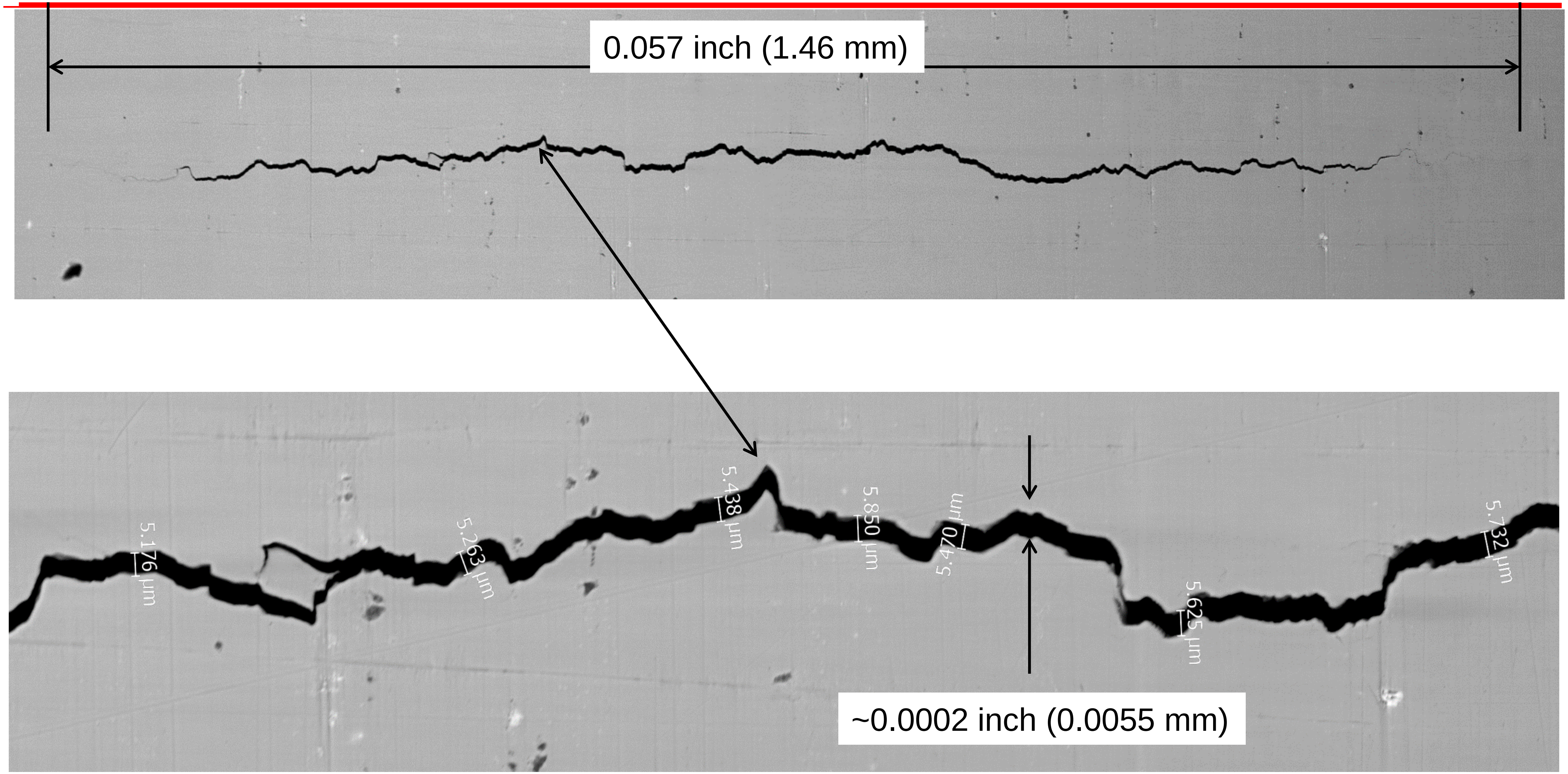
Example of Eddy Current Measurements, T-02

11/3/2020



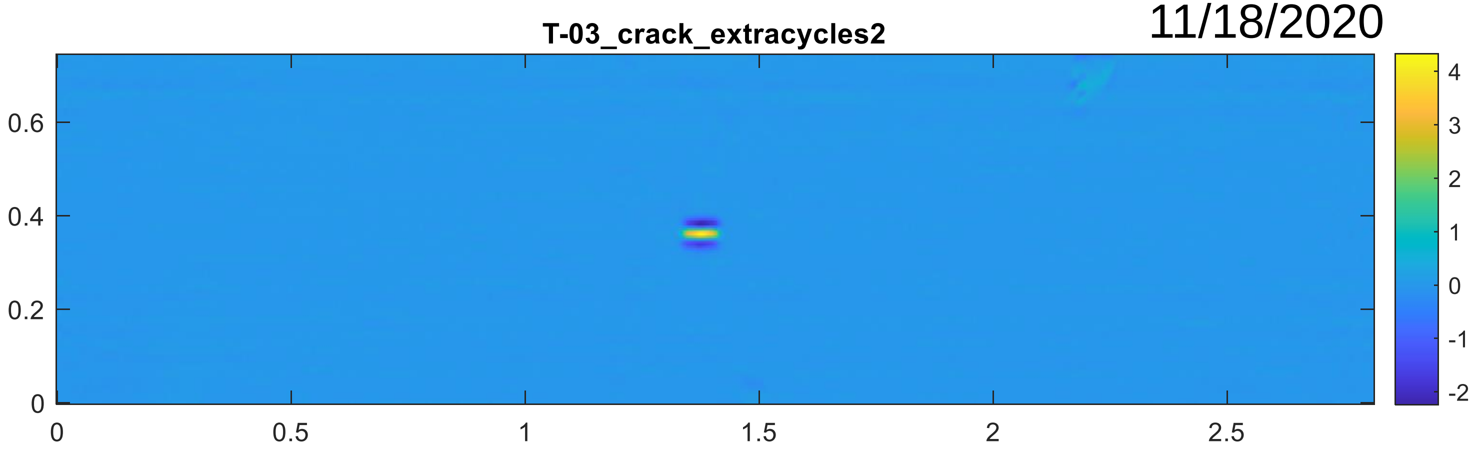
3.680 Peak, 54.197 peak sum 18 points, Length at 0.5V threshold = 0.086” (- ~0.02)

