Microwave Inspection of Complex Wind Turbine Blade Structures

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TPI Composites
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Advanced Microwave Imaging

Presentation Content

- Steve Nolet – TPI
  - Wind Turbine Blade Construction
  - Sample Correlation
- Bob Stakenborghs – Advanced Microwave Imaging
  - Microwave inspection background
    - Microwave NDT Characteristics
    - Microwave NDT systems
  - Microwave inspection results NOWRDC Samples

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Part 1

Wind Turbine Blade Construction
and
Sample Correlation

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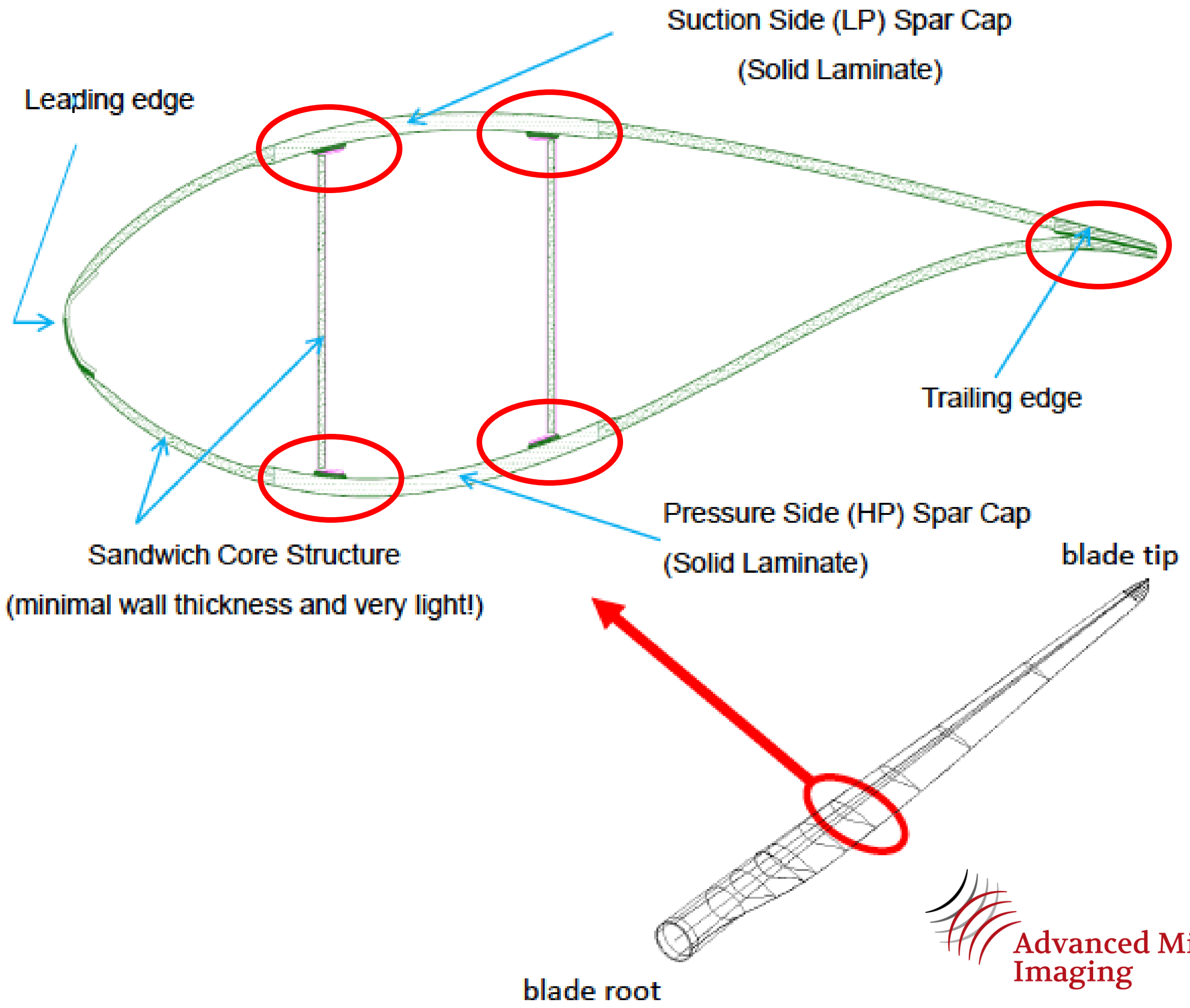
Blade Manufacturing Flaws of Particular Interest

- Trailing edge bonding.
- Shear web bonding to spar cap (both fiberglass and carbon).
- Delaminations.
- Porosity in the root section.
- Reinforcement waves
  - Trailing edge. (focus on root transition to max chord).
  - Root Section. (also root transition to max chord).



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Sandia Blade Test Specimen Library

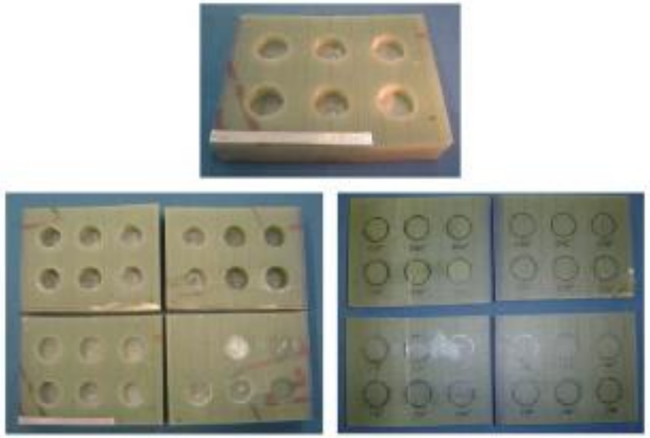
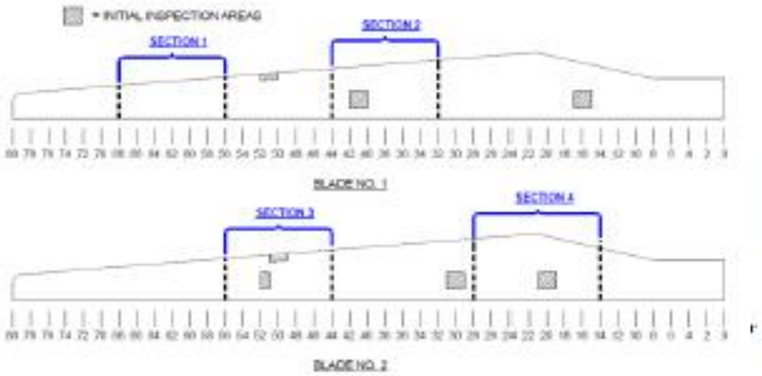


Figure 3-9: Laminate Thickness NDI Reference Standards



gure 3-6: Blade Sections for Sandia Wind Energy Test Specimen Library – Cut Plan f
Knight and Carver Blades

Figure 3-7: Wind Turbine Blade Test Specimen Library – Actual Airfoil and Blade Root Sections Representing Multiple Blade Sizes, Manufacturers and Construction Types

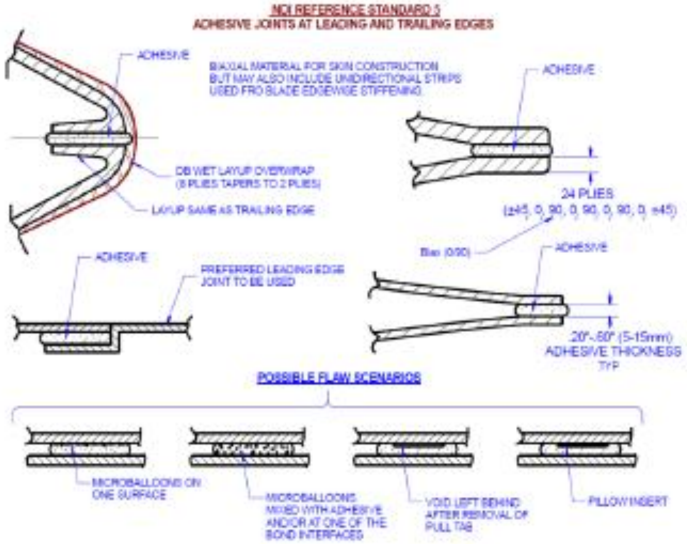


Figure 3-12: Element of Adhesive Joint in Trailing Edge NDI Test Specimens

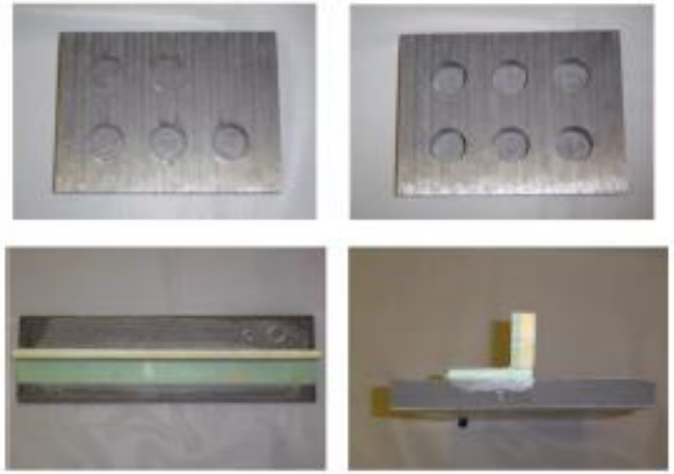


Figure 3-10: Sample Carbon NDI Reference Standards –
Spar Cap and Shear Web Specimens

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Trailing Edge Bond Paste, Complications

Trailing edge assembly of larger blades:

- Not so different than previous generations
- However, bond paste is required to extend under core.
- Not easily verified by conventional methods.

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Panel #1: Cored Panel With Bond Paste (details)

Panel #1: Propose 250mm wide by 400mm long, Indications to be applied/molded on "B-surface of panel
Which will ensure the A-surface remains plane. Include open (void) in 7mm thick bond paste on b-surface (after molding)

(starting from mold surface)

A-Surface	Ply #	Material	thickness	notes	
	1	DB-600	0.611	face up	
	2	UD-1800	1.12	face up	
	3	DB-600	0.611	face up	
	4	DB-600	0.611	face down	
	5	UD-1800	1.12	face down	
	6	DB-600	0.611	face down	
		Thickness	**4.68**	**mm**	
Core	7	SB100 standard sheet with 3/16" perferations on 2" centers	**50.00**	mm	(negotiable, 25mm ok too)

Maintain symmetry (plies 1–6)

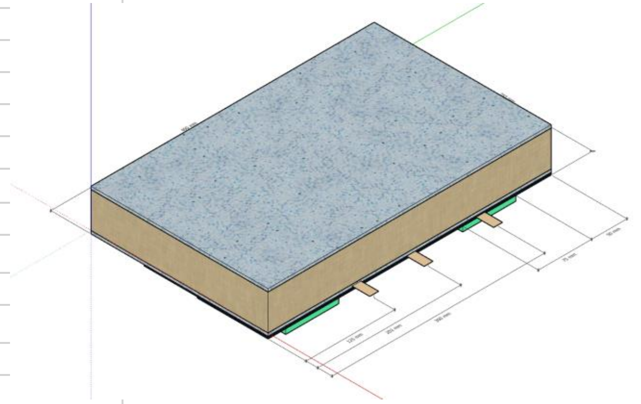
(starting from core surface)

B-Surface	Ply #	Material	thickness	width	notes	comment
	8	DB-600	0.611	250	face down	
	9	UD-1800	1.12	250	face down	
	10	DB-600	0.611	250	face down	
	11	DB-600	0.611	250	face up	
	12	UD-1800	1.12	250	face up	
	13	DB-600	0.611	250	face up	
	14	DB-600	0.611	175	face down	ply drop 1
	15	UD-1800	1.12	175	face down	ply drop 1
	16	UD-1800	1.12	100	face up	ply drop 2
	17	DB-600	0.611	100	face up	ply drop 2
		Thickness	**8.15**	**mm**		

Maintain symmetry (plies 8–13)

Ply drops (plies 14–17)

Cored Panel #1



Defect #1: Ply drops on B-surface are built into this laminate as part of layup.
Defect #2: B-surface bond paste 7mm thick applied (width wise 25mm from 1 edge and 50mm from opposite edge and 75mm wide, 2ea.).
Defect #3: Include a6mm, 12mm and 25mm square "voids" equally spaced in center of bond paste (using PE inserts that will be removed or other removable block).
Defect #4: Include a 12mm wide by 25mm long (embedded) "pull tabs" as delaminations in 3 places along long direction panels ("thick edge") as shown in dwg).
Defect #5: Include a 12mm wide by 25mm long (embedded) "pull tabs" 2 places between bond paste and lower edge to simulate a "kissing" bond, located as shown in dwg.
Defect #6: slice PET core 1.5mm thick and 25mm by 50mm and place in B-surface side in center of thickest section of b-side panel (see drwing).

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Panel #1: Cored Panel with Bond Paste: Embedded Features

(1) Ply Drops on B-Surface built into laminate as part of layup.

(2) B-Surface bond paste applied , 7mm thick (2 places).

(i) 25mm from edge and 75mm wide.

(ii) 50mm from opposite edge and 75mm wide (with voids).

(3) 6mm, 12mm and 25mm square paste voids molded into pasted layer (ii).

(4) 12mm wide by 25mm long “pull tabs” as delamination (3 places).

(5) 12mm wide by 25mm long “pull tabs” (2 places) between paste bond and laminate (kissing bonds).

(6) PET insert, 25mm by 50mm, 1.5mm thick centered on B-Surface.

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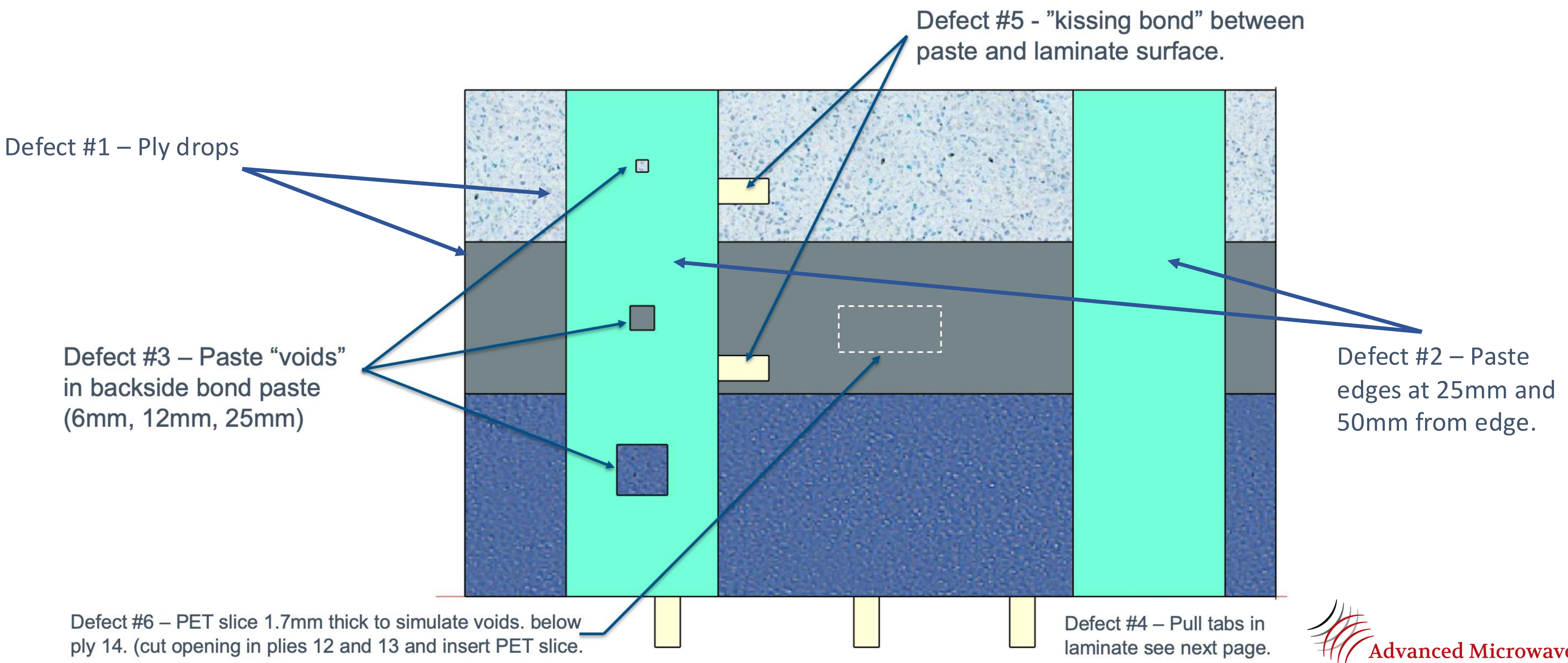
Construction of Inspection Panel #1 (2 ea.)



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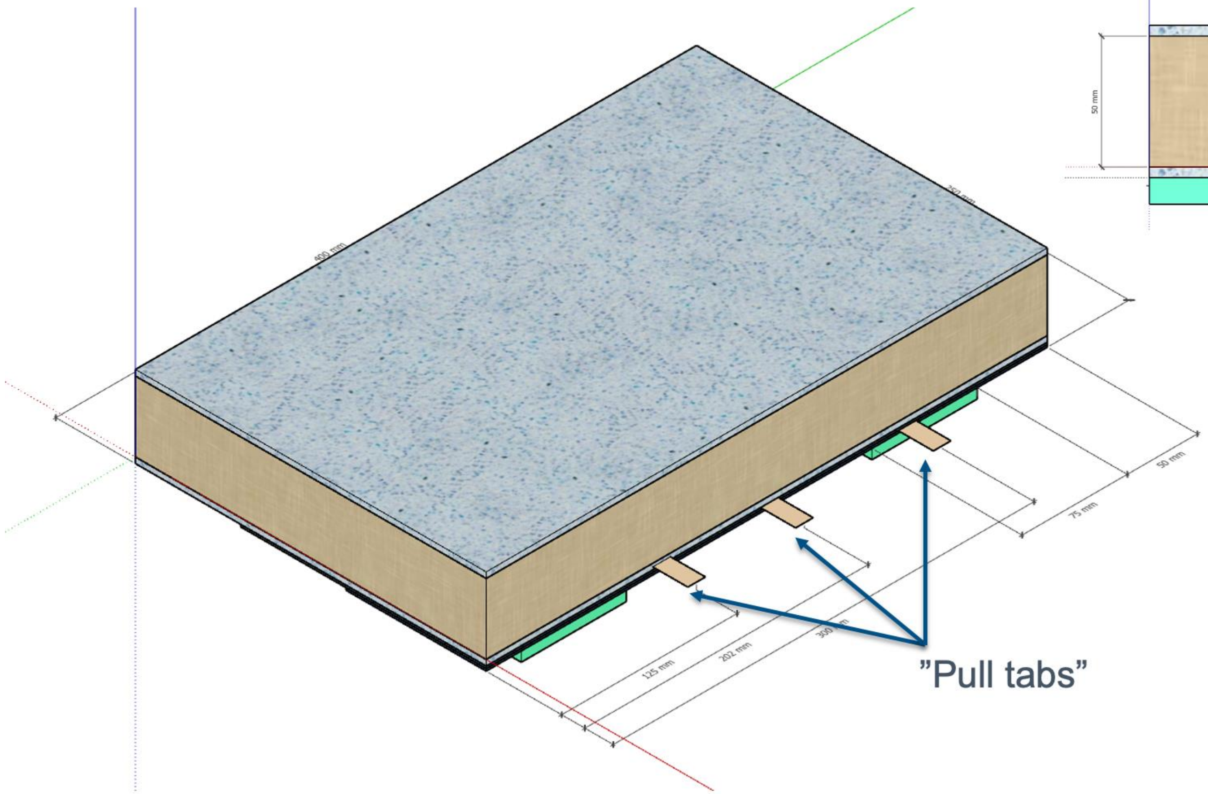
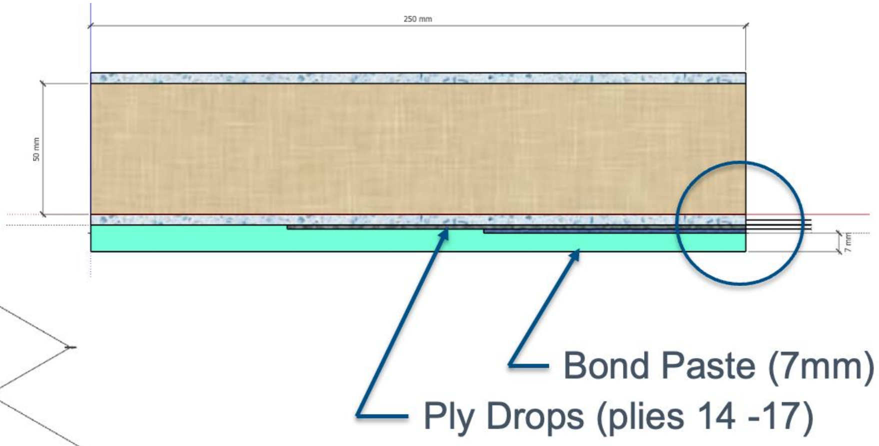
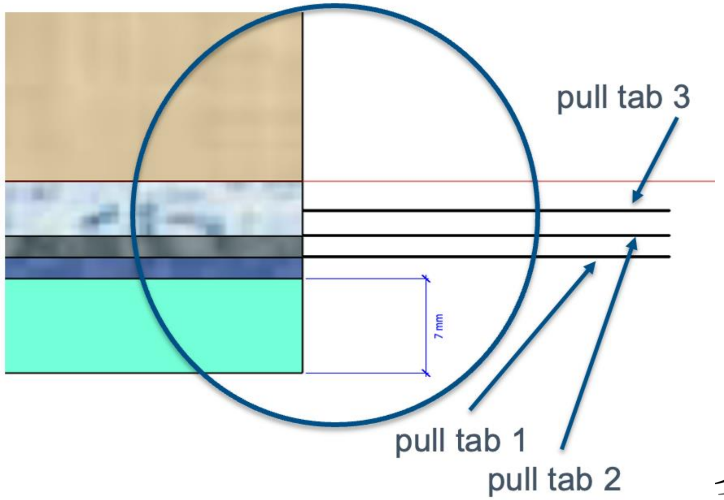
Construction of Panel #1 (Cont.)