Example of SEM Measurements, T-03



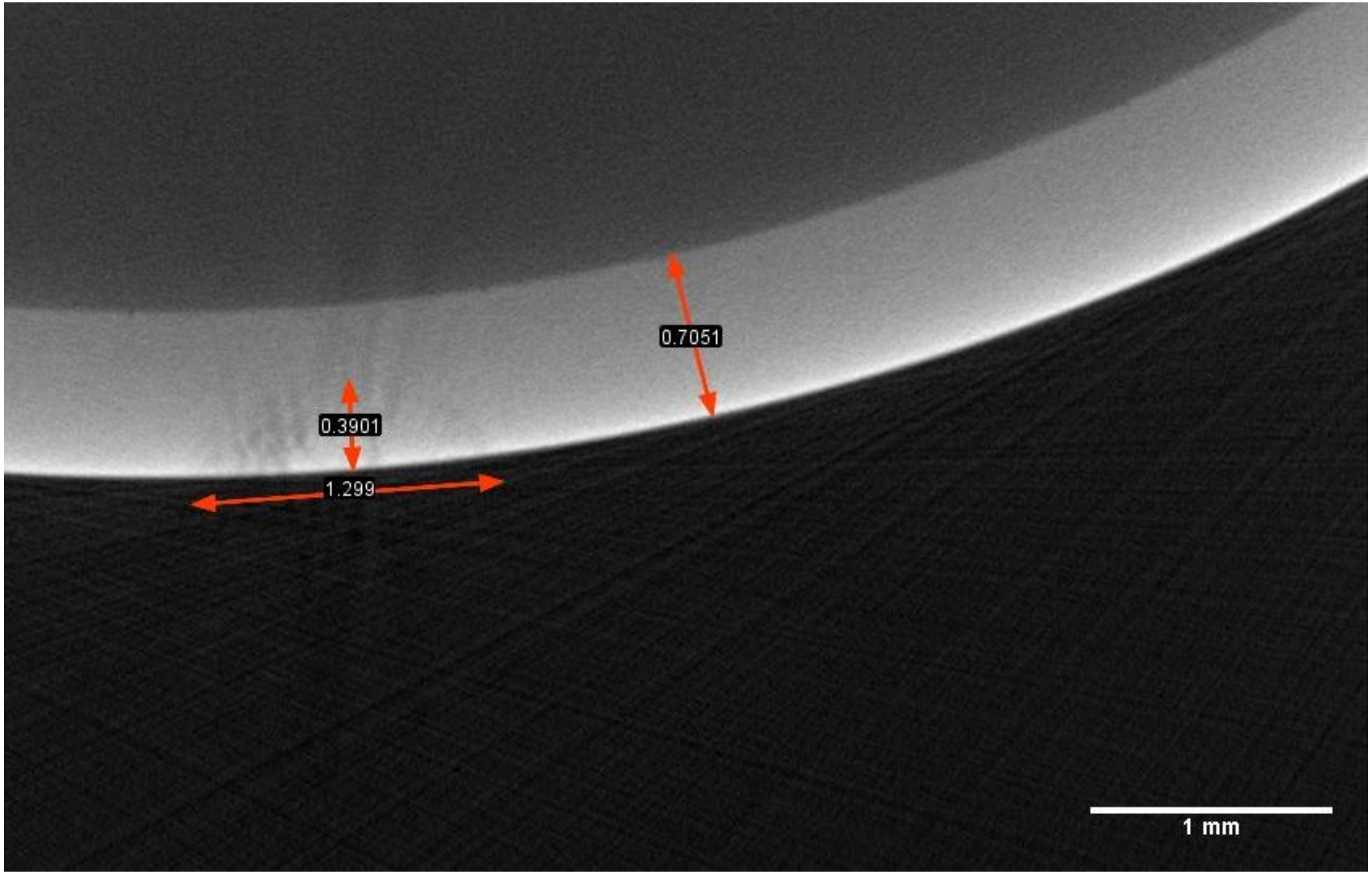
Example of Eddy Current Measurements, T03

11/18/2020

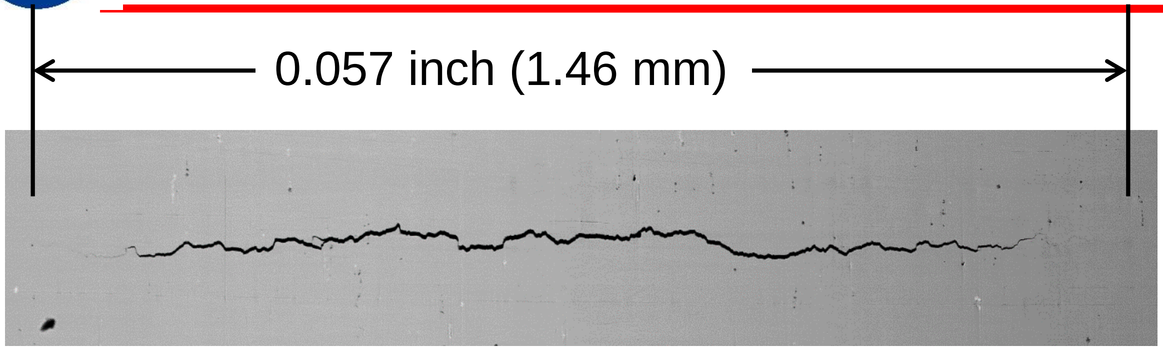


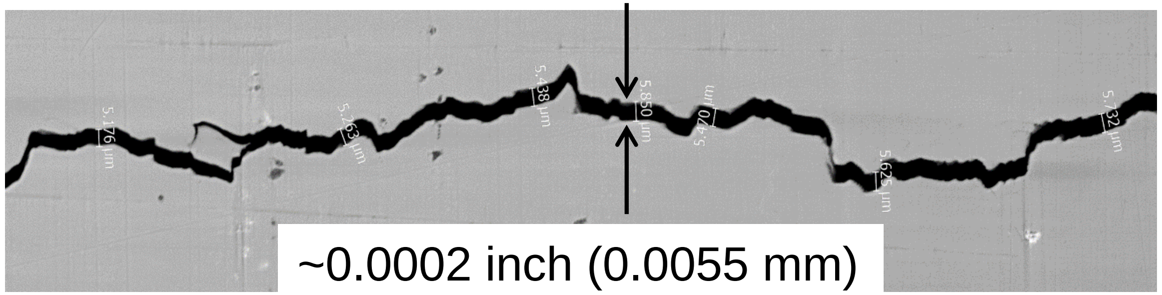
4.331 Peak, 62.529 peak sum 18 points, Length at 0.5V threshold = 0.091” (- ~0.02”)

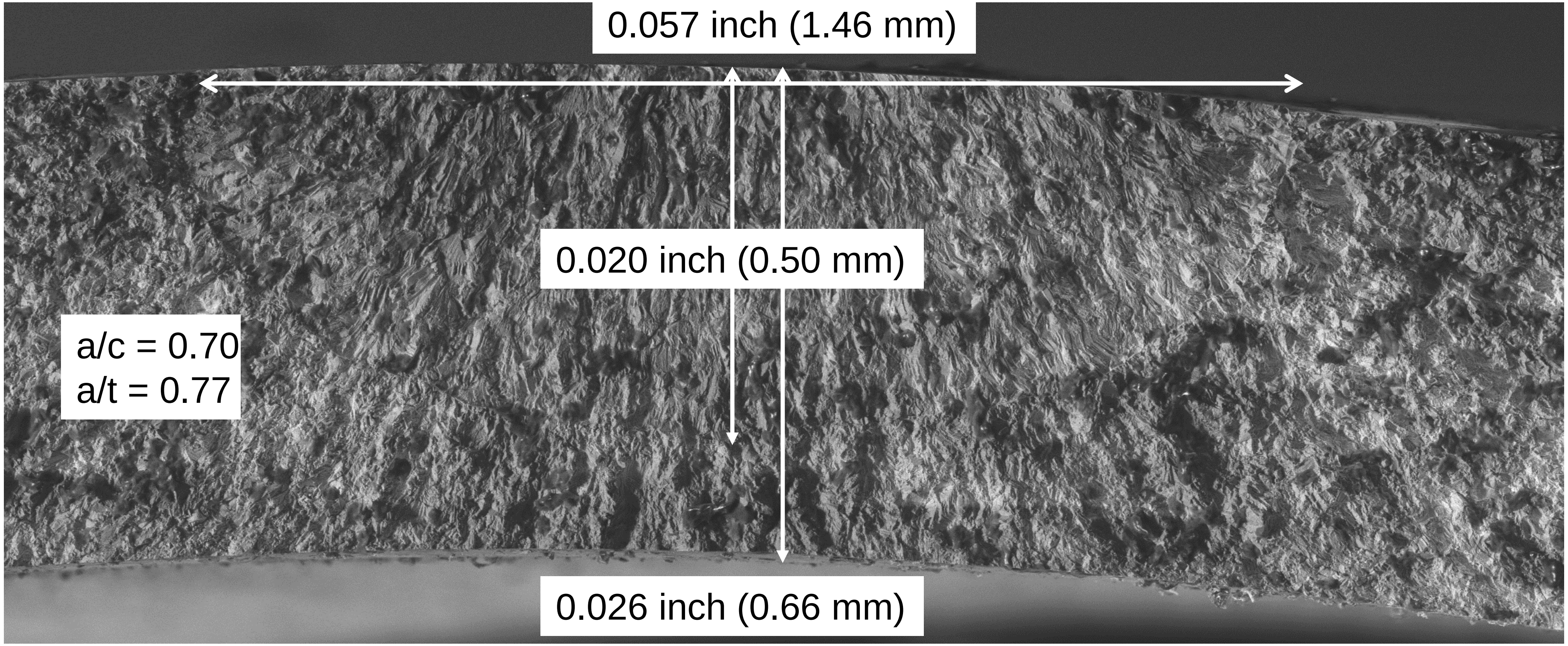
Example of CT Measurements, T-03



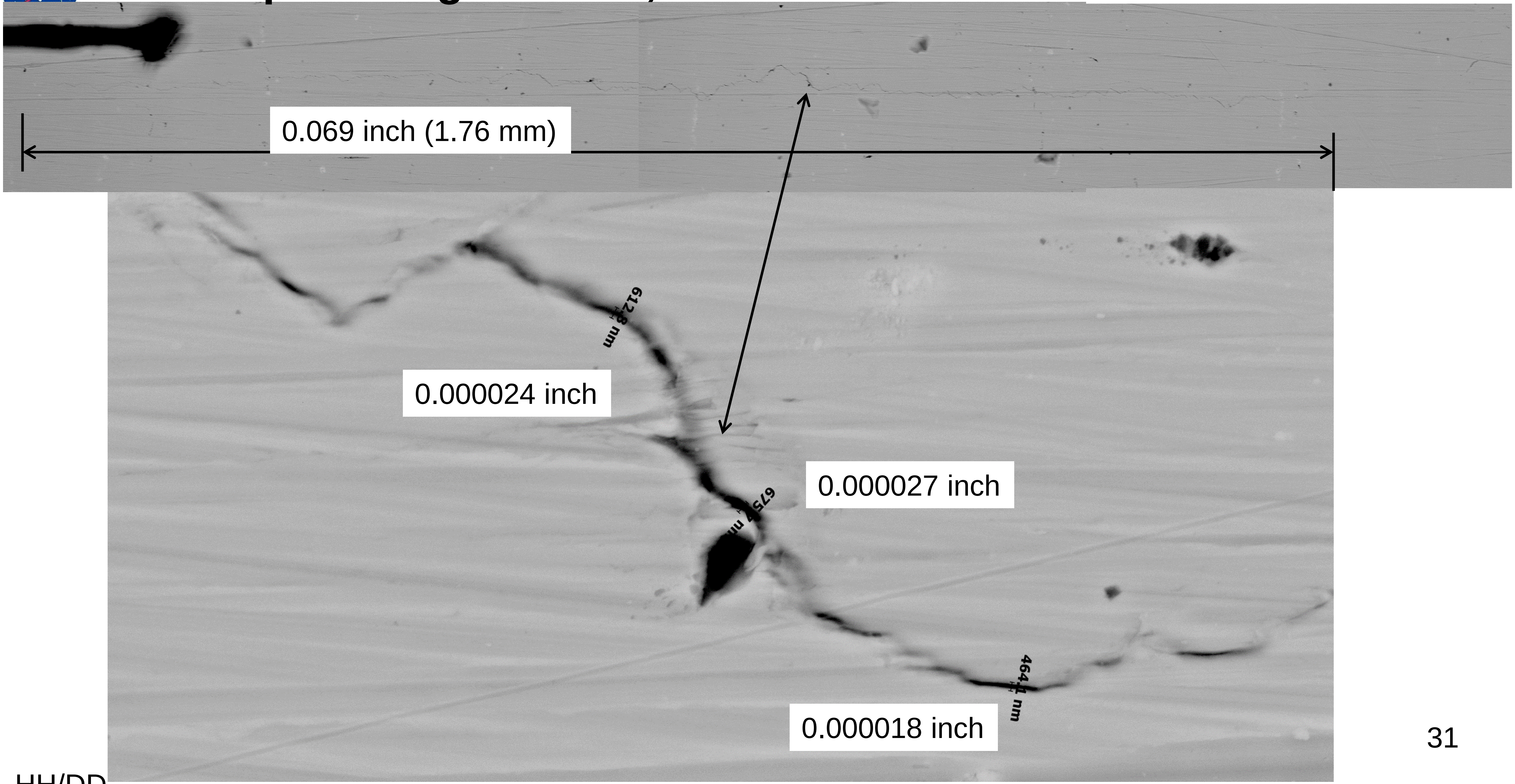
Example of Destructive Testing and Crack Measurements: T-03