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Root Section Porosity

- Blade root includes laminate > 100mm thick.
  - Highly loaded are of the blade.
  - Root inserts complicated infusion.
- Porosity is visible but little correlation between visible appearance and porosity level.
- Repairs require removal and replacement of large amounts of material.

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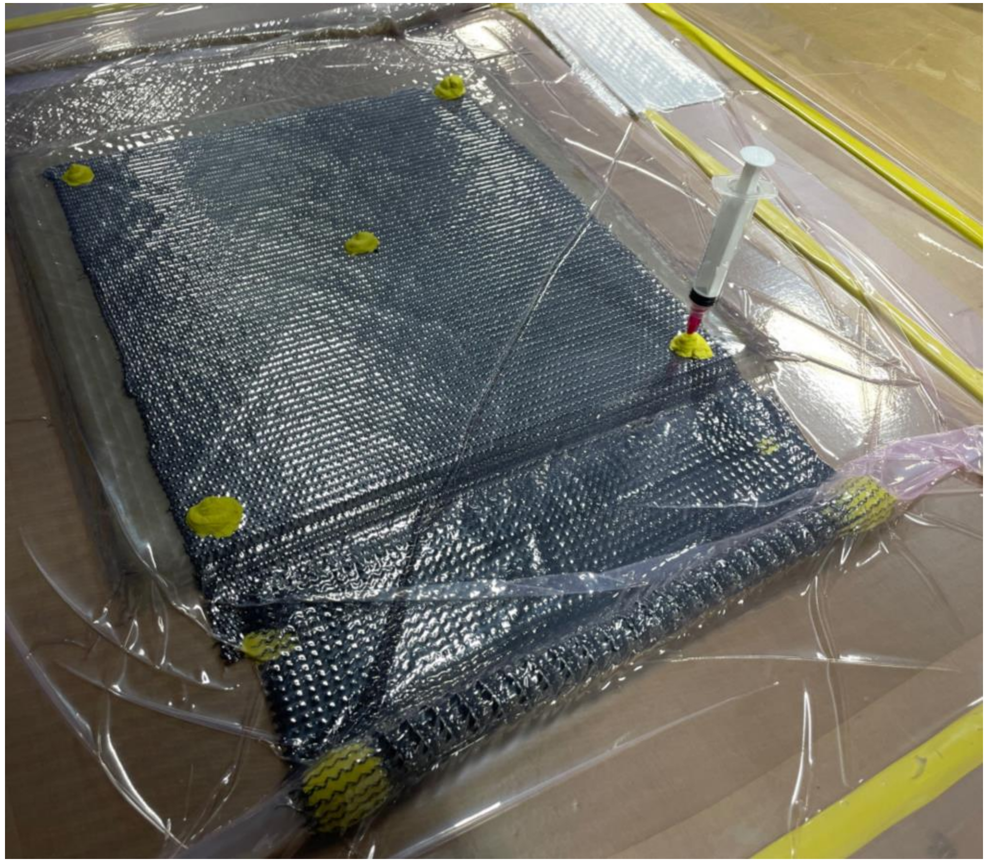
Panel #2: Generation of Controlled Porosity

- Early efforts to "inject" fixed volume of air.
  - Resulted in unrepeatable porosity.
  - Unrepresentative visible morphology.



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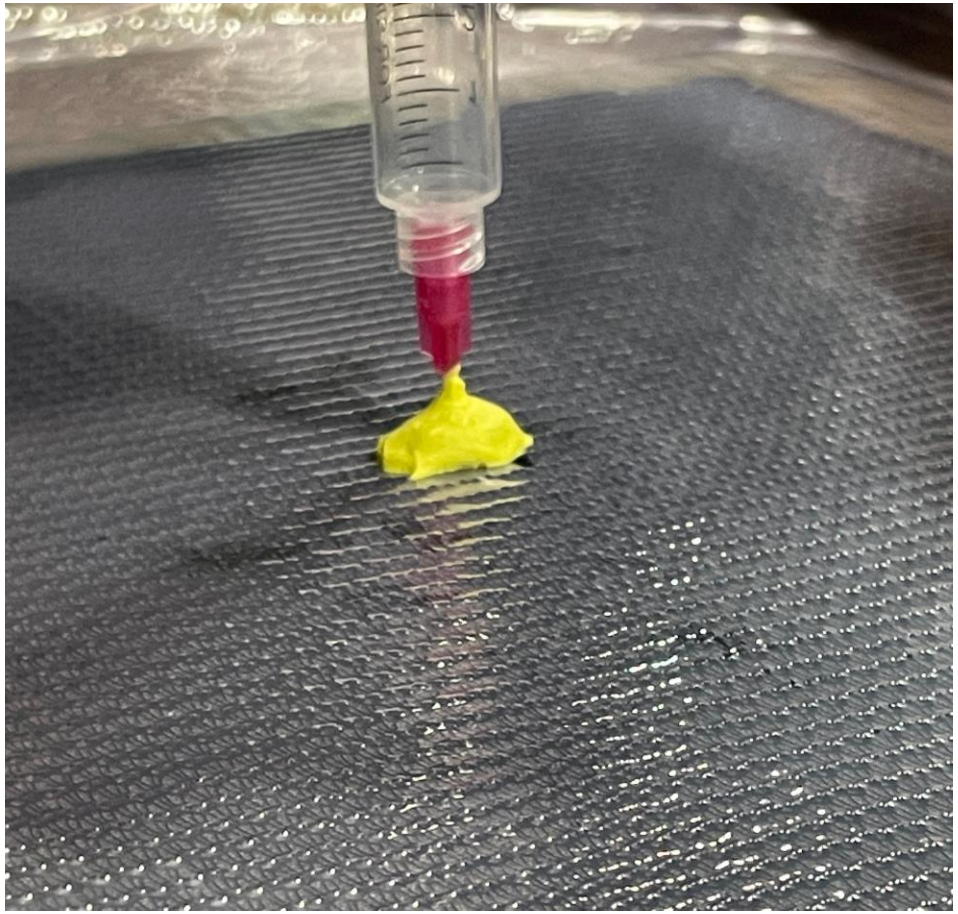
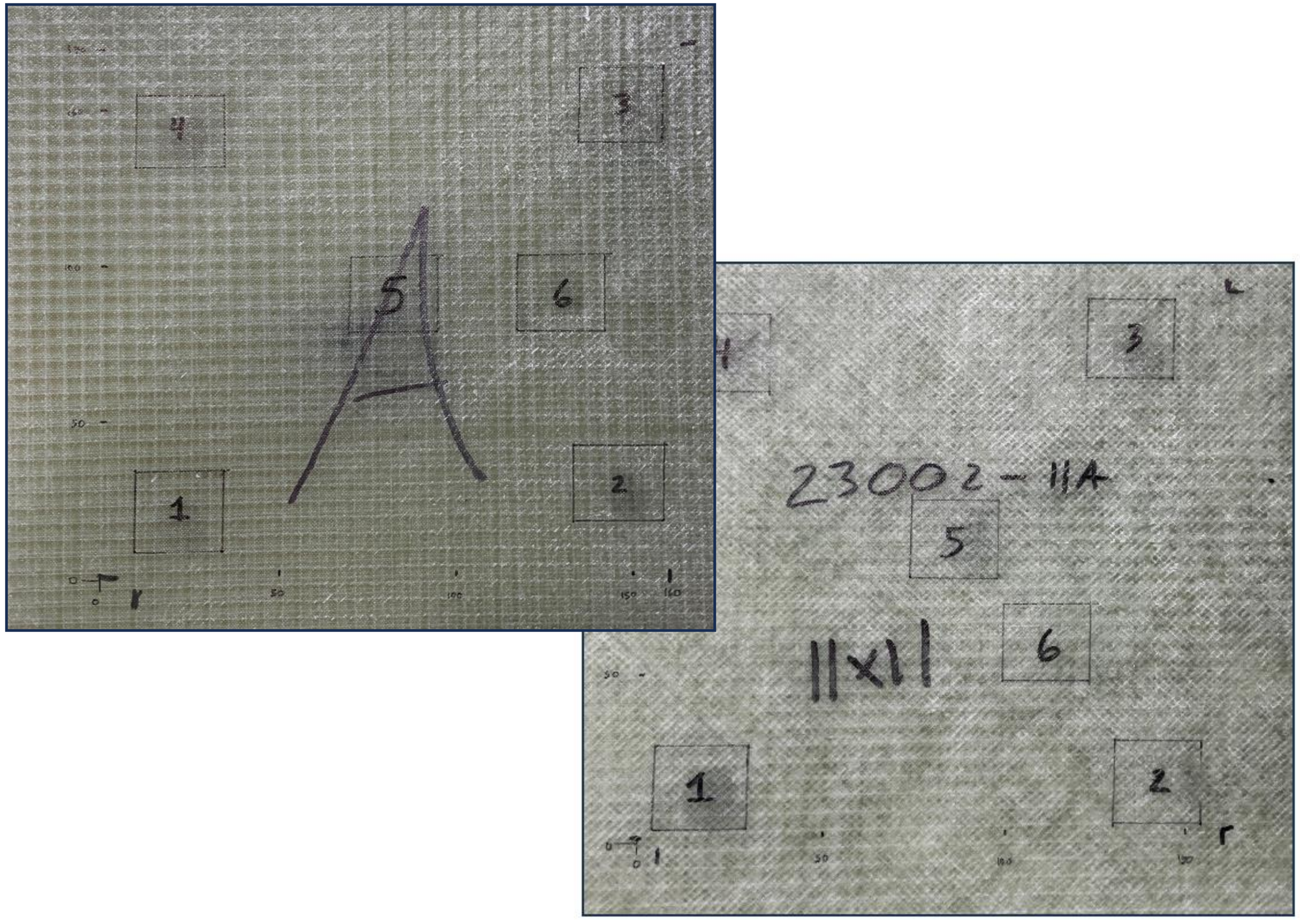
Panel #2: Generation of Controlled Porosity

- **Subsequent work:**
  - Infuse laminate with 0.61mm blunt needle inserted and sealed.
  - Open to atmosphere at fixed periods of time after infusion completion.
  - Predictable and repeatable levels of porosity.
  - Representative of visual defects seen in affected blades.



Two Sets of Four Panels Fabricated

- 300mm x 300mm 18 plies with nominal thickness of ~10mm.
- 800gsm Biaxial [(+/-45),(-/+45)]$_9$ Laminates.
- Target Porosities:
  - Void Free (~0%) Panel 10A
  - “Low” void content ~5% Voids 11A
  - “Mid” void content ~15% Voids 13A
  - “High” Void content ~25% Voids 12A
  - Void Free (~0%) Panel 14A



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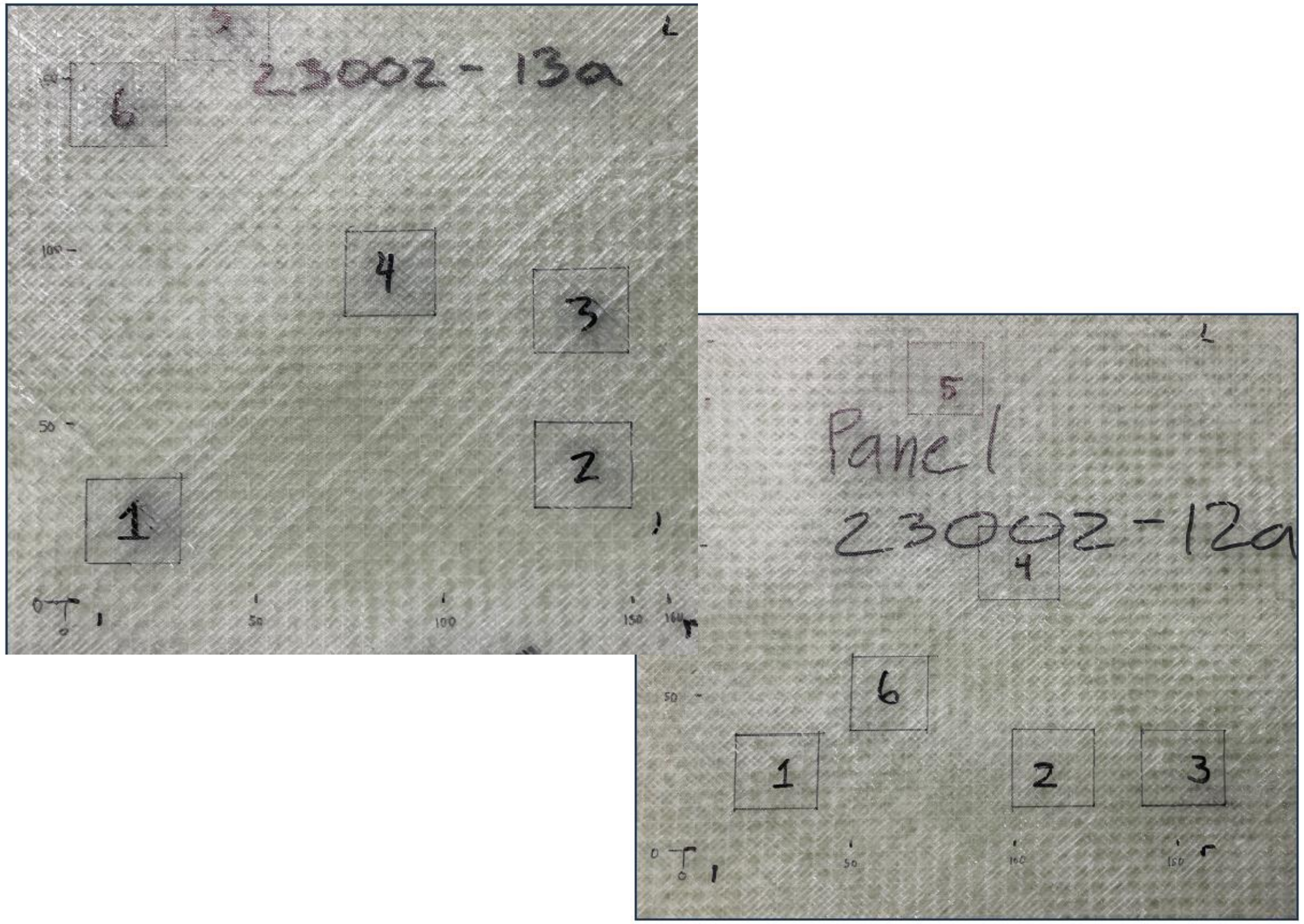

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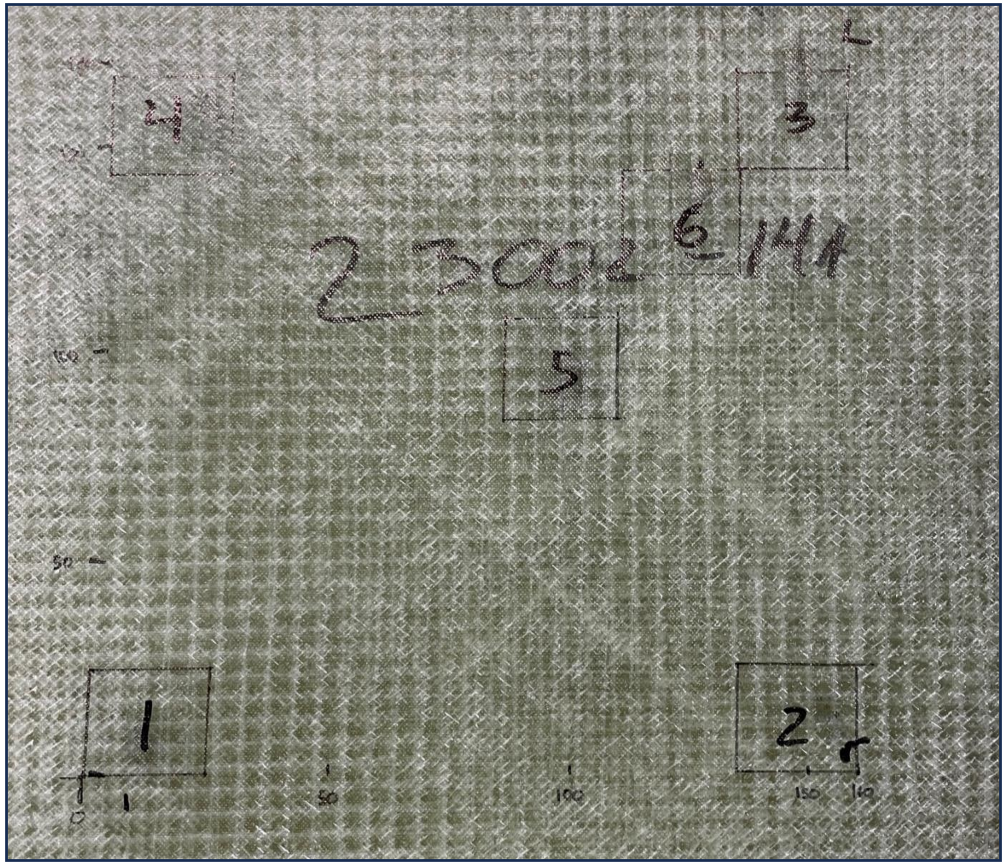

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- Target Porosities:
  - Void Free (~0%) Panel 10A
  - "Low" void content ~5% Voids 11A
  - "Mid" void content ~15% Voids 13A
  - "High" Void content ~25% Voids 12A
  - Void Free (~0%) Panel 14A