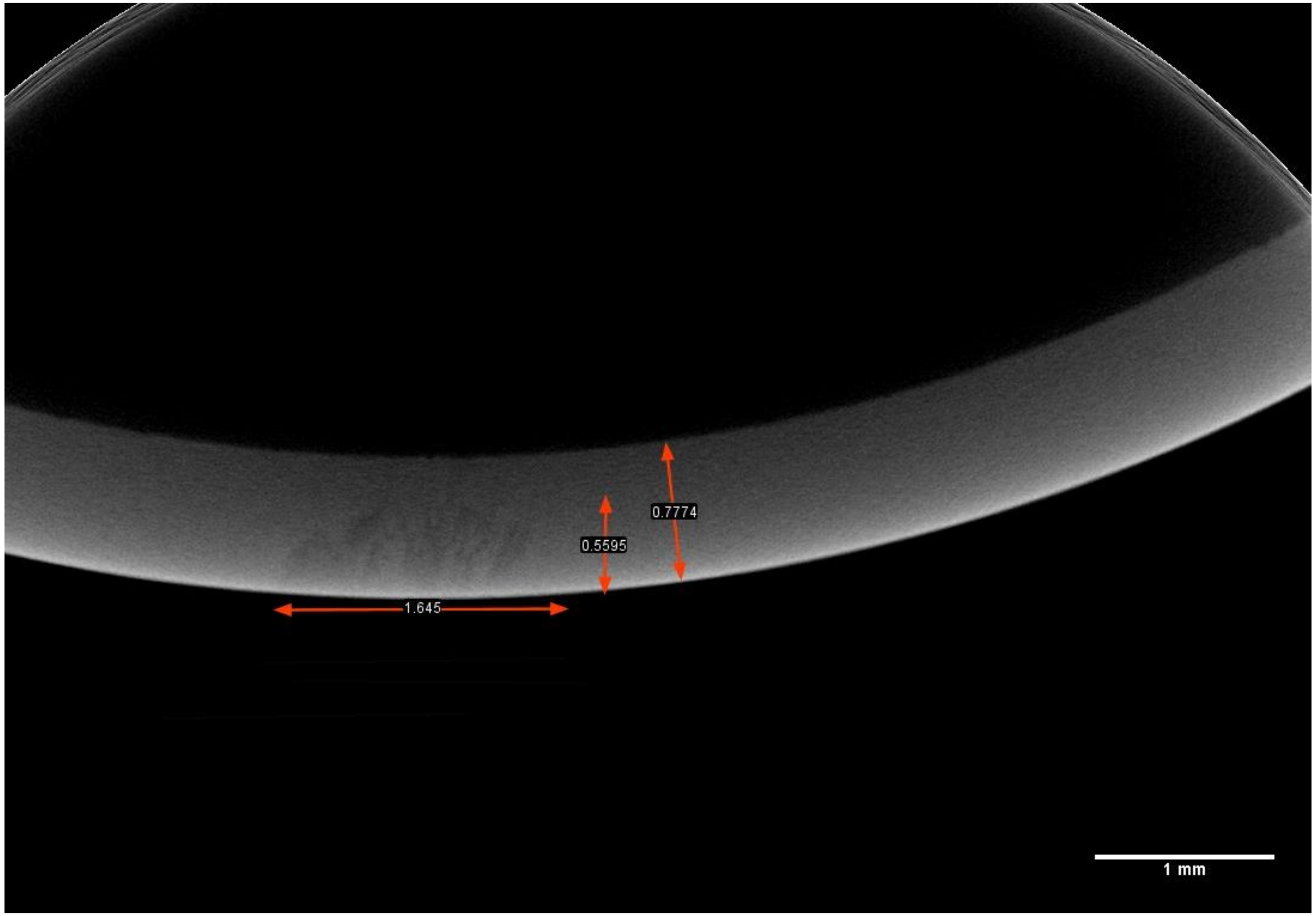




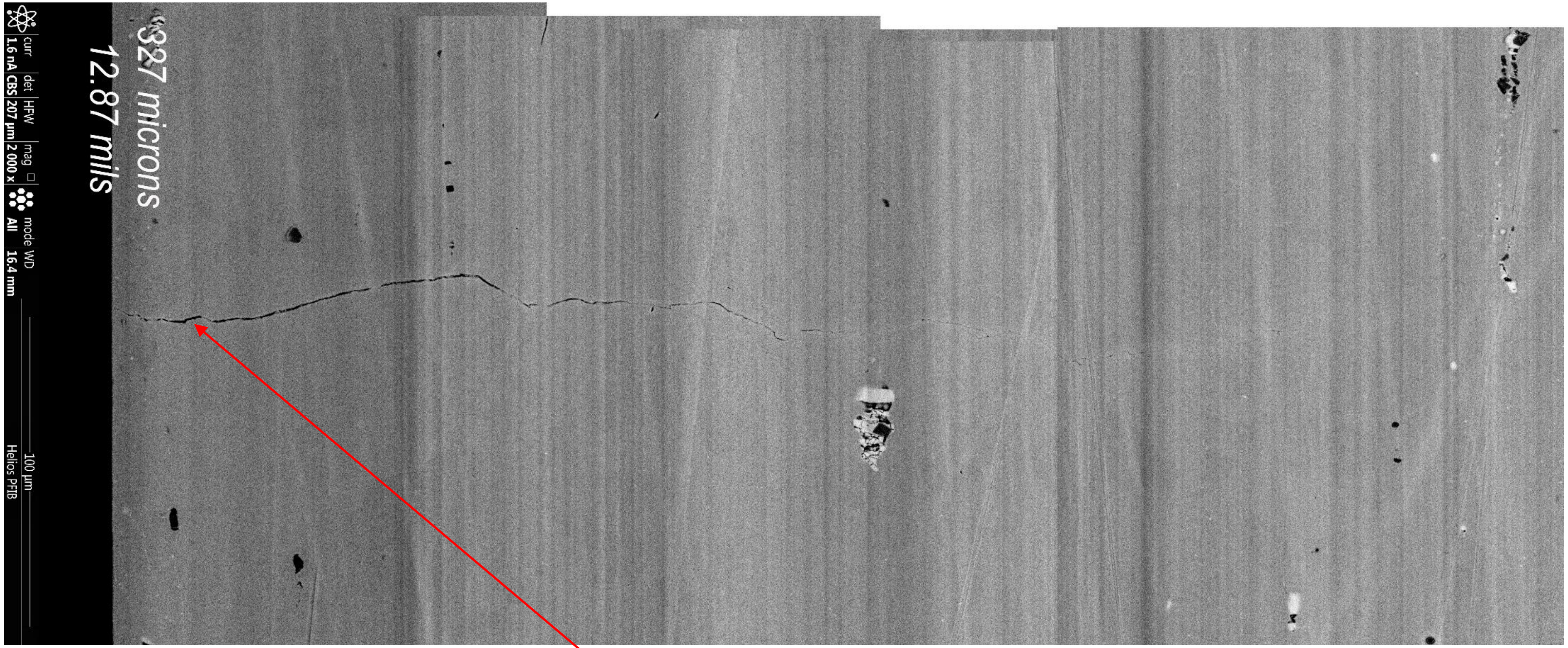
Example of Tight Crack, SEM Surface Measurement- T-05



Example of Tight Crack, CT Scan Measurements -T-05



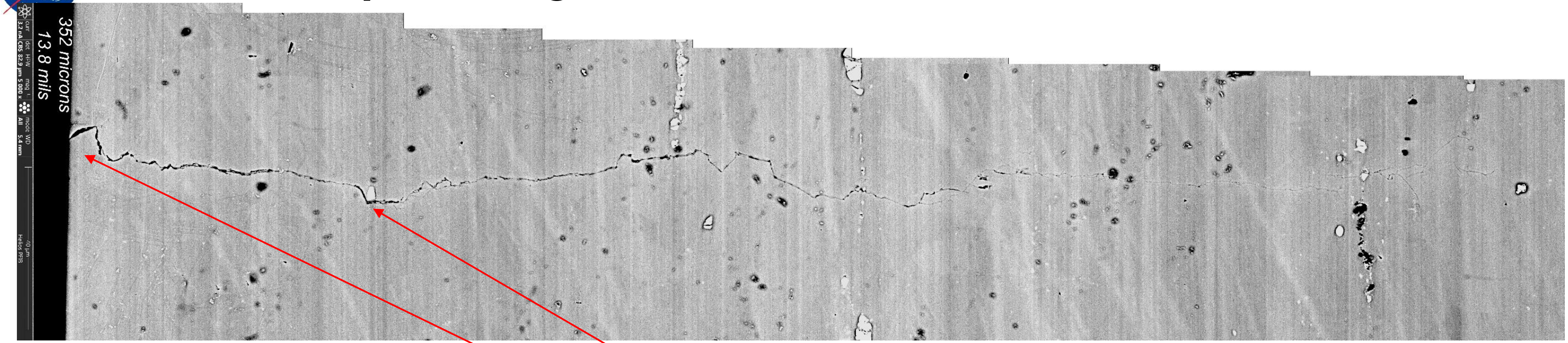
Example of Tight Crack: T-06 Section Location #3



1.08 microns/.042 mils
Widest area of crack

2000x

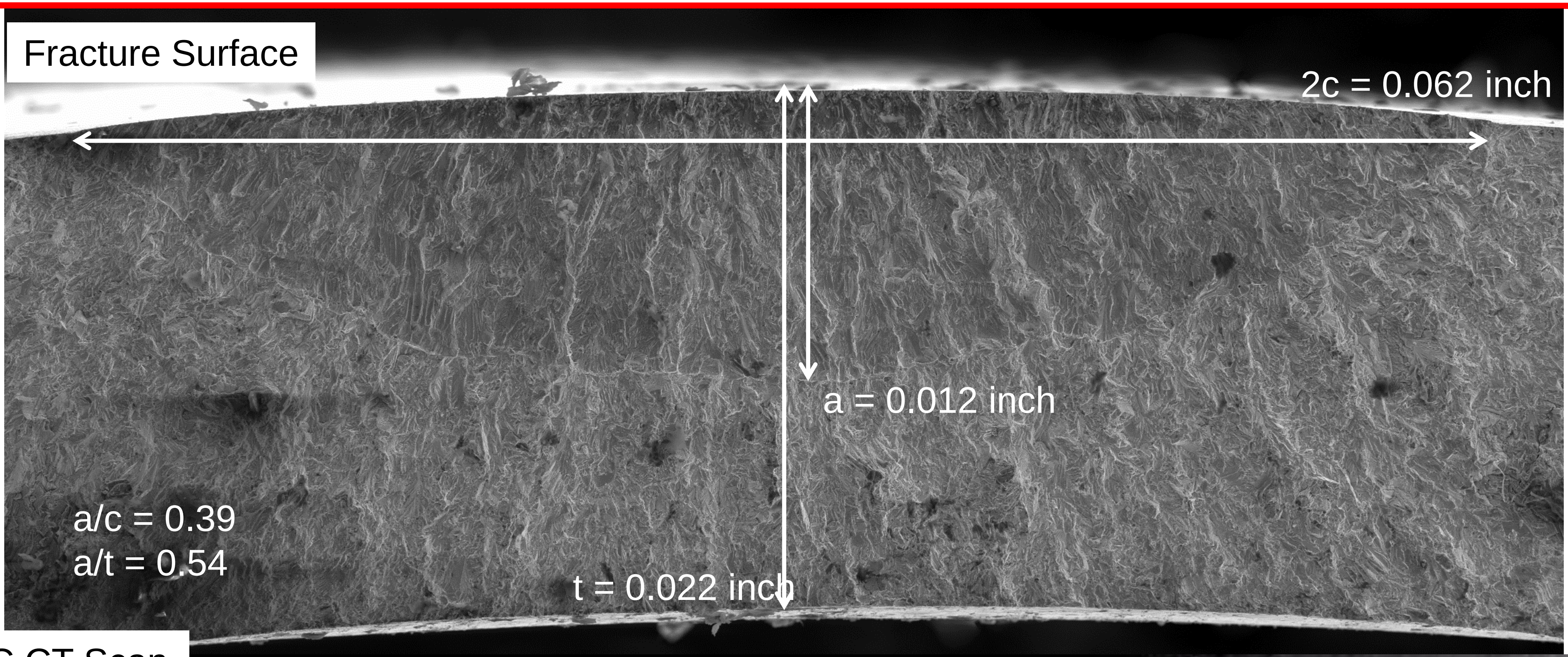
Example of Tight Crack: T-06 Section Location #4

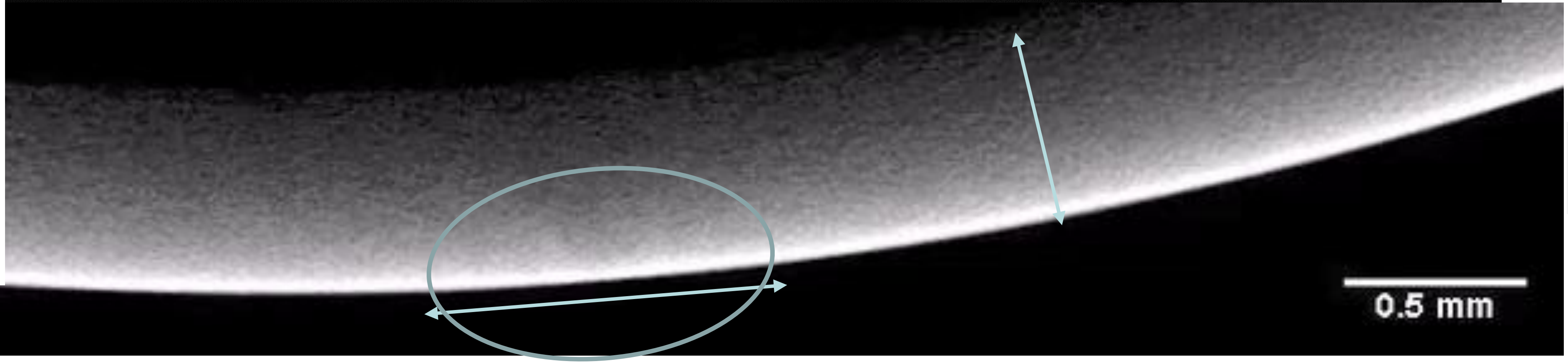


2000x

0.89 microns/.035 mils
Widest area of crack

X-ray CT and Fractography Crack Measurement, T-10





LaRC CT Scan
a = 0.015 inch
2c = 0.041 inch
t = 0.022 inch
a/c = 0.73
a/t = 0.68

HH/DD/
BW/EB

Example of Summary of Flaw Measurements and Eddy Current Readings During Crack Manufacturing