Panel	Porosity (%)
10	0.0
11	7.0
12	28.6
13	21.3
14	0.13

Panel	Porosity (%)
10	0.0
14	0.13
11	7.0
13	21.3
12	28.6

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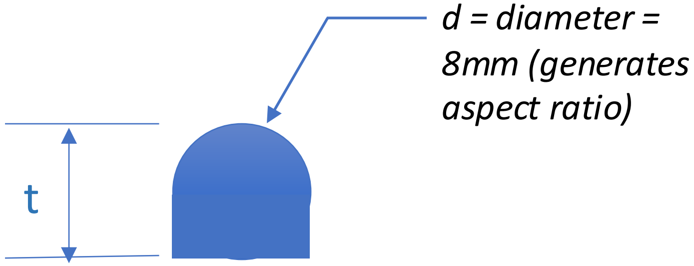
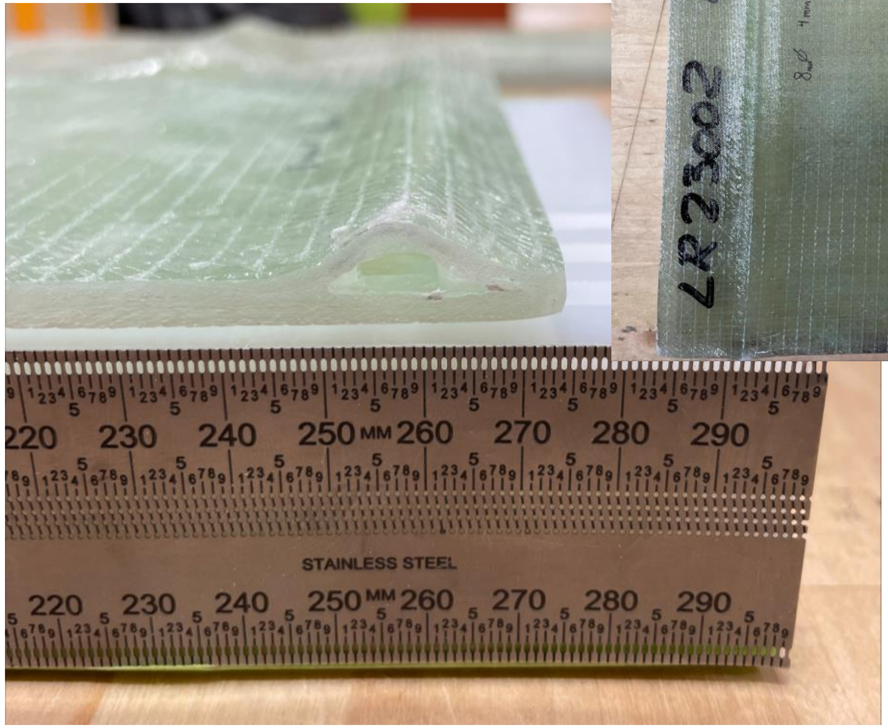
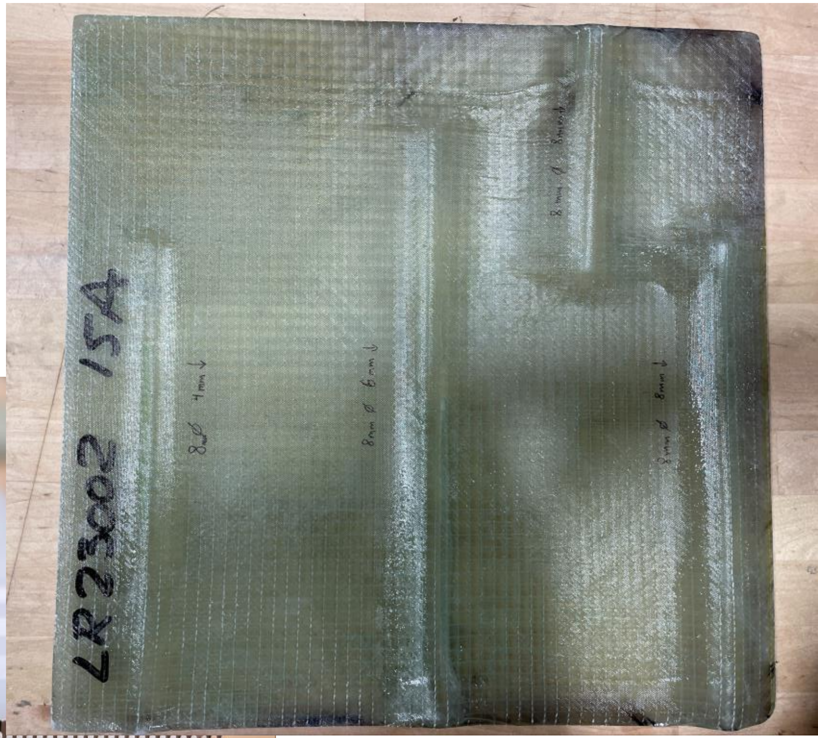
Panel #3: Out-of-Plane Reinforcement Waves (Marcels)

- Panel fabrication with four embedded marcels.
  - 8mm diameter, hemi-spherical epoxy cast of variable thickness.
    - 4mm
    - 6mm
    - 8mm (2 places)
  - Located at center-line of 8 ply 810gsm Biax NCF laminate.



Cast epoxy resin dowels embedded at mid-plane of glass laminate.





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Part 2

Microwave Inspection Background

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Microwave vs UT Similarities (Pulse Echo)

Microwave

- Electromagnetic Radiation(EMR)
- Reflections from differences in Complex Permittivity

Ultrasound

- Acoustic waves
- Reflections from differences in acoustic impedance

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Microwave vs UT Differences (Pulse Echo)

Microwave

- Reflected signals are EMR
- Reflected signals contain a Real portion (dielectric constant) and an Imaginary portion (Loss tangent)
- Surface inspection only of metallic or conductive components
- Transmits well through most non-metallic materials
- Air coupled – requires no couplant
- No surface contact

Ultrasound

- Reflected signals are sound waves
- Reflected signals contain amplitude and frequency
- Volumetric inspection of metallic or conductive component
- Sound waves are attenuated through many composite materials
- Predominantly requires a liquid or gel couplant
- Typically, surface contact through couplant

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Microwave System Characteristics

- Low output power (10mW) so its inherently safe
- The system is lightweight
- The advanced multi-frequency systems accurately detect, size, and locate flaws in X Y space and depth
- The electronics are robust and have been field deployed in harsh conditions
- The architecture allows it to be easily adapted to multiple scanners and scanning systems and field situations

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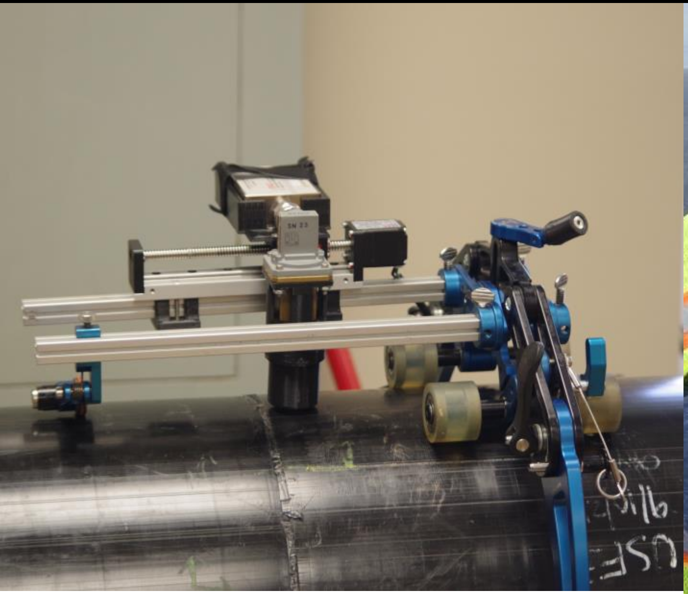
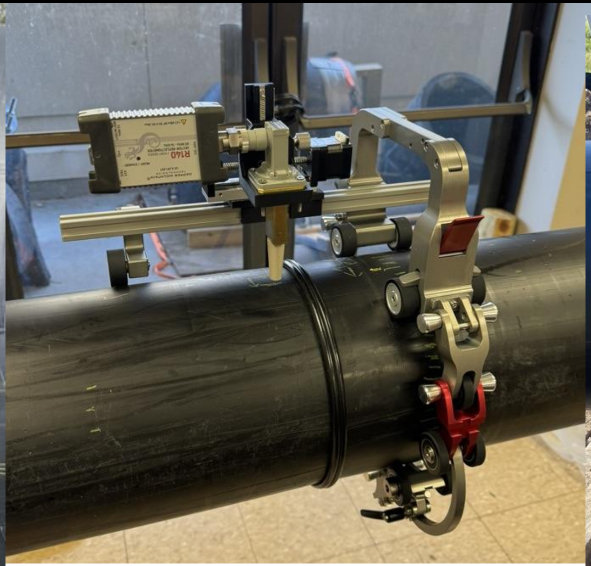
MICROWAVE NDT SYSTEMS





- Pipe Scanner Systems

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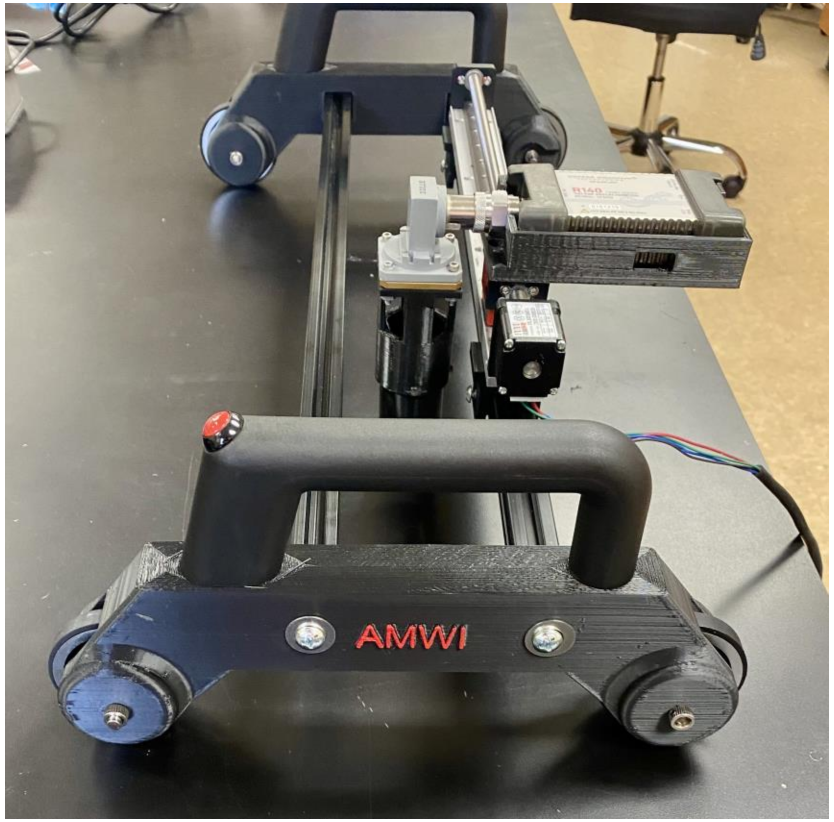
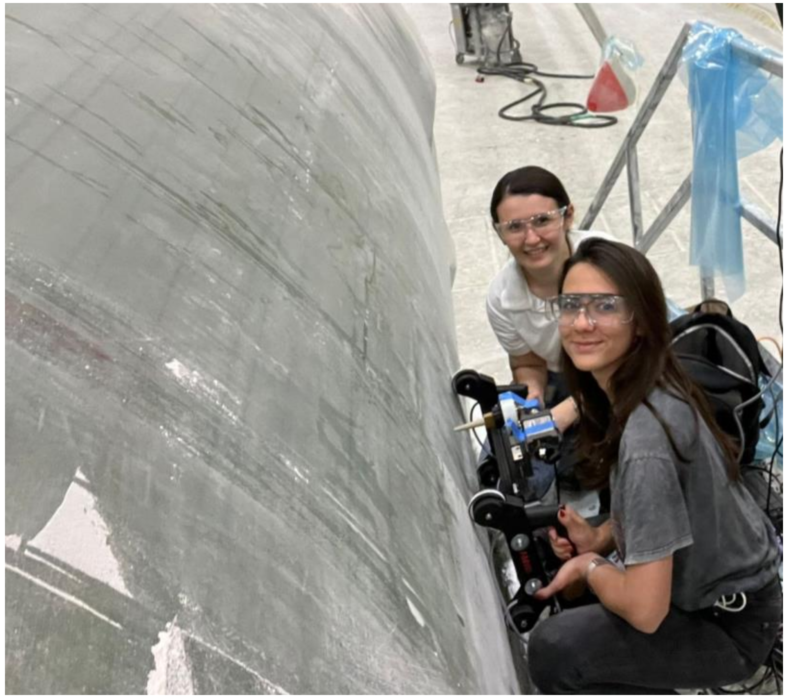
MICROWAVE NDT SYSTEMS

- Motorized Axis Portable Scanner Systems





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MAPS In Field Use

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MICROWAVE NDT SYSTEMS

- Portable Tank Scanner Systems

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MICROWAVE NDT SYSTEMS

- COBOT ROBOTIC SYSTEMS

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COBOT In Use

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MICROWAVE NDT SYSTEMS

- HAUSBOT Vertical Wall Crawler

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MICROWAVE NDT SYSTEMS

- Hand Held Time of Flight
- Thickness and Flaw Detector

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Part 3

Microwave Inspection
Sandia Panels

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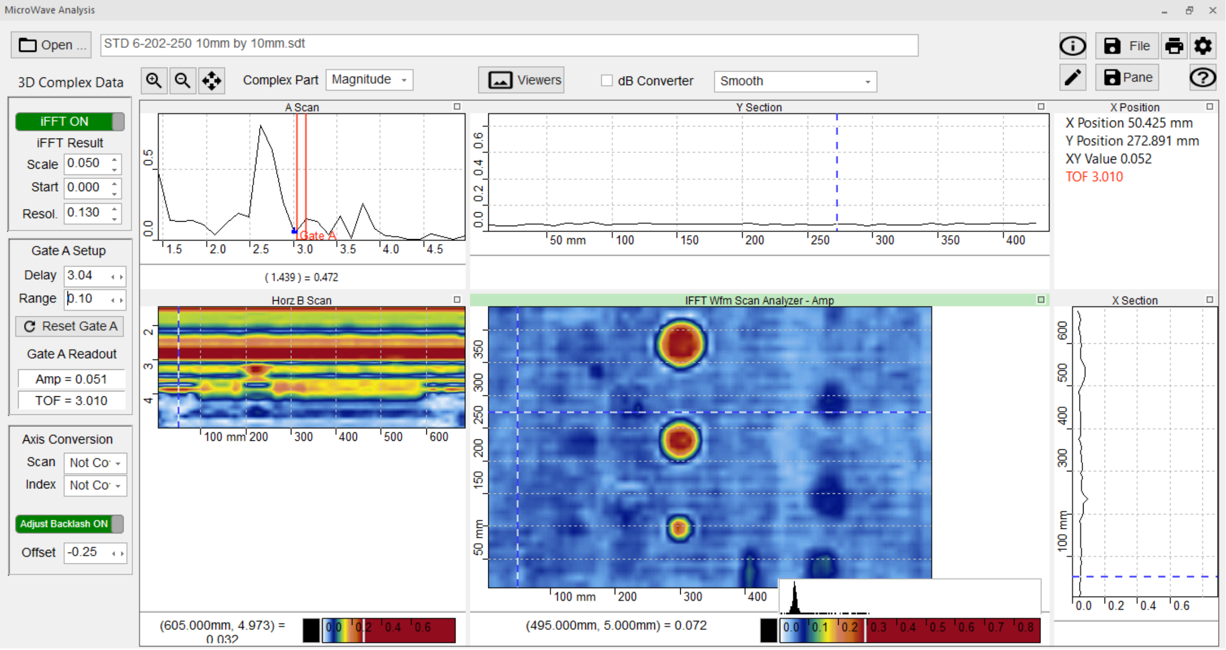
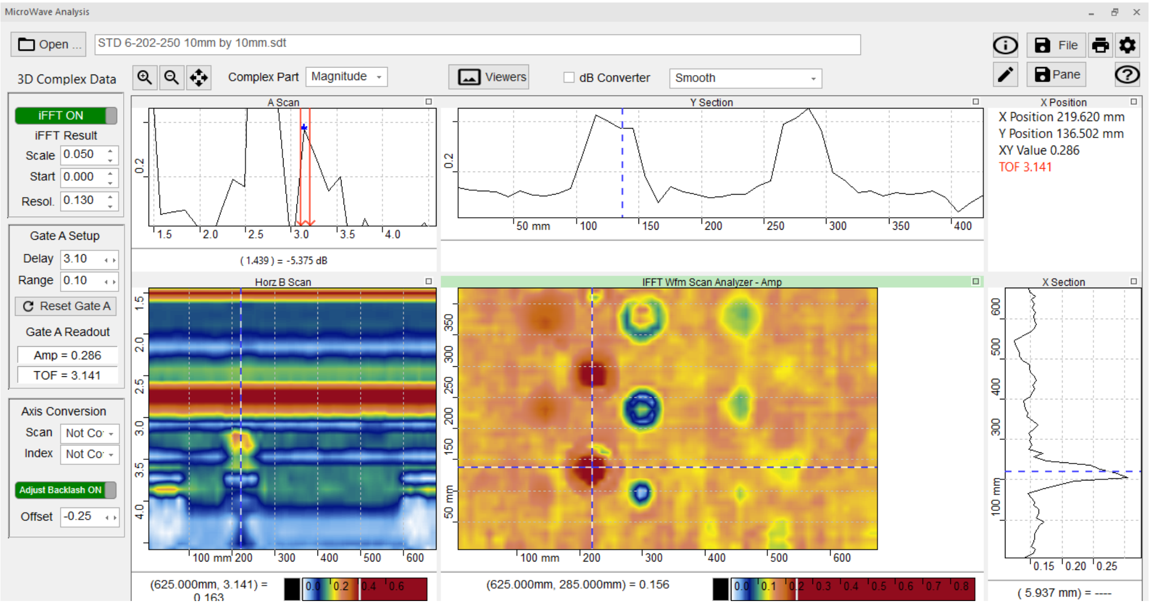
Sandia Panels





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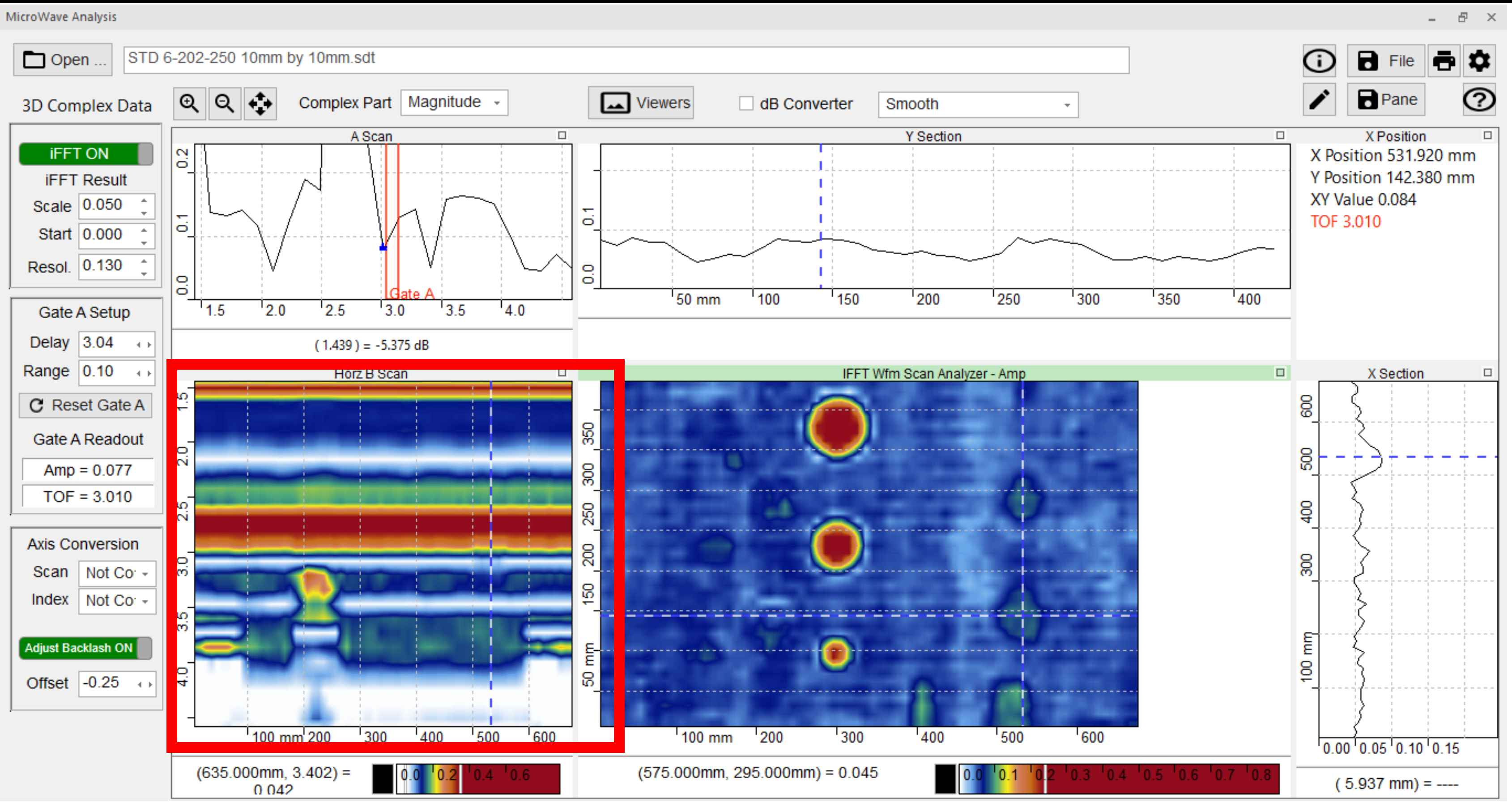
Horizontal B Information



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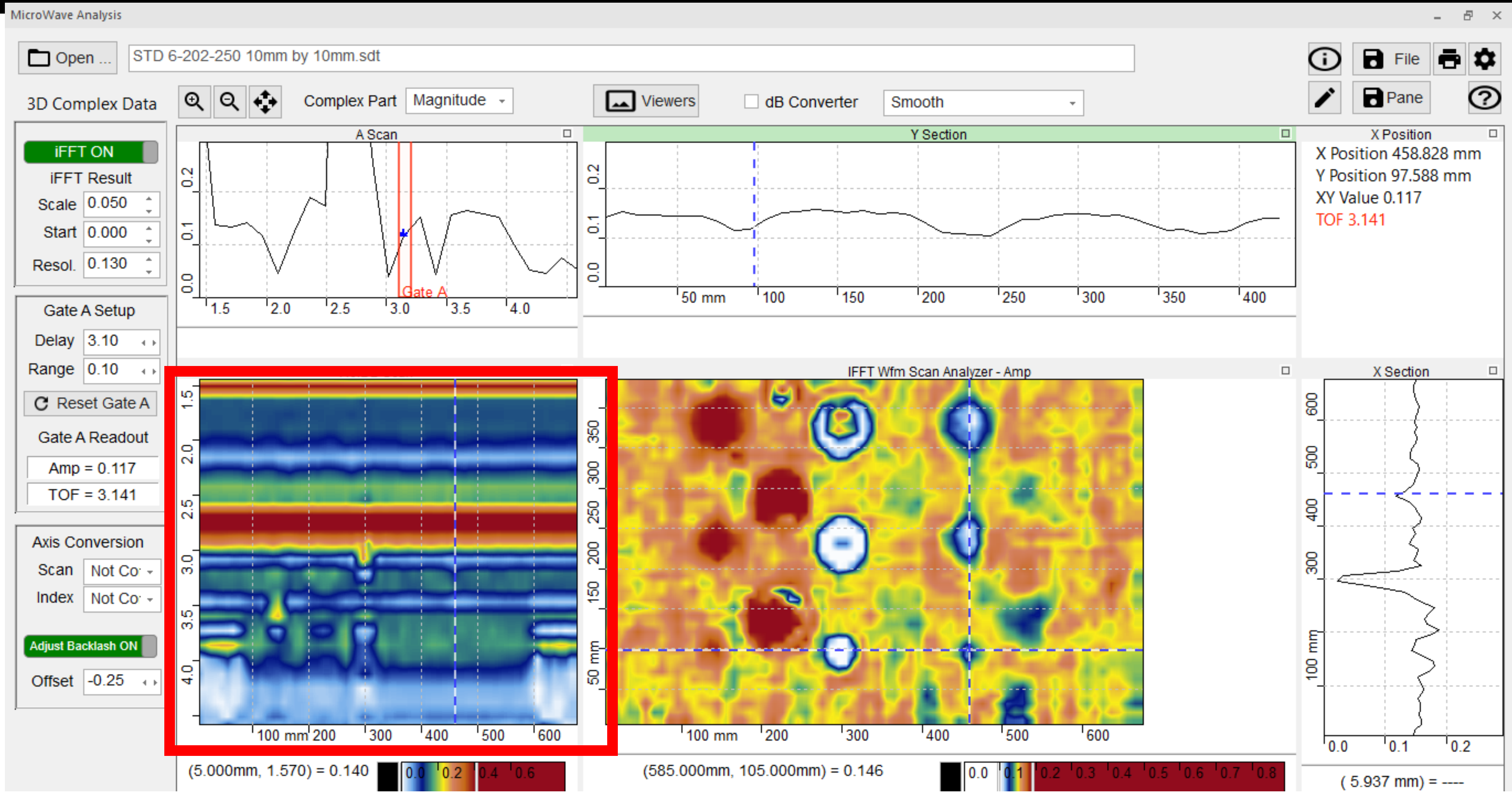

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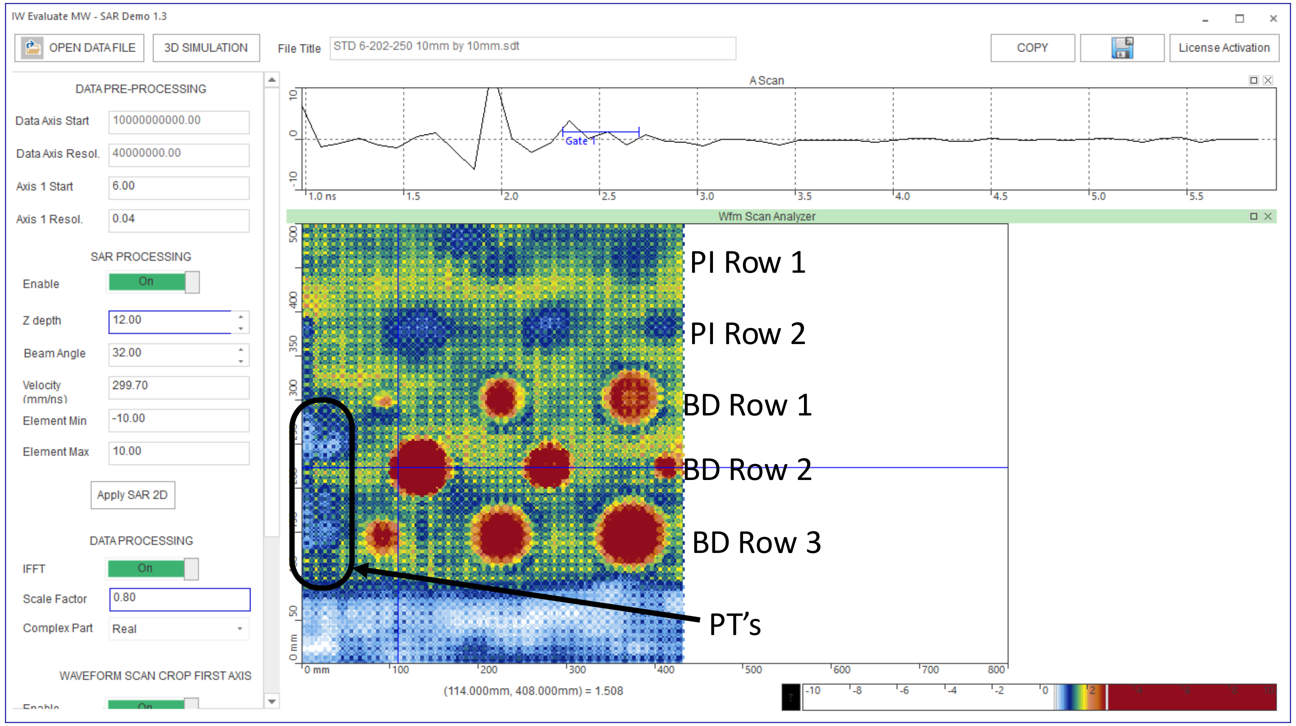
Synthetic Aperture Radar Focusing



BD = Back Drilled Hole
PI = Pillow Insert
PT = Pull Tab

Note the SAR image is truncated in the Y axis (500mm versus 680)

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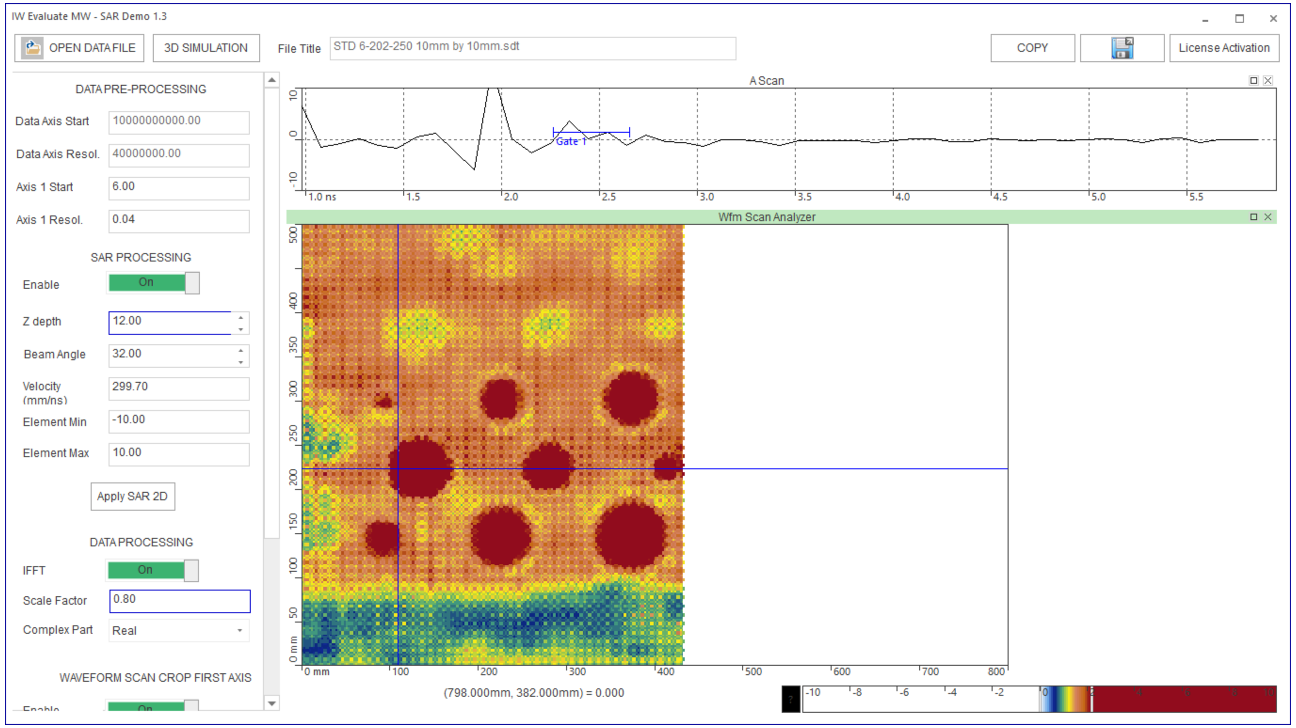
SAR Image



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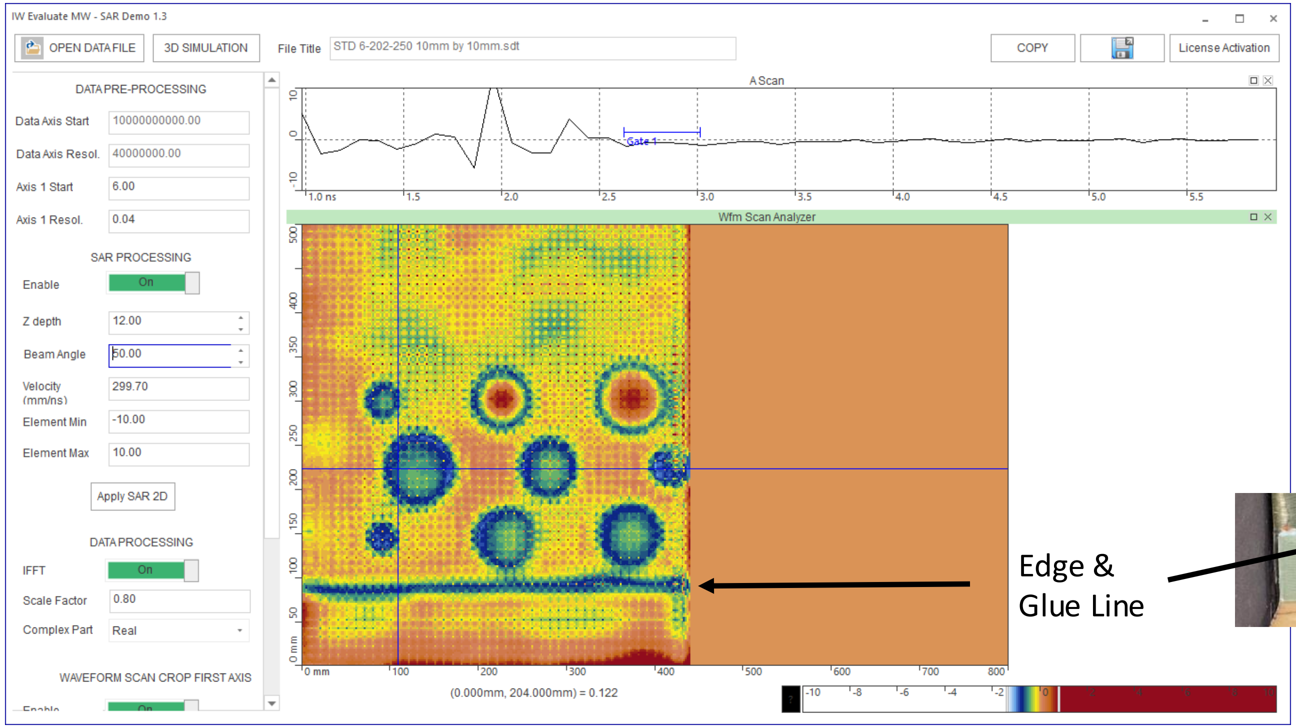
SAR Image



Edge & Glue Line

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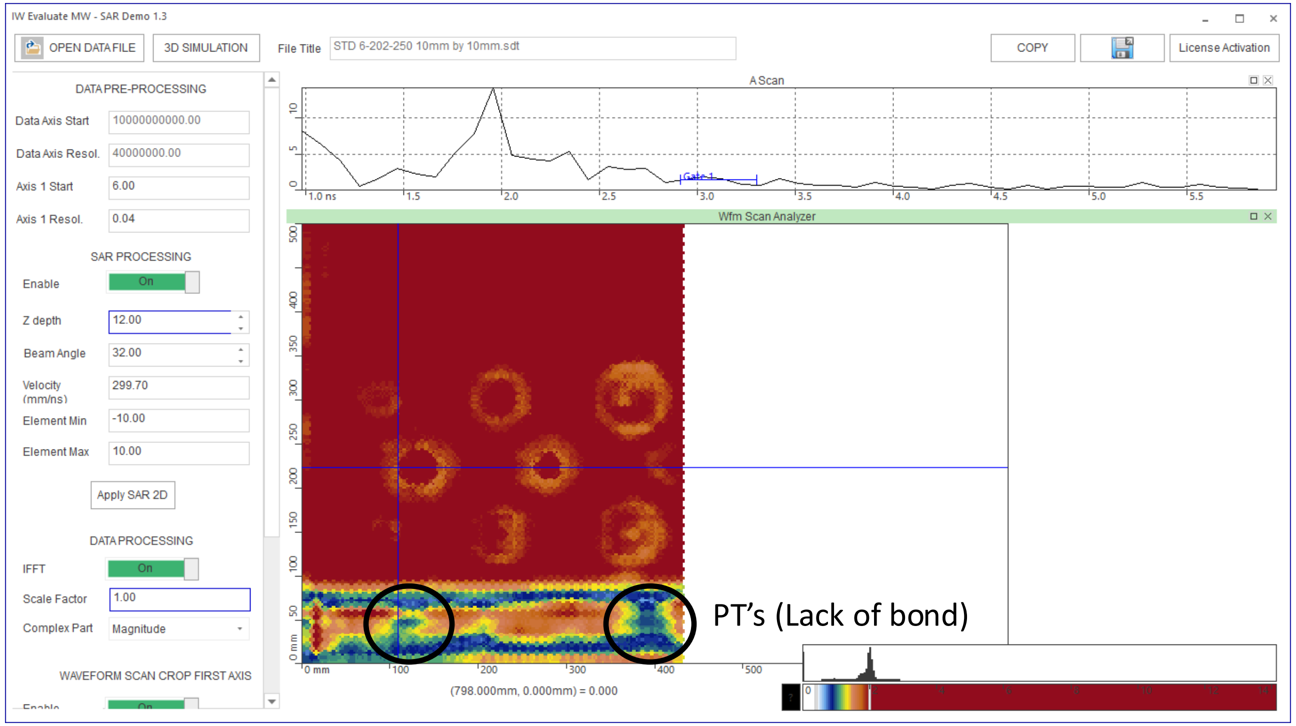
SAR Image



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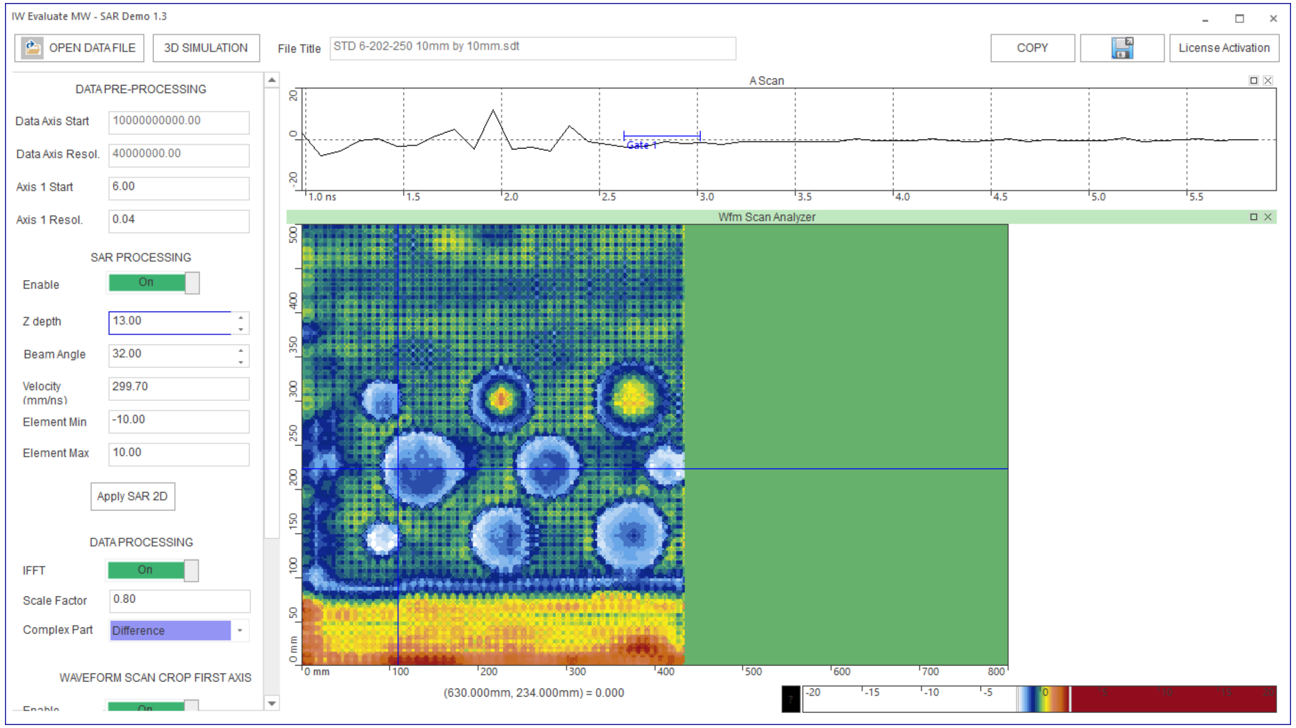