Scan Date	T-01		T-02		T-03		T-04		T-05		T-06		T-07		T-08		T-09		T-10		T-11		T-12	
	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)	EC(V)	a, 2c (mm)
10/22	39.6																							
10/29	**60.6**	.486, 1.61																						
11/3			**54.2**	.366, 1.44	25.8																			
11/9					28.5	.240, 1.12																		
11/12					38.5	.303, 1.15	2.7																	
11/16							3.4		17.4	-------	**57.3**	.395, 1.44												
11/18					**62.5**	.390, 1.30	4.6																	
11/23							6.6																	
12/04									**61.2**	.559 1.64			**68.6**	.403, 1.61	**66.4**	.373 1.54	59.8	.322, 1.08						
12/7							18.8												50.5		**66.2**			
12/8							36.1																**72.6**	

BW

Crack Size and X-ray Detectability Data as of March 3/18/2021

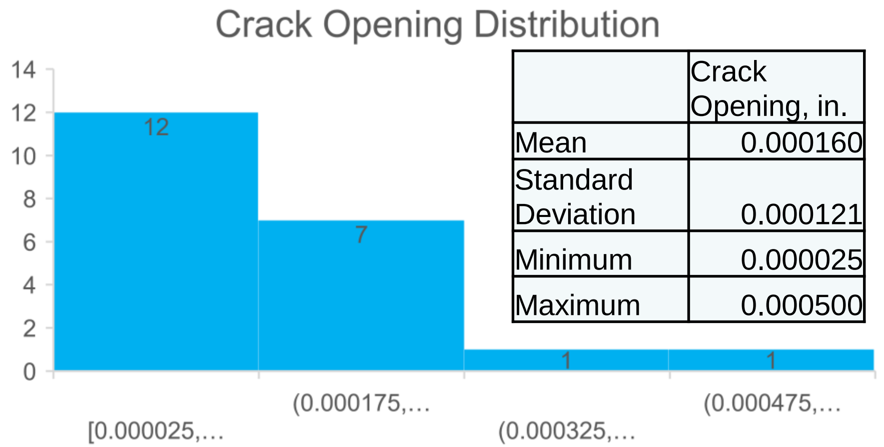
Tubes	EC, (V)	Optical Length, in.	Optical Crack Opening, in.	EC Length at 0.5V threshold (V)	CT Length, in.	CT Depth, in.	Comment	Fractography, Length, in	Fractography, Depth, in.	Fractography Thickness, in		Fractography Thickness, in	Measured Crack Opening	Sample	CR	Film Standard	Film Optimized	Film Micro-Focus	DR Standard	DR Optimized
T-01	60.6	0.069	0.000200	0.091	0.063	0.019							0.0002	T-01	1	1	1	1	1	1
T-02	54.2	0.063	0.000500	0.086	0.057	0.014							0.0005	T-02	1	1	1	1	1	1
T-03*	62.5	0.057	0.000200	0.091	0.051	0.015		0.057	0.020	0.026		0.026	0.0002	T-03	0	0	1	1	1	1
T-04	36.1	0.048	0.000200	0.069	0.042	0.015							0.000200	T-04	0	0	0	0	0	1
T-05	61.2	0.069	0.000024	0.095	0.065	0.022							0.000027	T-05	0	0	0	0	1	1
T-06*	57.3	0.048	0.000040	0.095	0.057	0.016							0.0002	T-06	0	0	0	0	1	1
T-07	68.6	0.061	0.000200	0.091	0.063	0.016							0.0002	T-07	0	1	1	1	1	1
T-08	66.4	0.063	0.000100	0.091	0.061	0.015							0.0001	T-08	0	0	1	1	1	1
T-09	59.8	0.063	0.000020	0.091	0.042	0.013							0.000025	T-09	0	0	0	0	0	1
T-10*	50.5	0.059	0.000200	0.086	0.041	0.015		0.062	0.012				0.0002	T-10	0	0	0	0	0	1
T-11	66.2	0.074	0.000200	0.095	0.040	0.015							0.0002	T-11	0	0	0	0	1	1
T-12*	72.6	0.072	0.000100	0.104	0.072	0.020	Post Overload						0.0001	T-12	0	0	0	0	0	1
T2-01	68.5	0.081	0.000079	0.104	0.076	0.026							0.000079	T2-01						1
T2-02	58.3	0.083	0.000079	0.095	0.050	0.018							0.000079	T2-02						0
T2-03	66.7	0.075	0.000080	0.099	0.062	0.021							0.000080	T2-03						1
T2-04	90.5	0.094	0.000440	0.099	0.065	0.018							0.000440	T2-04						1
T2-05	91.0	0.076	0.000110	0.104	0.059	0.020							0.000110	T2-05						1
T2-06														T2-06						
T2-07	72.6	0.070	0.000097	0.095	0.059	0.017							0.000097	T2-07						
T2-08	109.0	0.075	0.000140	0.104	0.066	0.023							0.000140	T2-08						
T2-09	80.6	0.069	0.000035	0.095	*Not Detected*								0.000035	T2-09						
T2-10	100.3	0.077	0.000150	0.104	0.07	0.026							0.000150	T2-10						
T2-11	82.7			0.108	0.07	0.023								T2-11						
T3-01	59.4			0.086	0.052	0.016								T3-01						
T3-02	68.5			0.095										T3-02						
														% Detected	16.67	25.00	41.67	41.67	66.67	94.12

Technique	Ranking
DR Optimized	1 (best)
DR Standard	2
Film Micro-Focus	3
Film Optimized	3
Film Standard	4
CR	5 (worst)

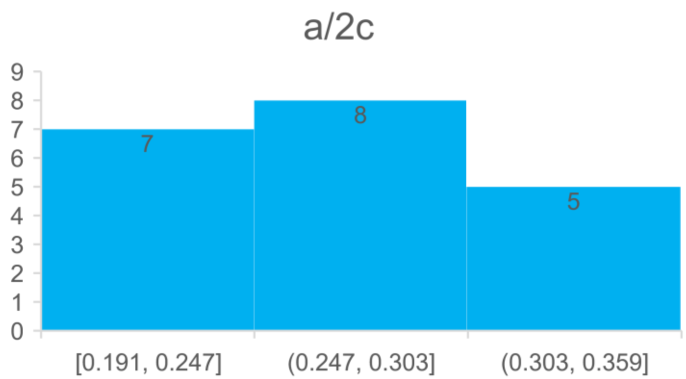
* - samples selected for destructive testing