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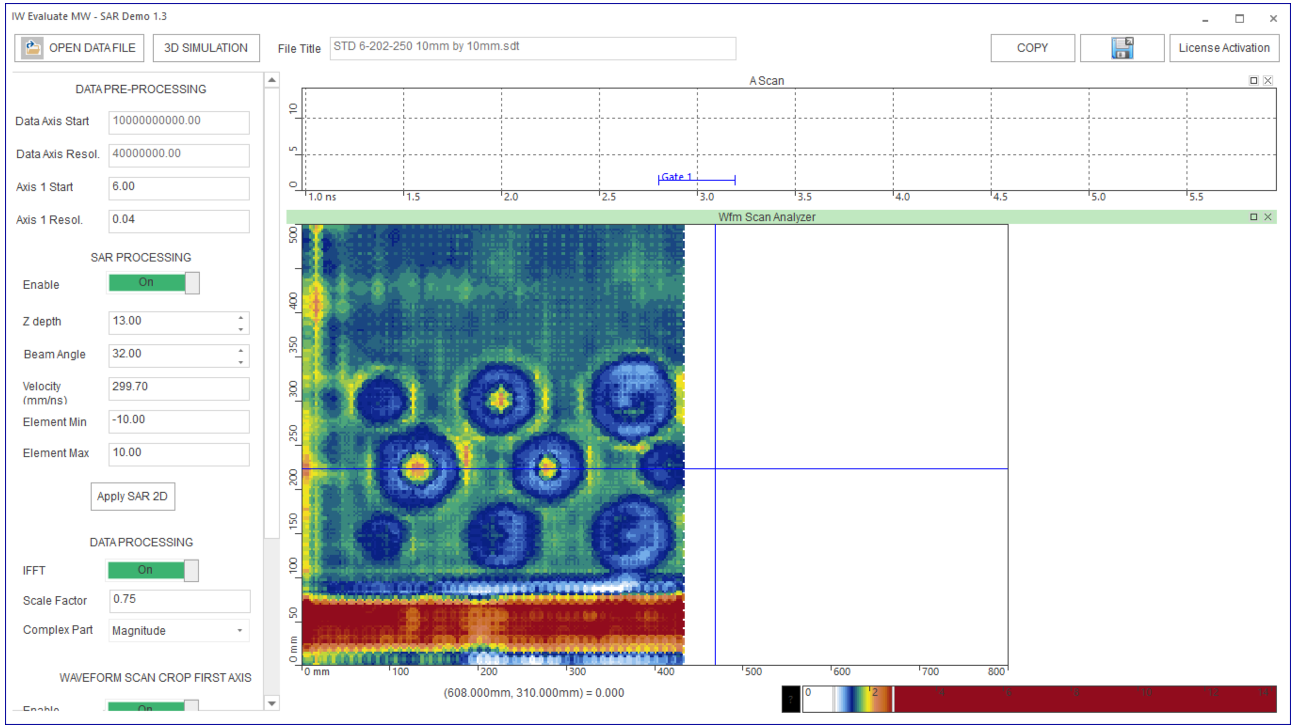

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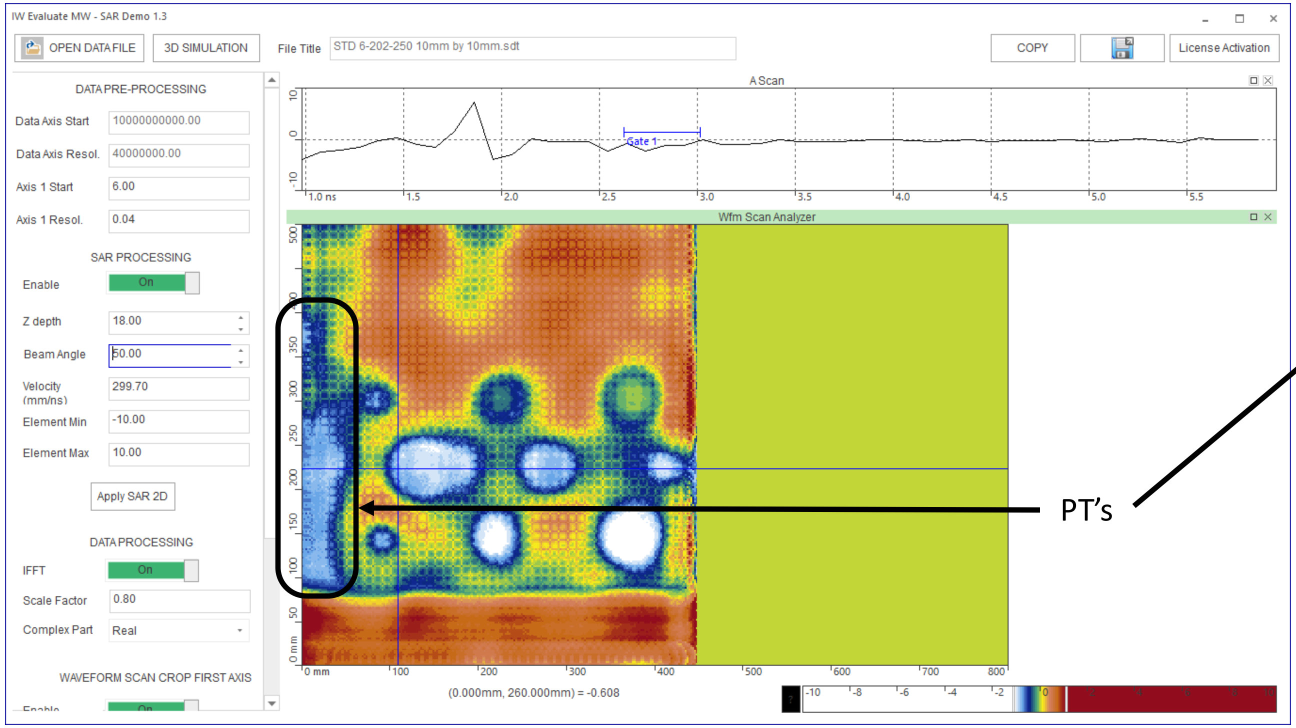

PT's

BD = Back Drilled Hole
PI = Pillow Insert
PT = Pull Tab

Note the SAR image is truncated in the Y axis (500mm versus 680)

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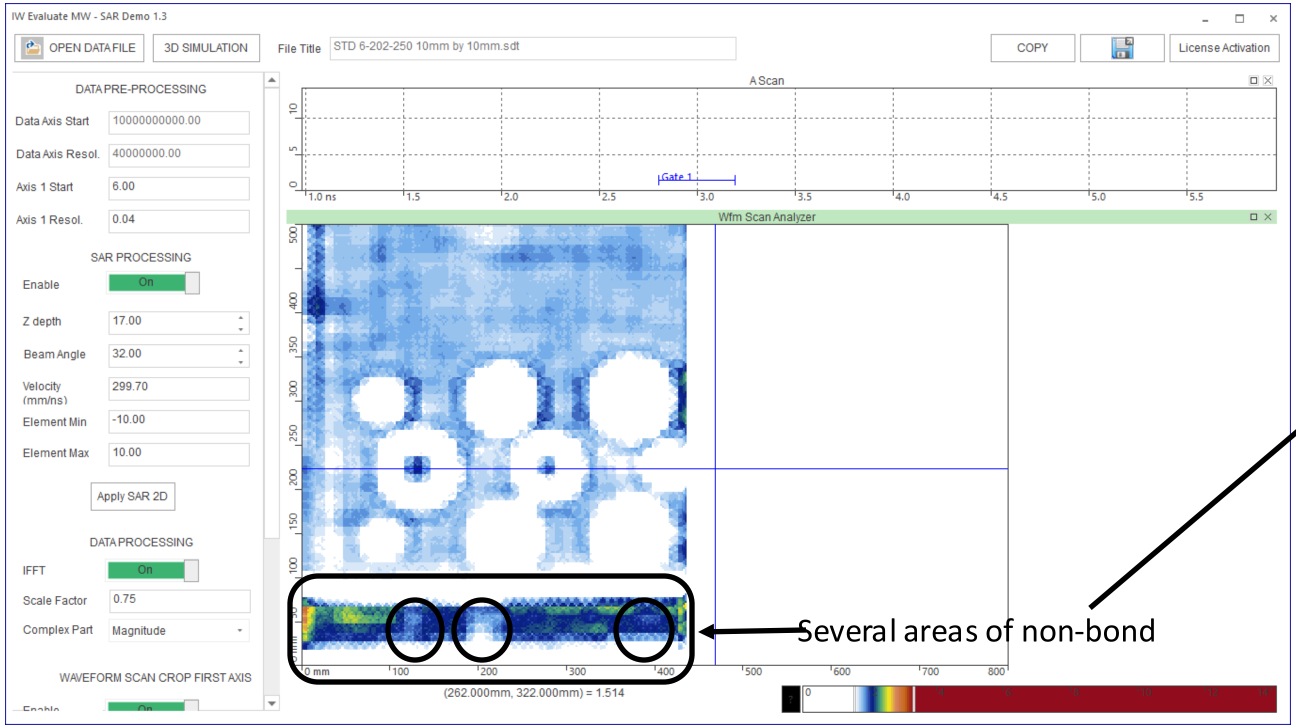
SAR Image



Several areas of non-bond

BD = Back Drilled Hole
PI = Pillow Insert
PT = Pull Tab

Note the SAR image is truncated in the Y axis (500mm versus 680)

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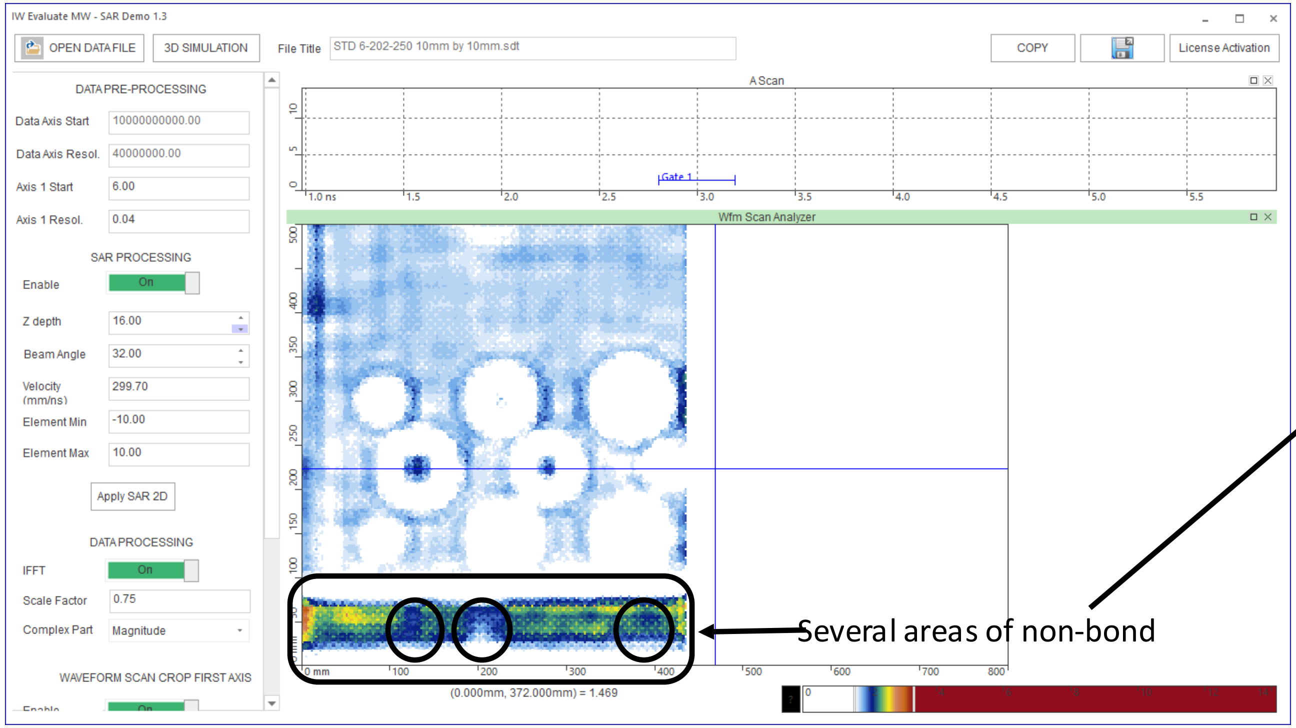
SAR Image



Several areas of non-bond

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Note the SAR image is truncated in the Y axis (500mm versus 680)

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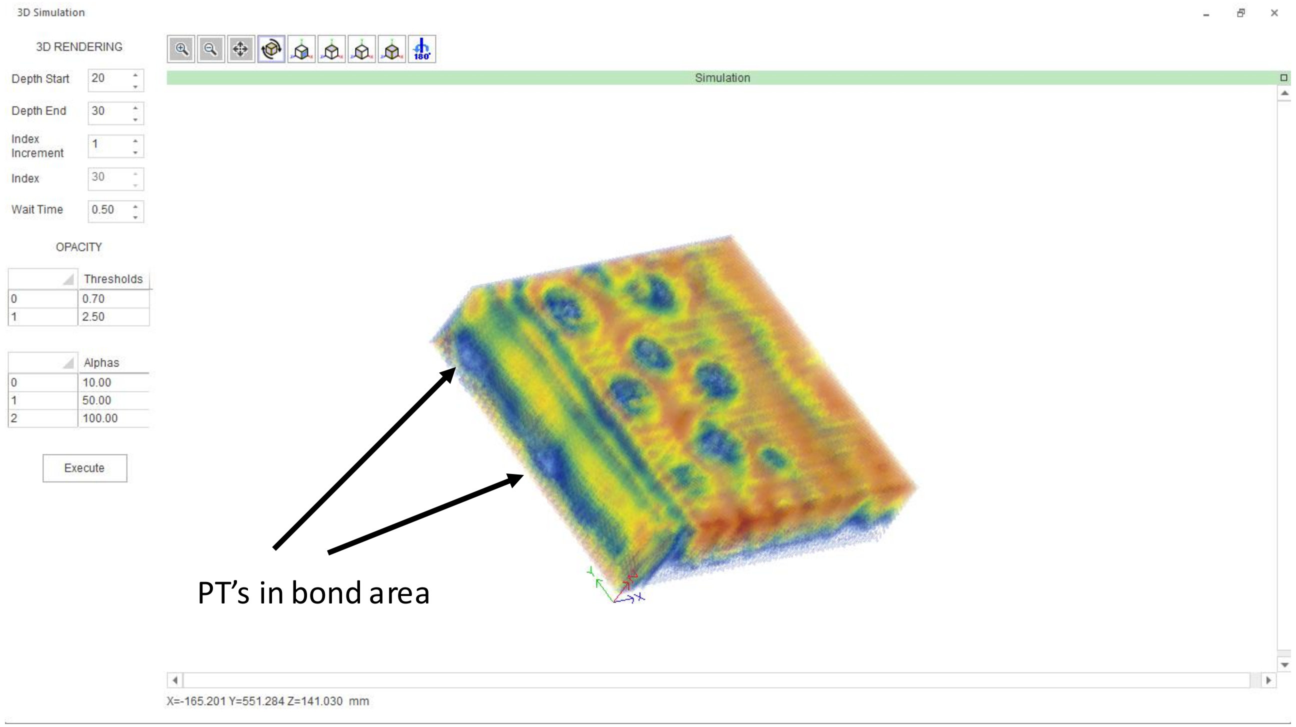
3D Render



PT's in bond area

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Part 4

Microwave Inspection
TPI Composite
Balsa and Foam Core Samples

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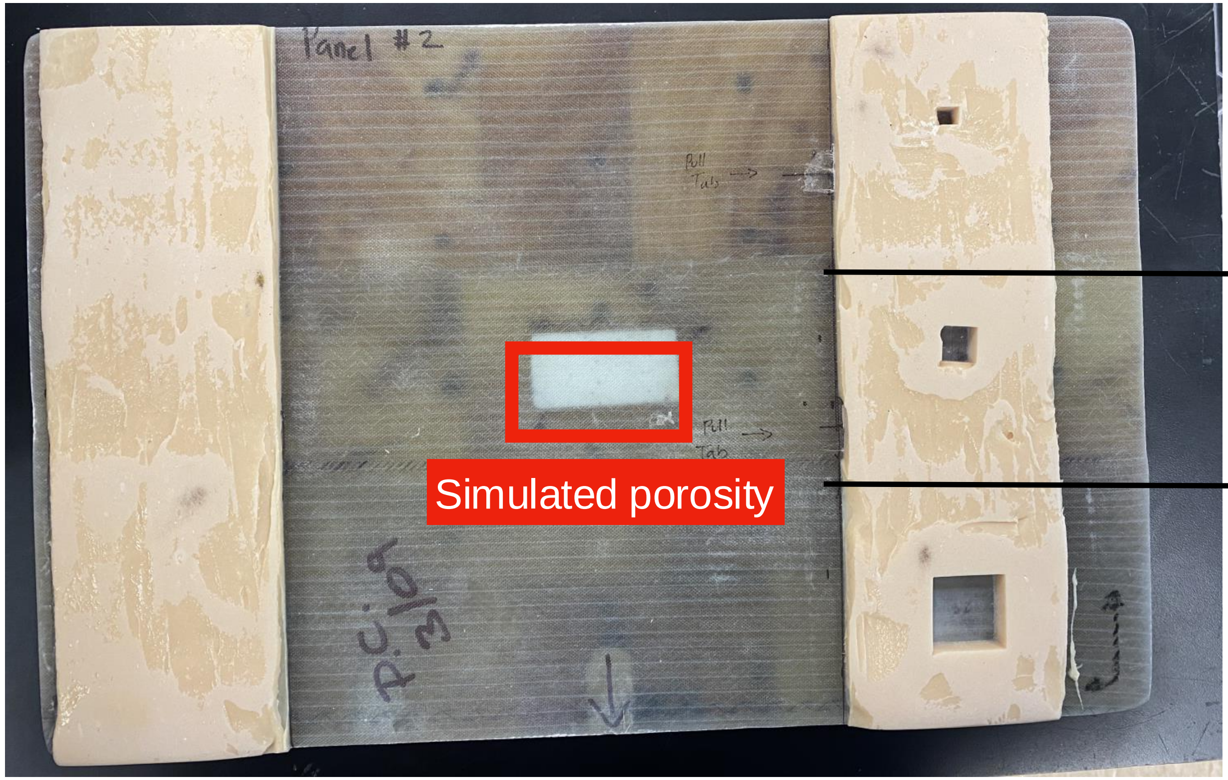
Balsa Sample



Underside of balsa panel

Ply Drop

Ply Drop

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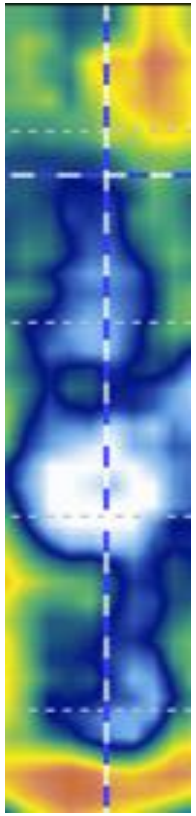
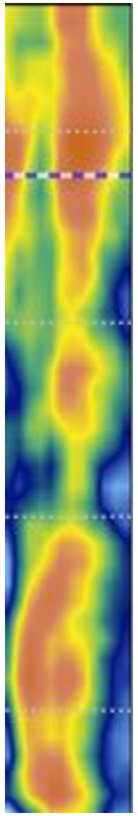
Balsa Bond Line Results





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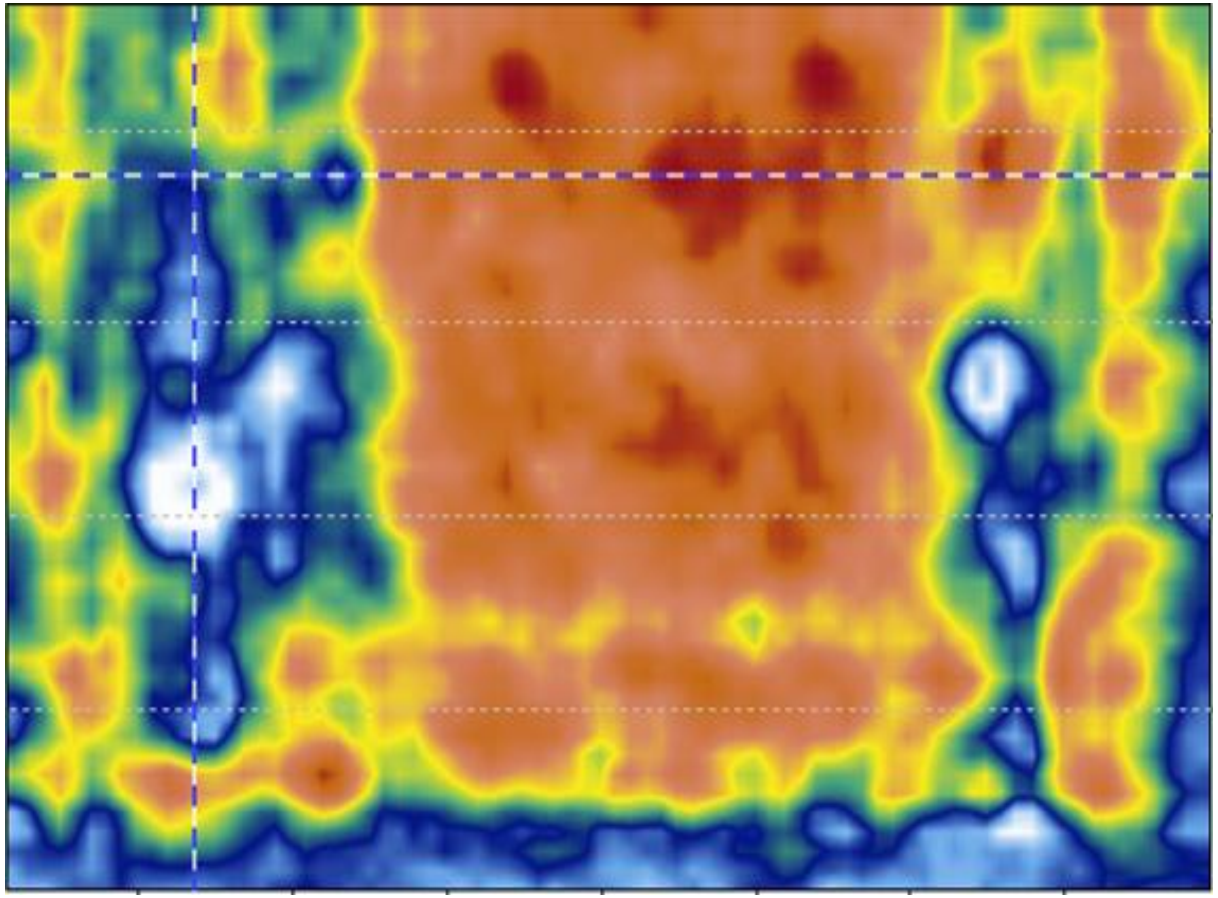
Balsa Core –MI Image



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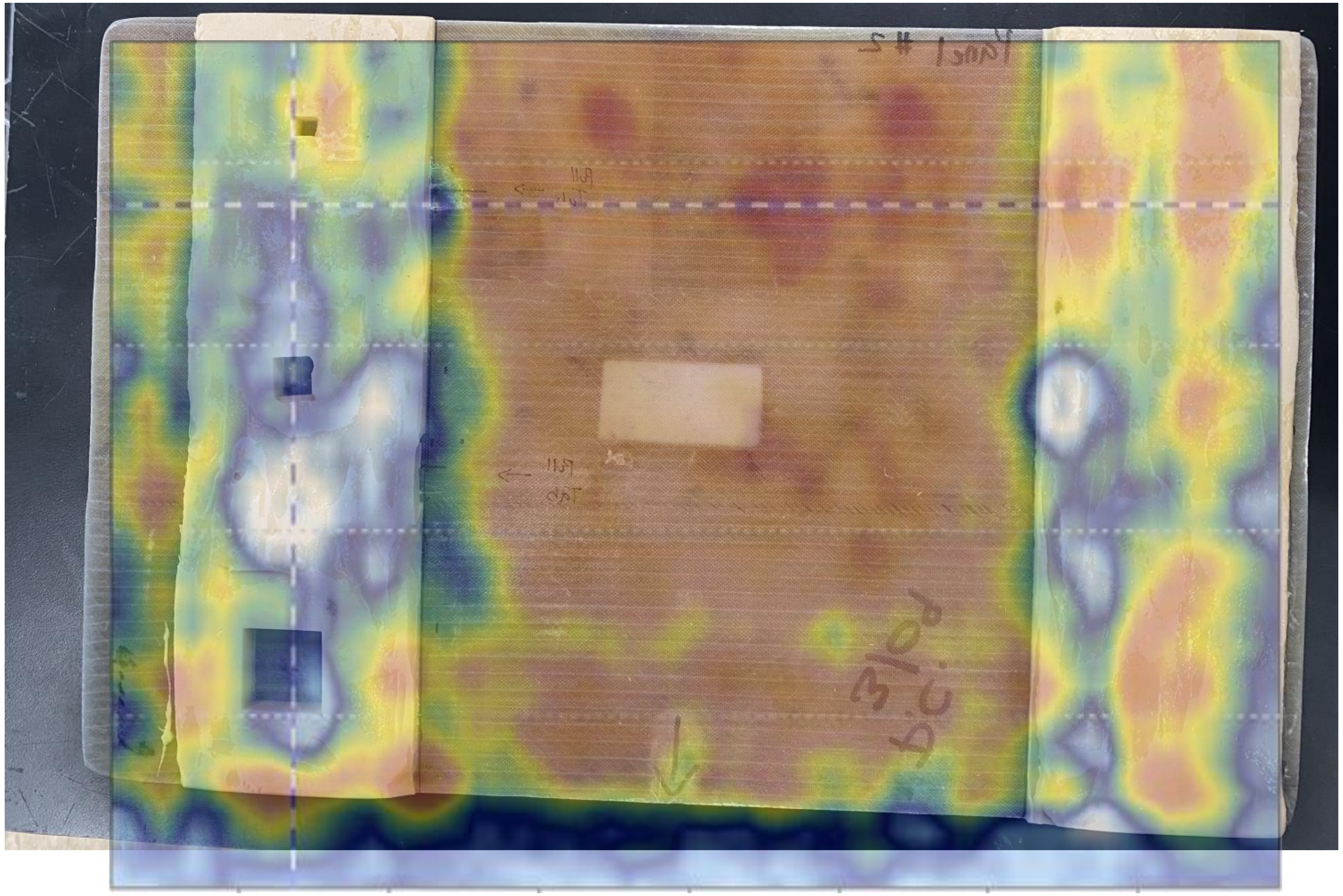
Balsa Core – Overlay of MI Image



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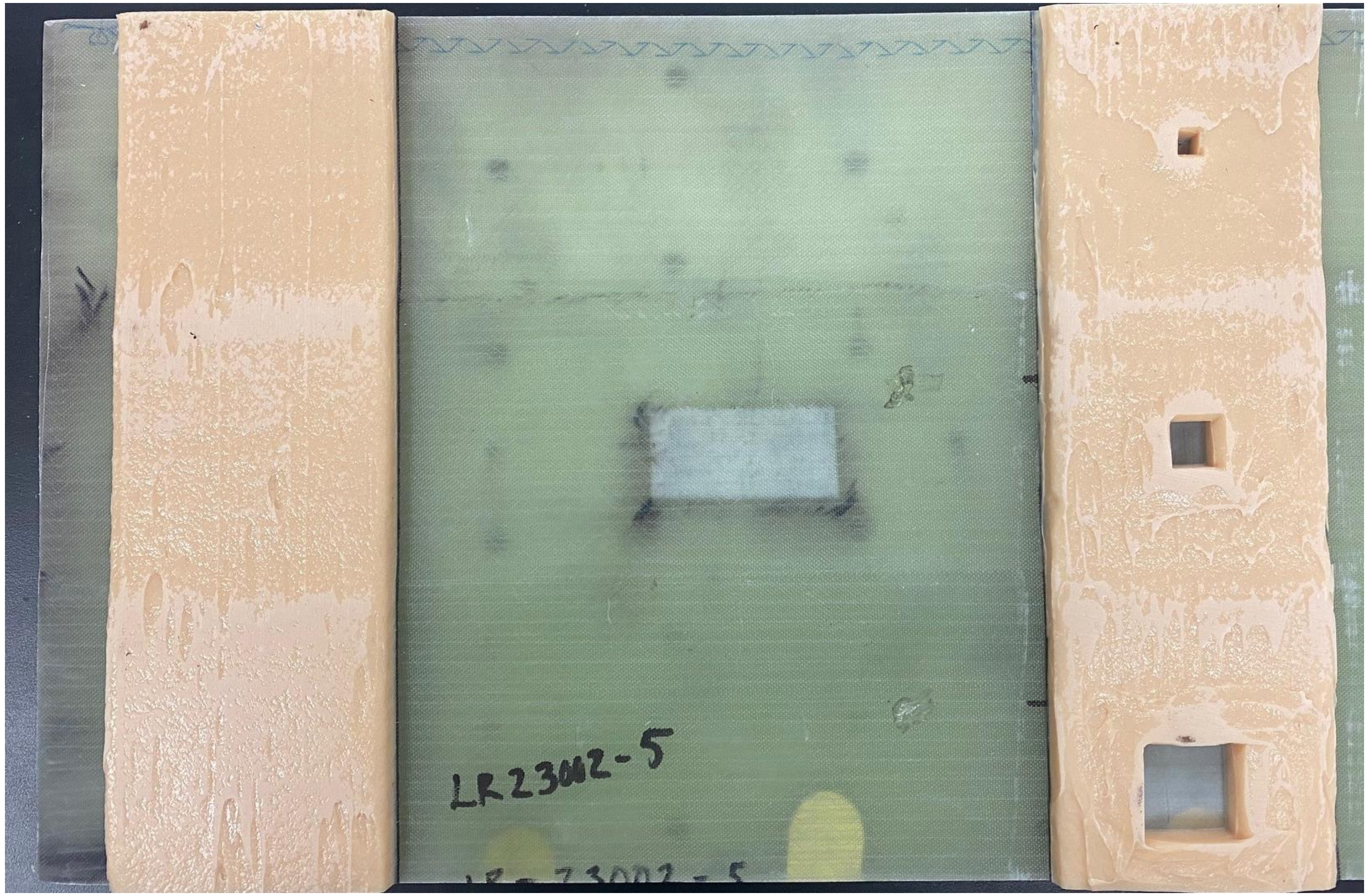
Foam Core Sample



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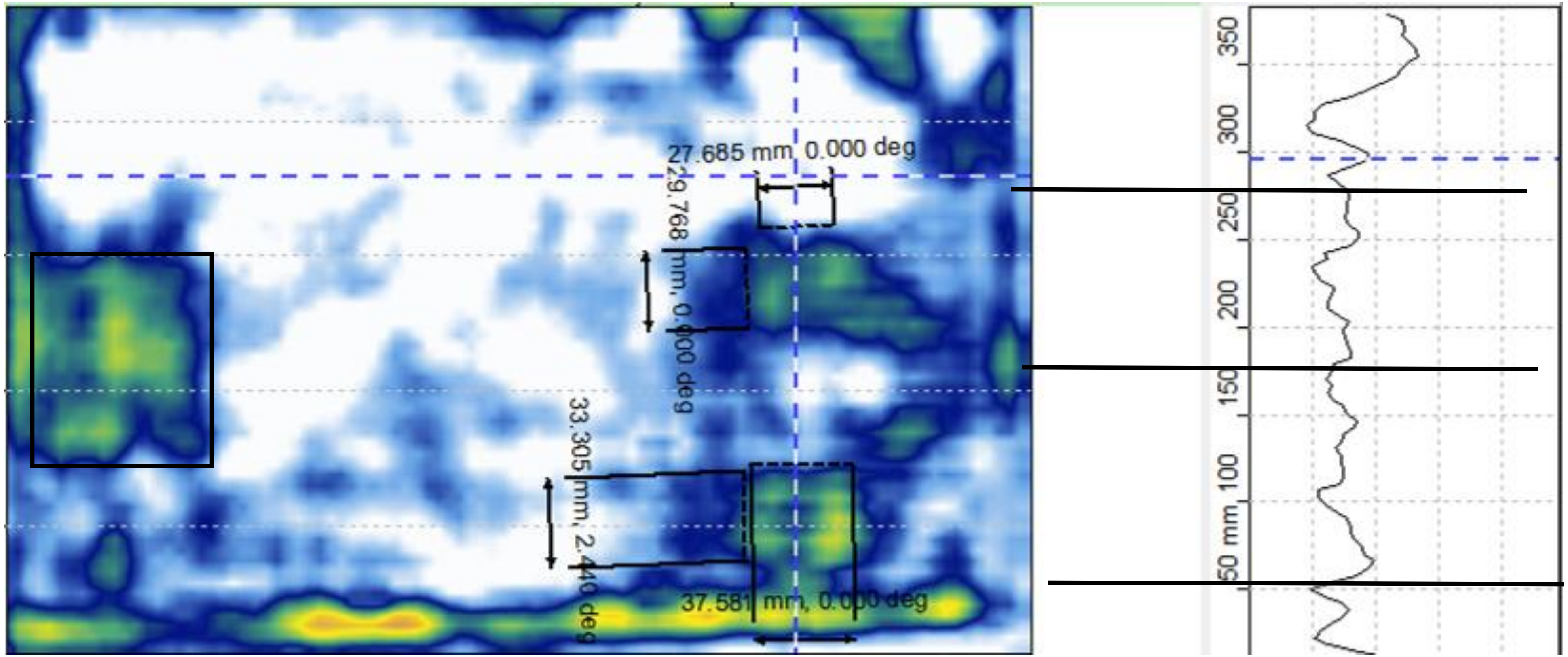
Foam Core-MI Image



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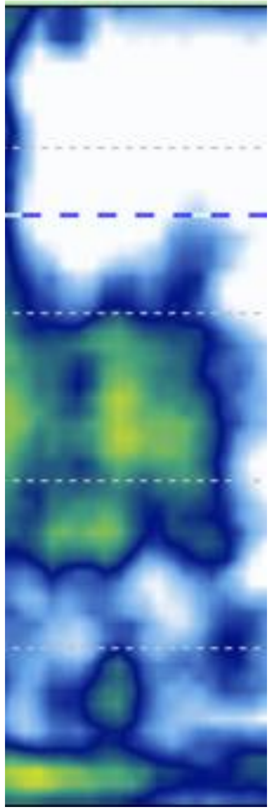
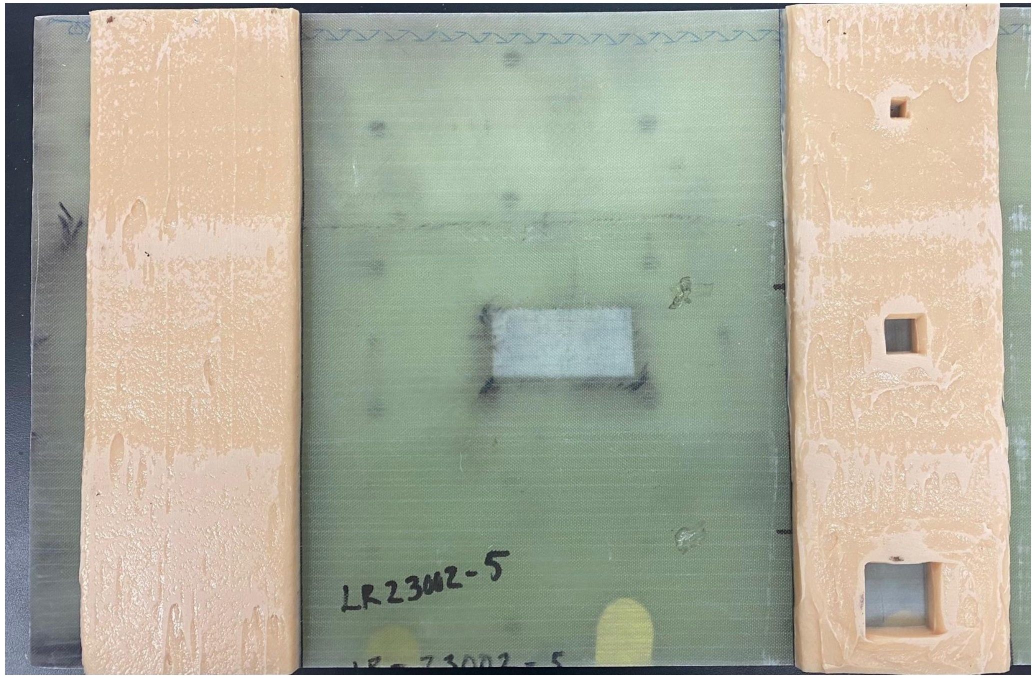
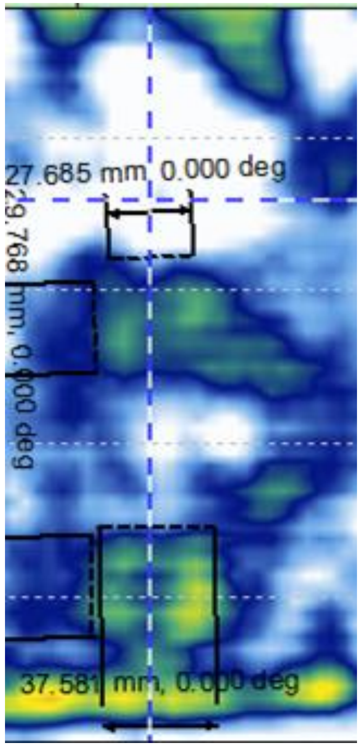
Foam Core Bond Line







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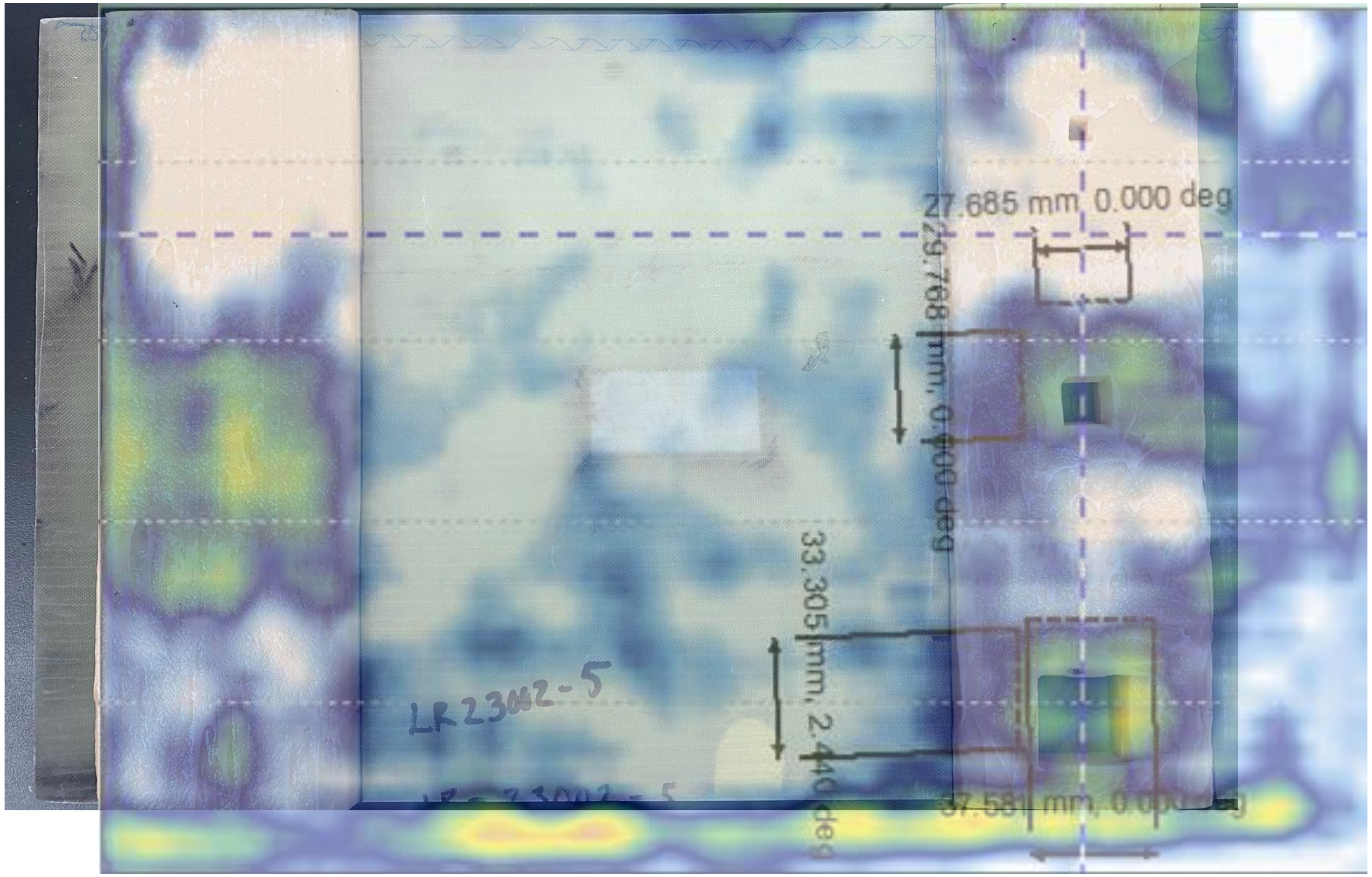
Foam Core Overlay