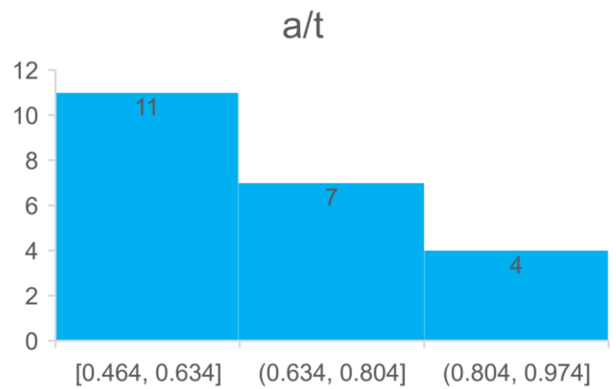
AMK

Crack Dimension Statistics and Set-up Geometry

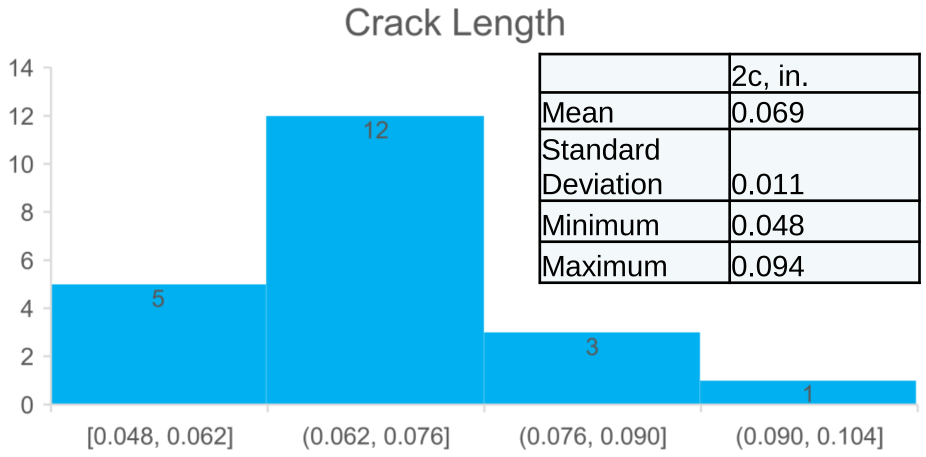


	Crack Opening, in.
Mean	0.000160
Standard Deviation	0.000121
Minimum	0.000025
Maximum	0.000500

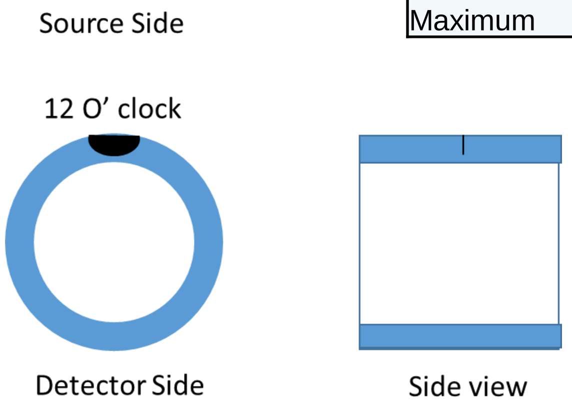




	a/2c	a/t
Mean	0.266	0.653
Standard Deviation	0.044	0.138
Minimum	0.191	0.464
Maximum	0.338	0.929



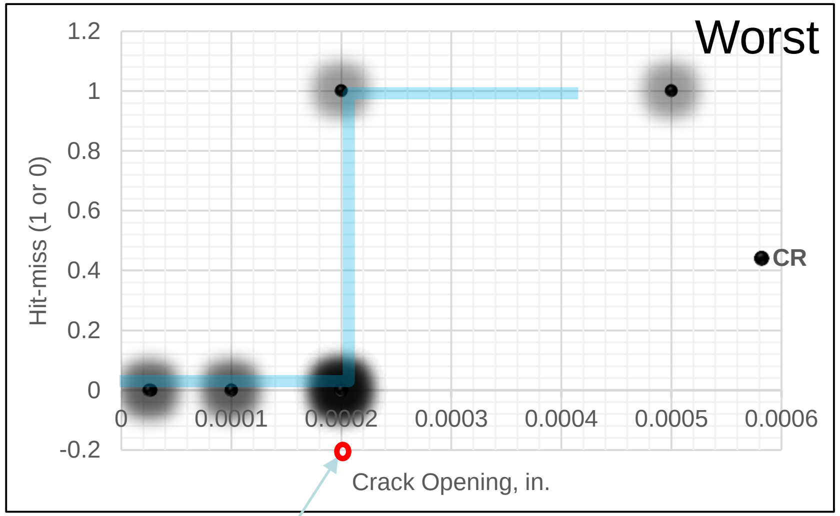
	2c, in.
Mean	0.069
Standard Deviation	0.011
Minimum	0.048
Maximum	0.094

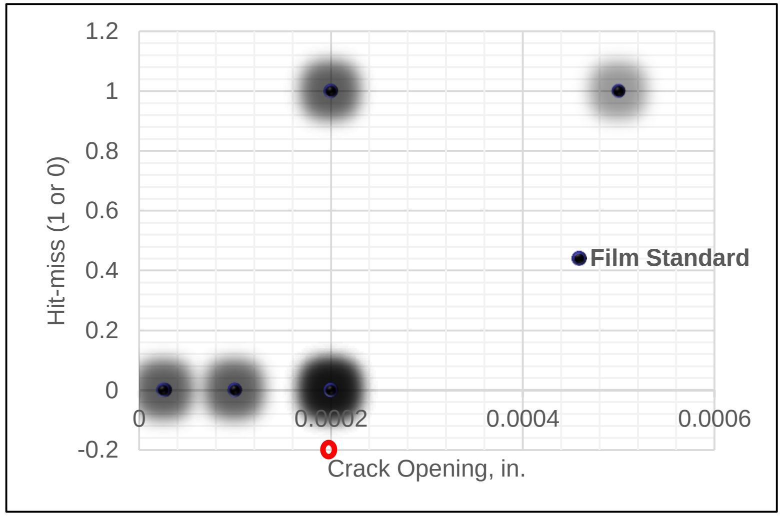


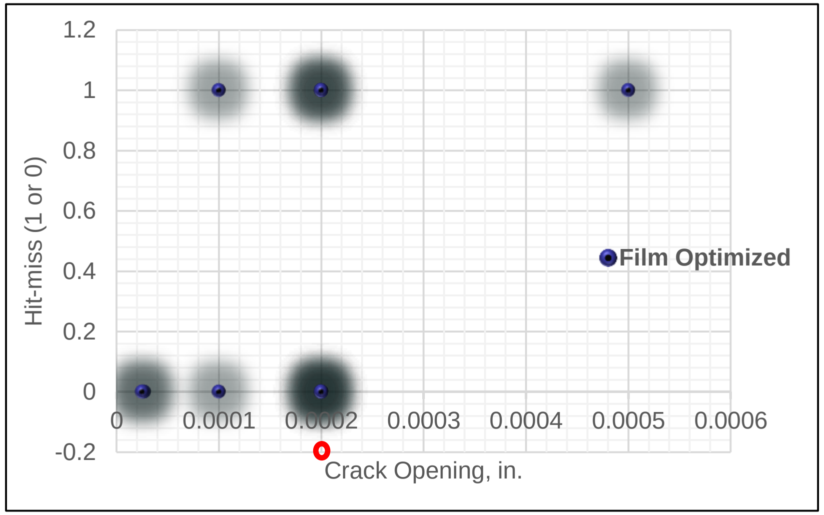
Tube Flaw Schematic

- The shots are at nearly 0 deg. x-ray angle to crack plane.
- The cracks are oriented at 12 O' clock i.e. on the side of x-ray source
- The cracks may be clocked to 1:30 or 10:30 O'clock in actual inspection
- The techniques are considered to be ideal for crack clockwise location and x-ray angle