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Part 5

Microwave Inspection
TPI Composite
Porosity Samples

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Methodology

- All 5 samples were inspected in a 150mm by 170mm section in the center of the part
  - This was done to eliminate the edge effect from the result
- The samples were inspected in order from 10-14
- Inspection parameters are as follows:
  - 10-18GHz with the antenna located approximately 7mm from the surface
  - Real, Imaginary and Magnitude data at 11.56 GHz (arbitrary selection) was used to generate images for porosity
  - Using this data, the samples were arranged based on the result from high dB to low in the following order
  - This should be the approximate order of porosity, either more to less or less to more (TBD)
- Typically, in GFRP inspection, the higher dB value would be interpreted as a dry area
  - For this inspection, this will be interpreted as more porosity but should be validated

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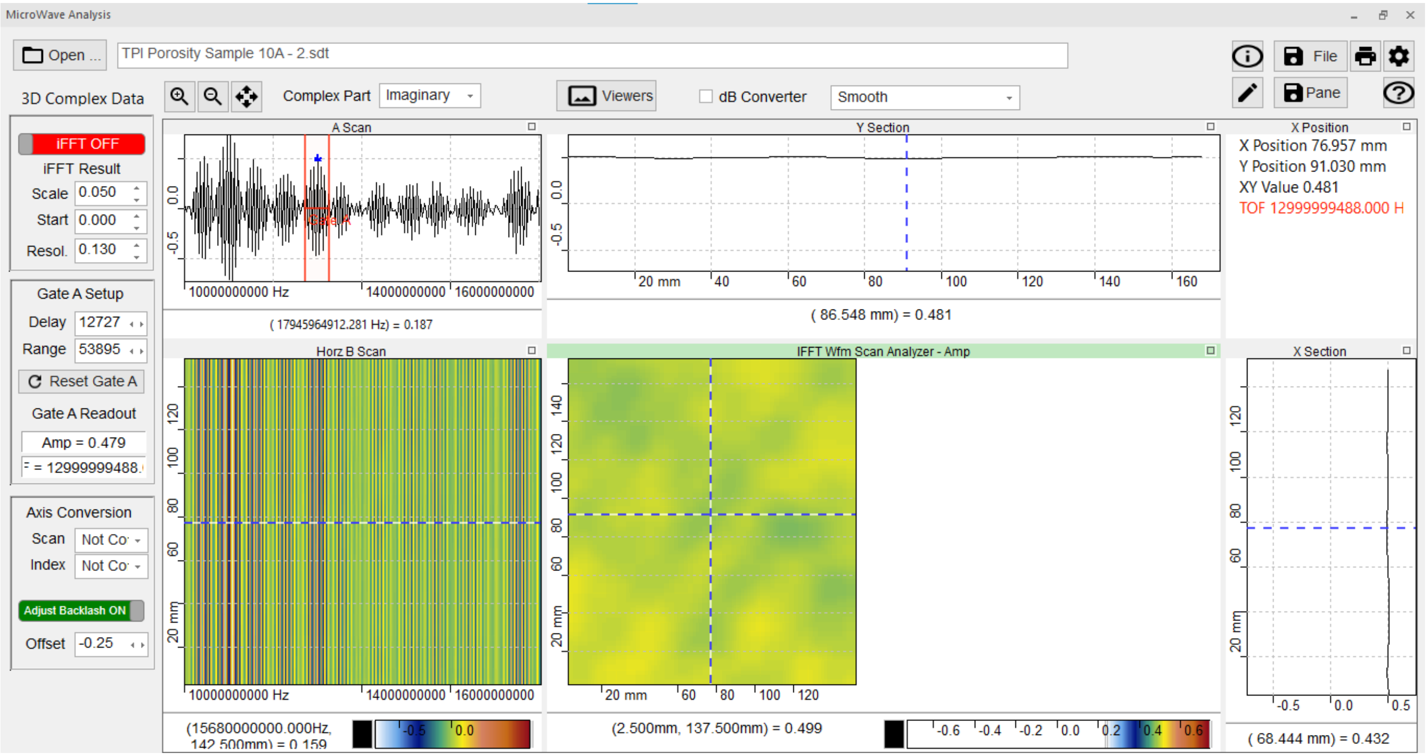
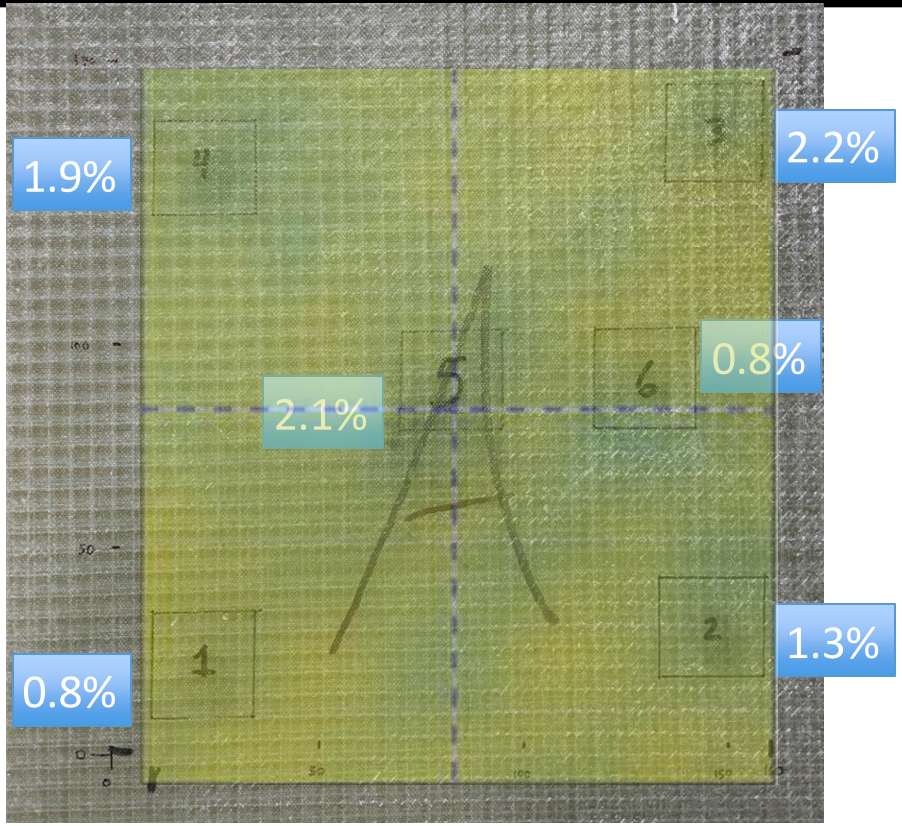
Sample Data Image





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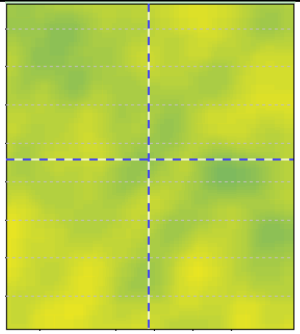
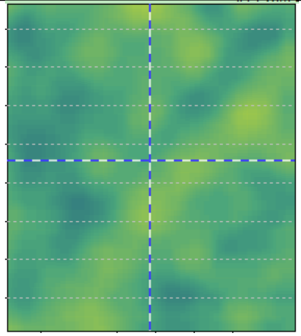
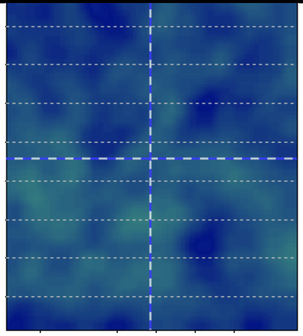
Real Data for Each Panel



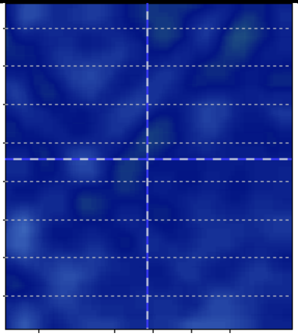
10A - 1.5%



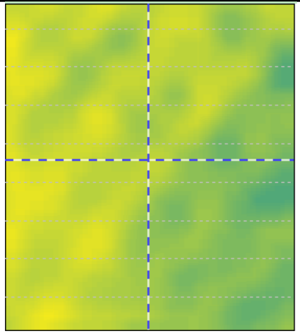
11A - 9.6%



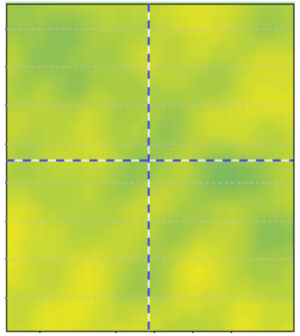
12A - 15.8%



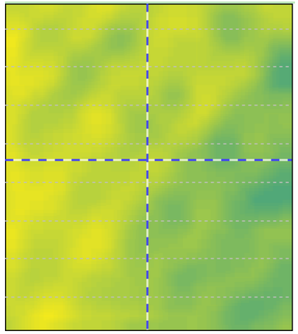
13A - 22.1%



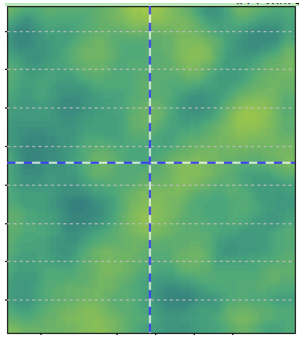
14A - 3.4%



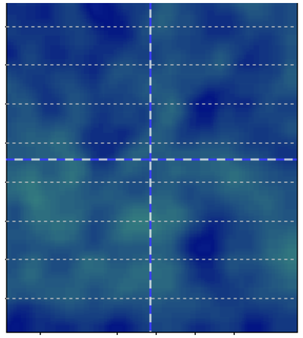
10A - 1.5%



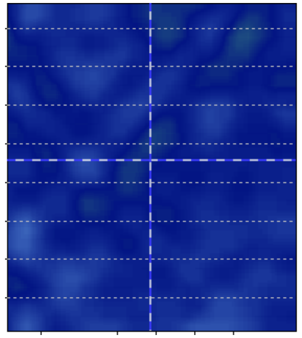
14A - 3.4%



11A - 9.6%



12A - 15.8%



13A - 22.1%

The top row is arranged numerically while the bottom row is arranged by porosity. Notice how the panels become darker as the porosity increases.

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Image J Data

Table 1

	Area	Mean	Min	Max	IntDen	RawIntDen
	85800	**152.135**	**0**	**226**	**13053153**	**13053153**
	85800	123.972	0	221	10636833	10636833
	85800	79.413	0	209	6813619	6813619
	85800	67.618	0	206	5801594	5801594
	85800	148.400	0	227	12732706	12732706

The images were analyzed using ImageJ and the image Integrated Density (INTDEN) determined.

The integrated density is a way to measure the image brightness. It is used in medical research imaging.

Rows 1-5 correlate to Panels 10A-14A.

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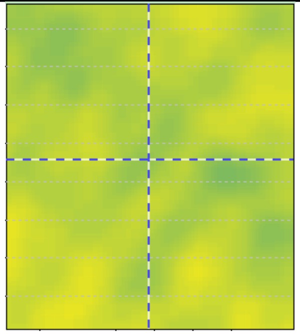
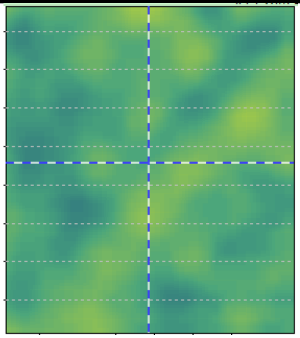
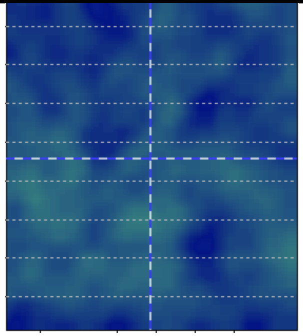
Image Density



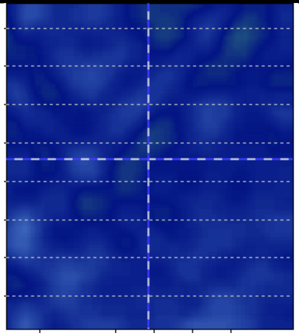
10A - 13,053,153



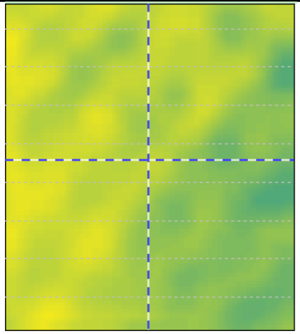
11A - 10,636,833



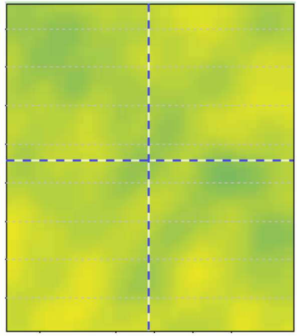
12A - 6,813,619



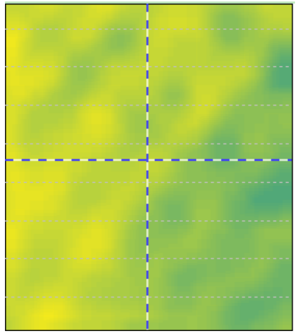
13A - 5,801,594



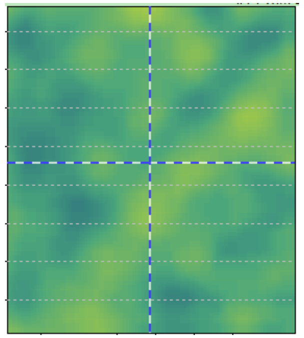
14A - 12,732,706



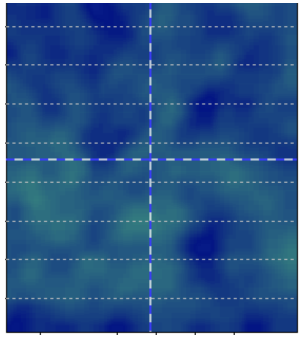
10A - 13,053,153



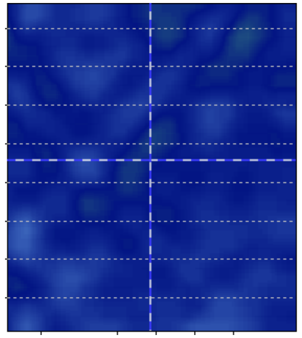
14A - 12,732,706



11A - 10,636,833



12A - 6,813,619



13A - 5,801,594

The top row is arranged numerically while the bottom row is arranged by porosity.

The Integrated Density of the image correlates in a nice fit with the porosity.

Since the integrated density can be calculated via software, it may be a useful tool to automatically determine porosity of a sample in the future.

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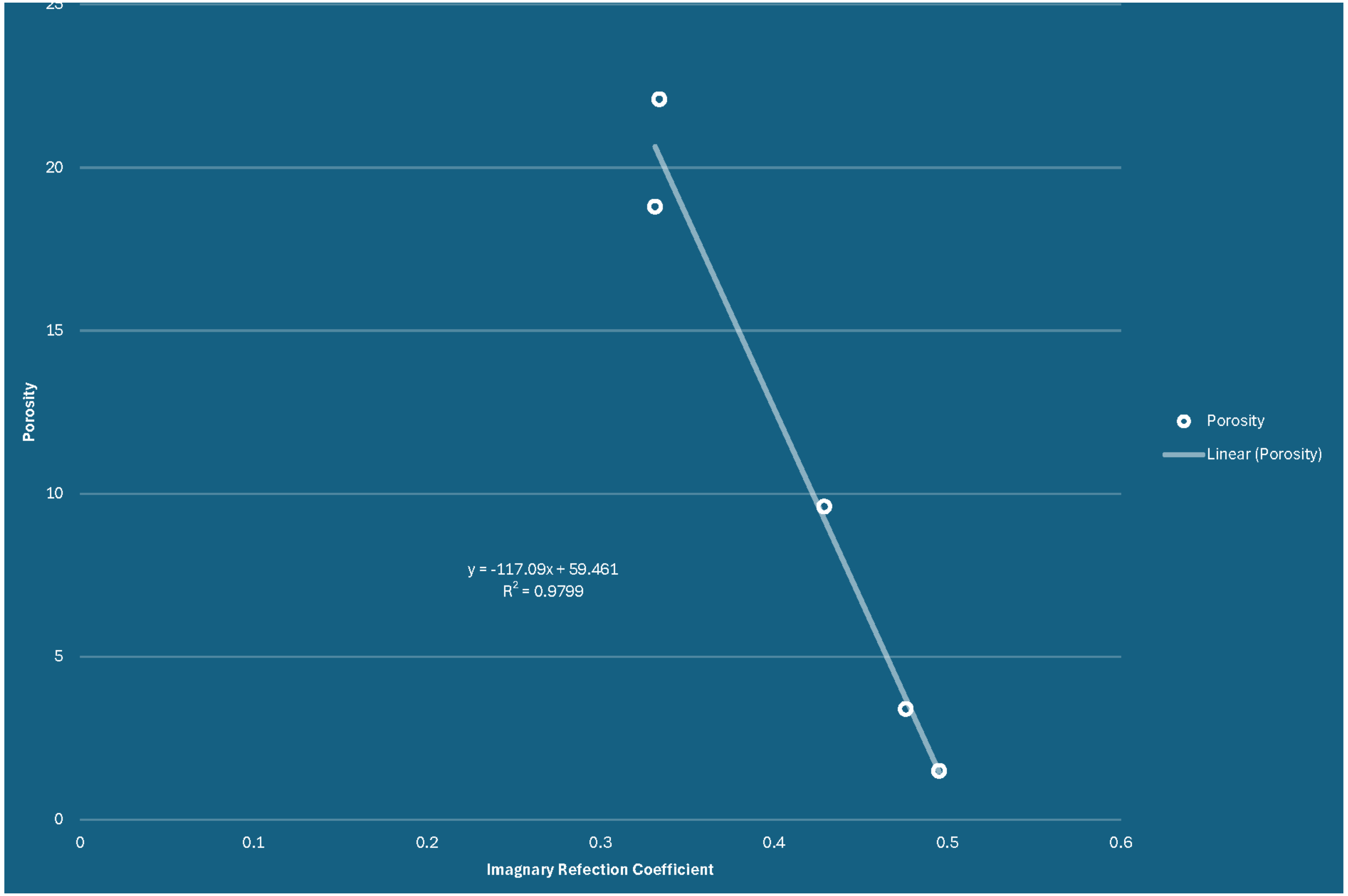
Porosity Curve Real Reflected Signal