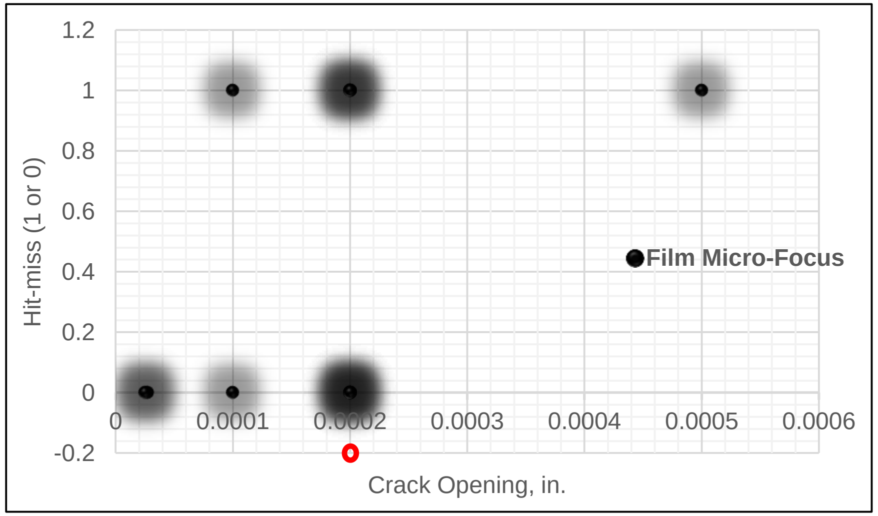
Hit-miss versus Crack Opening for Various X-ray Techniques

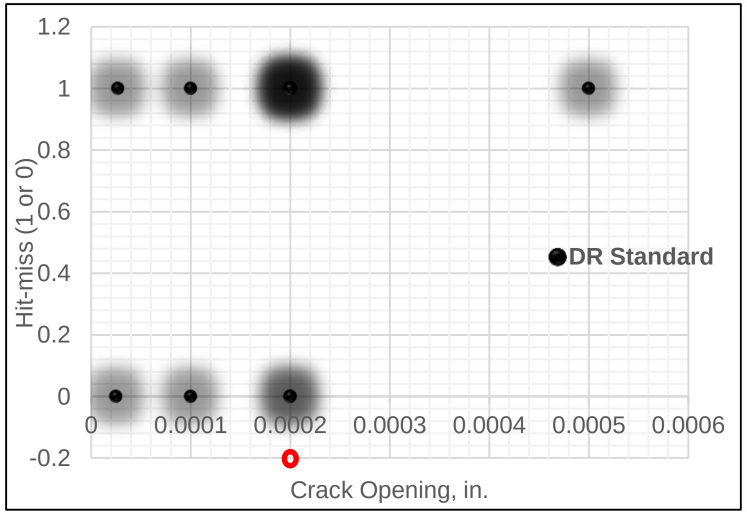


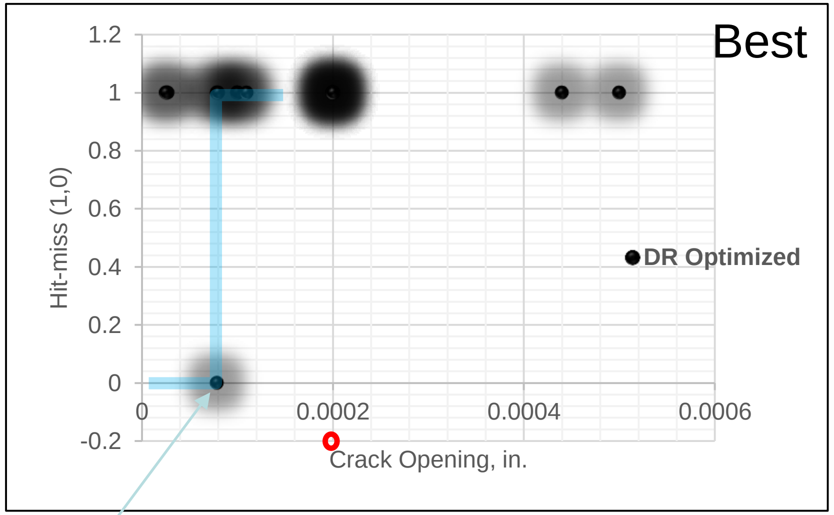




5 micron







Darker glow indicates more data-points

o - 5 micron crack opening

2 micron

NT

Interim Conclusions

- Flaw Specimens
  - Material: Inco 625
  - Nominal values for crack dimensions
    - t = 0.028”
    - a/t = 0.7
    - a/c ≈ 0.53 (a/c ≈ 1 is desired as it is commonly used in fracture control)
  - Crack opening
    - Range: 0.00002” (0.5 micron) to 0.0005” (12.7 micron)
    - Mean: 0.000160”
    - Standard Deviation: 0.000121”

	a/2c	a/t
Mean	0.266	0.653
Standard Deviation	0.044	0.138
Minimum	0.191	0.464
Maximum	0.338	0.929

- Conclusions
  - All techniques detected some flaws of minimum 0.0002” crack opening (5 micron i.e. 5 micro-meter)
  - Only DR-optimized detected all flaws of minimum 0.0002” (5 micron) opening
    - DR uses magnification i.e. detector is away from part. Such set-up is possible when tubing is in a sub-assembly form allowing it to be inspected in the X-ray facility. It may not be possible to perform the set-up in-situ, where the tubing is part of the hardware system
    - DR-Optimized missed one crack with crack opening measured at 2 micron. DR-Optimized detected 94% of all flaws.
  - **Standard x-ray Film radiography detected only 25% of the fatigue cracks for optimal crack clocking and optimal x-ray angle**
    - With additional data it may be possible to demonstrate that Standard film radiography can detect cracks with crack opening of ≥ 0.0003” (8 micron)
    - Optimized film radiography uses lower kV and provides better flaw detectability but the technique shot time is longer
    - Optimized film x-ray or micro-focus film x-ray may be better suitable for in-situ x-ray inspection
- Forward Work
  - Need to complete NDE and other testing on all test specimens and analyze all available data towards meeting objectives