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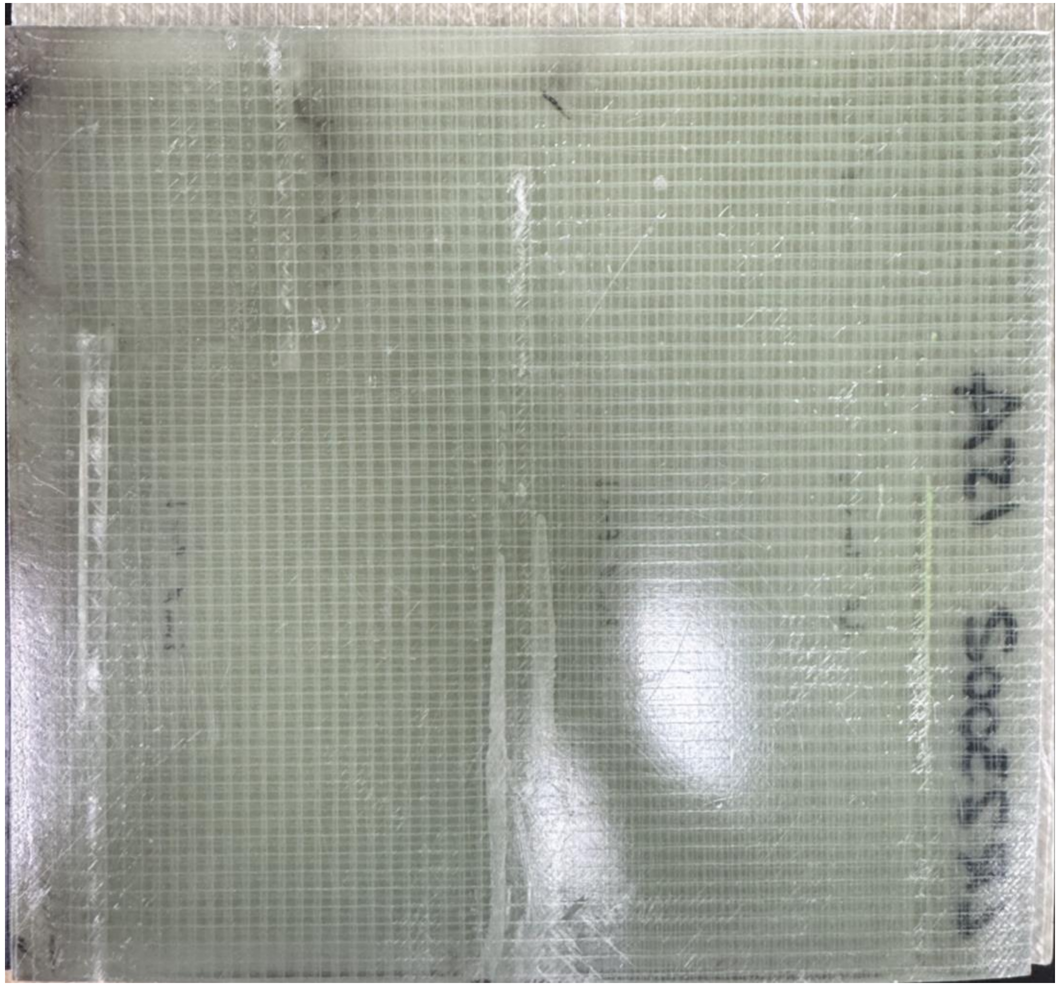
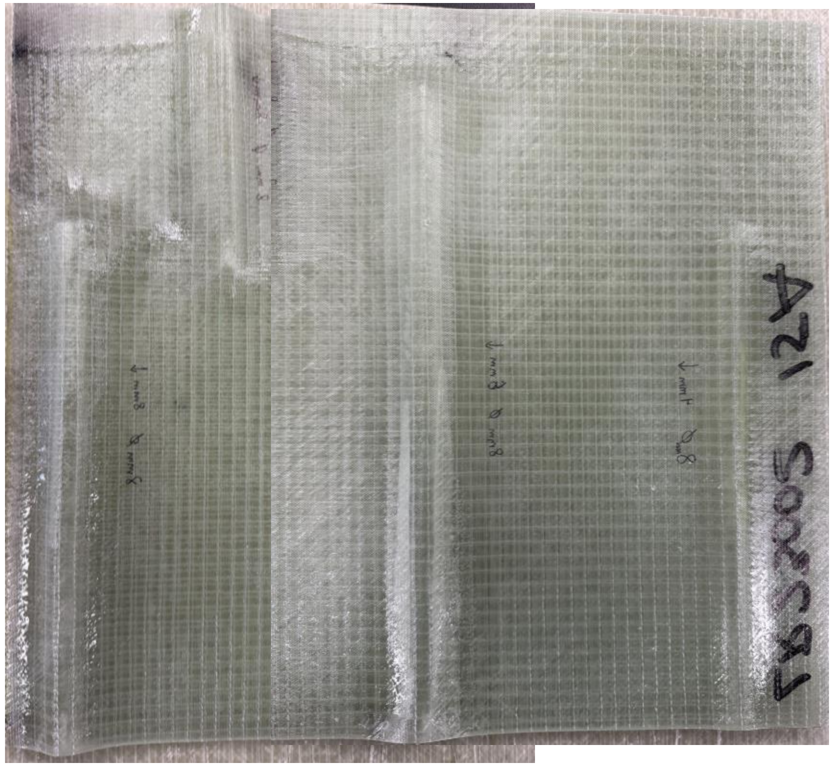
Part 6

Microwave Inspection
TPI Composite
Wrinkle Samples

Advanced Microwave Imaging

Wrinkle Sample





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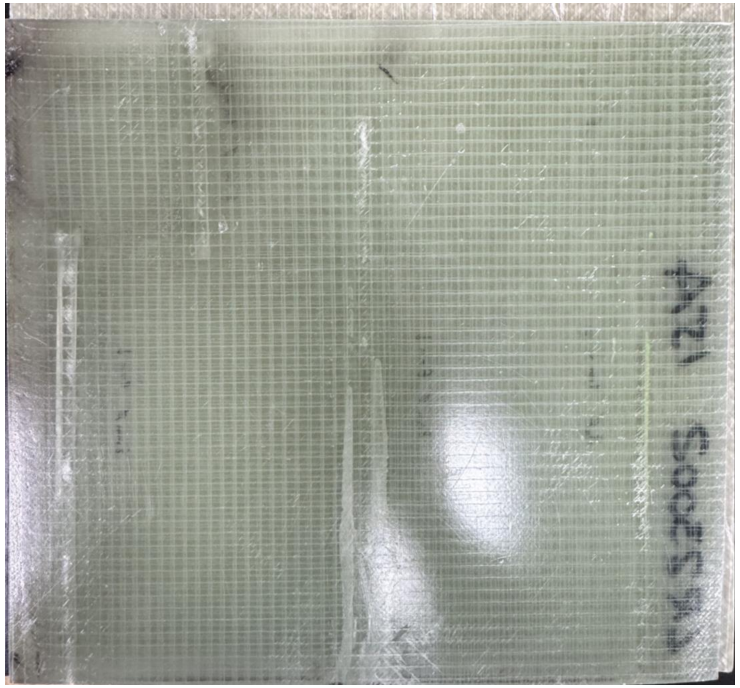
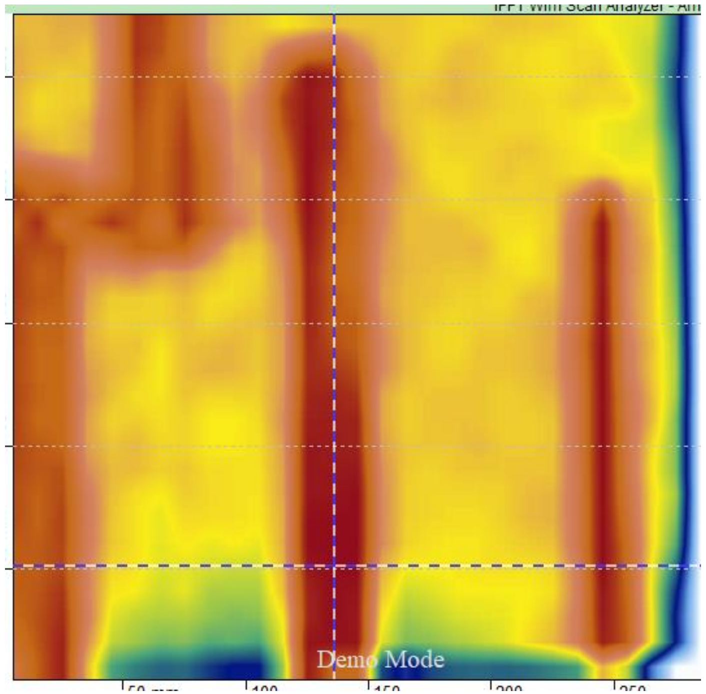
Wrinkle MI Image





Topside Image

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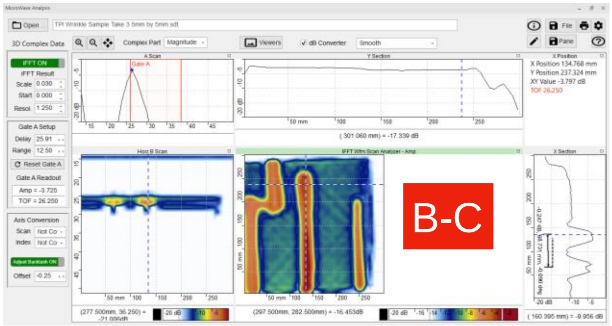
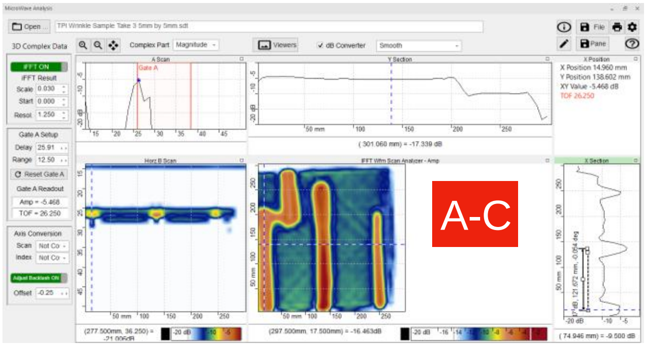
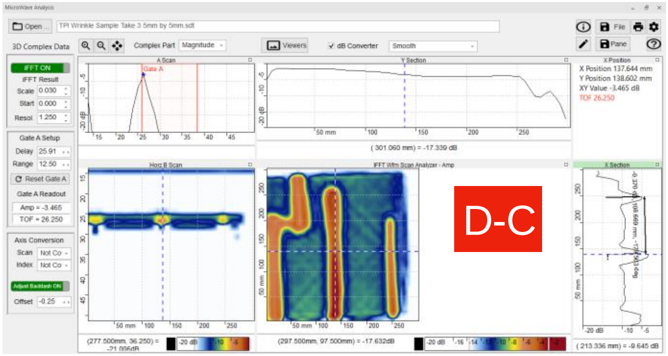
Wrinkle Measurement







B-C = 68.73mm

A-C = 121.67mm

C-D = 108.667mm

Note that because we do not start scanning from the edge of the part, absolute location on the panel is difficult. We can locate the wrinkles with respect to each other.

	Measured	Delta
A-C = 121.67mm	A-C = 125mm	A-C = (-) 2.7%
A-B = 52.9mm	A-B = 50mm	A-B = 5.8%
C-D = 108.667mm	C-D = 120mm	C-D = (-) 9.4%

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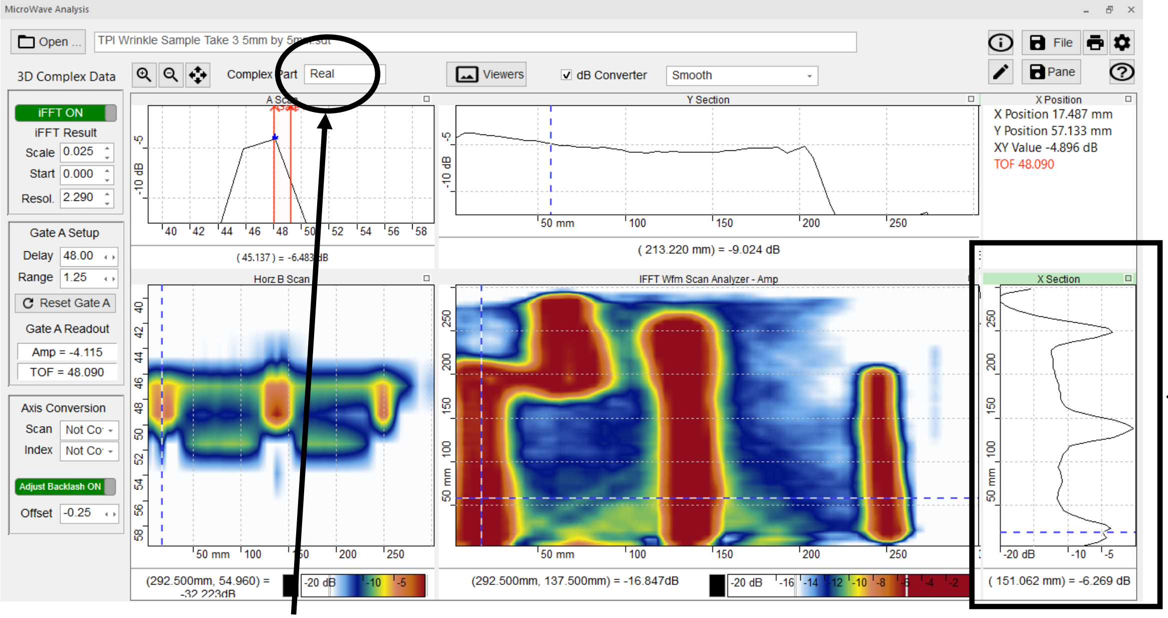
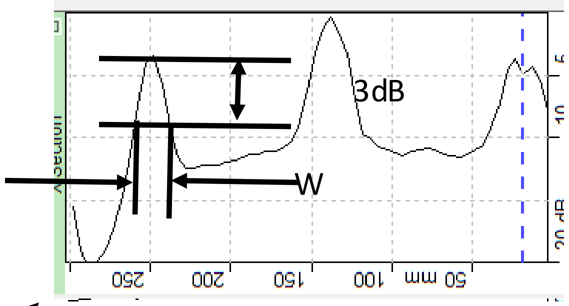
Aspect Ratio

- These are the most challenging dimensions to obtain because the limits of the measurement are not clear.
- The width of the wrinkle will be determined using the data line(i.e. - the X section data) and the 3dB down method from the peak.
  - This is a typical NDT technique to determine the 50% point of the peak.



The REAL portion of the reflection coefficient provides a better view of the neat resin layer.



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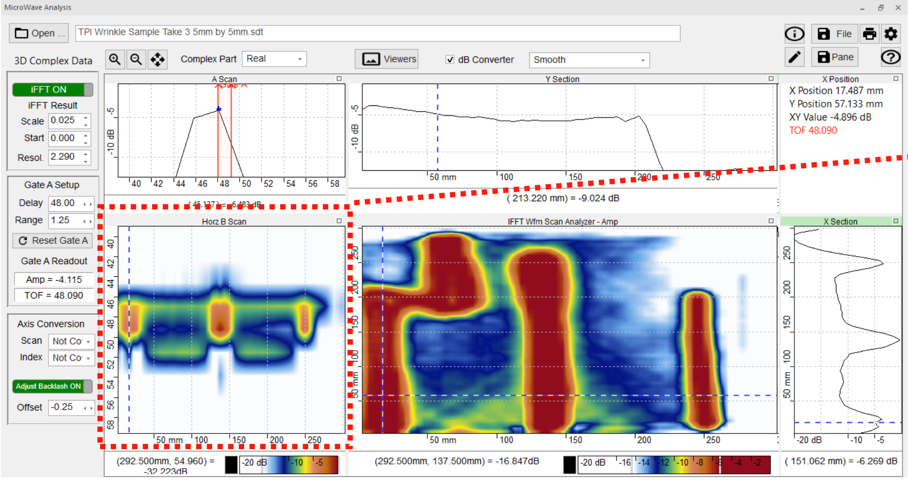
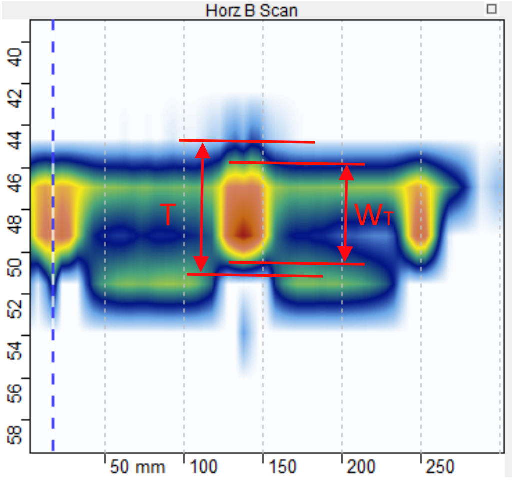
Aspect Ratio

- To determine wrinkle thickness we will isolate on the “resin rich” core and use its thickness.
- This will be accomplished using the “Horizontal B” image as shown below.





T = Total Thickness
W_T = Wrinkle thickness

Note the difference between the wrinkle and total thickness.

In this case both the Real and Magnitude data signals provides a well defined interface to start the measurement from.

The fact that this interface is identifiable indicates that it might be possible to identify the start of a wrinkle (i.e. - depth) in a thick laminate. That could be useful to understand how far down the material would need to be “scarfed” for a repair.

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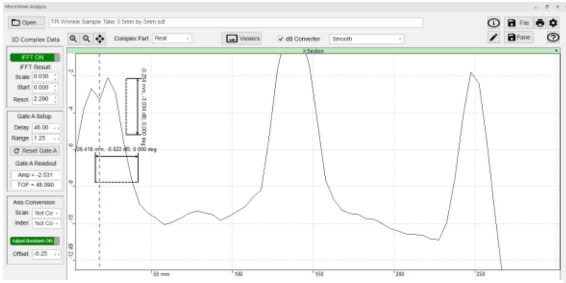
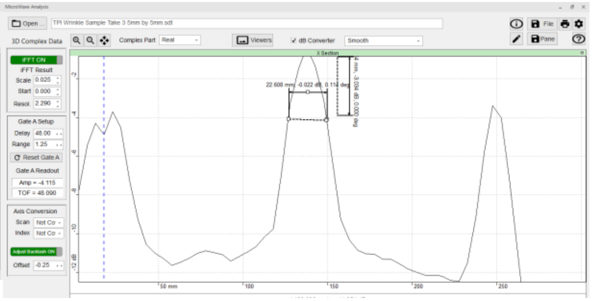
Aspect Ratio



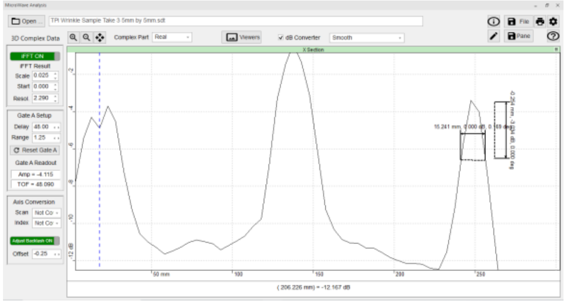
MI Data W_A= 26.4*

Measured W_A= 15.7



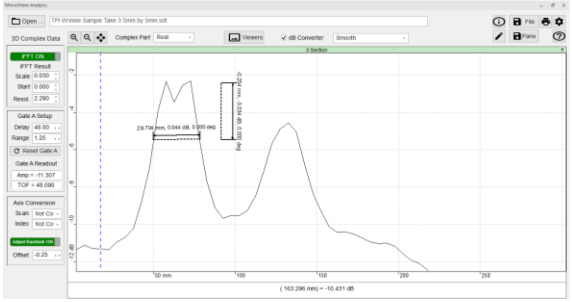
MI Data W_C = 22.6mm

Measured W_C = 28.61mm



MI Data W_D= 15.24 mm*

Measured W_D= 26.7 mm



MI Data W_B = 28.7

Measured W_B = 22.8

* - Note that these widths are considered to be less accurate because of the proximity of the flaw to the side of the panel. This situation is not likely to occur in an actual inspection environment.

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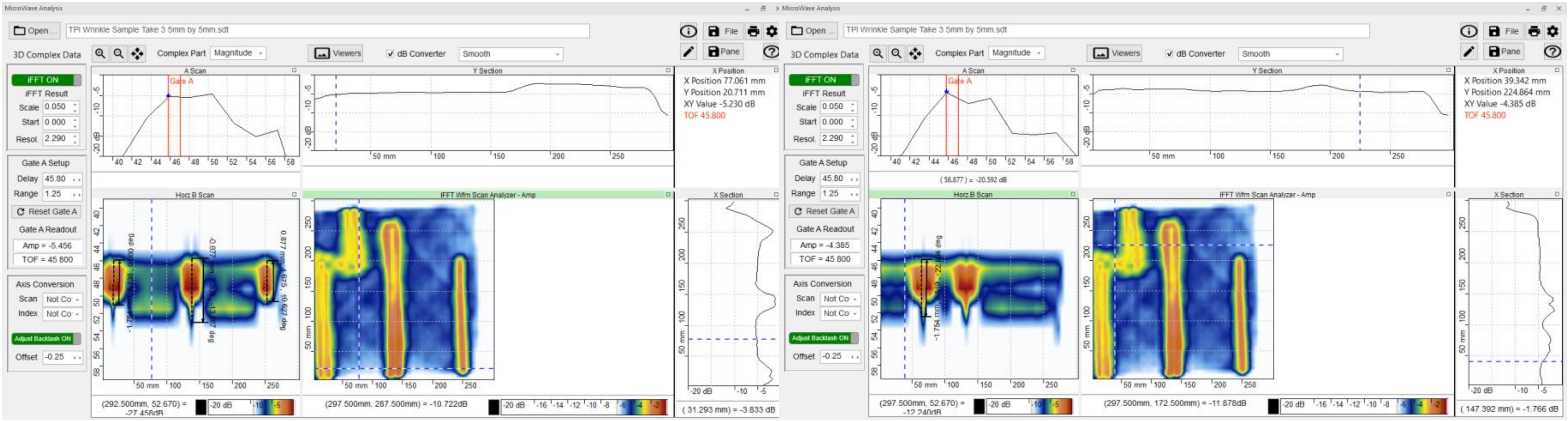
Aspect Ratio



Data T	Measured T
TA = 5.136 mm	TA = 3.60 mm
TB = 7.309 mm	TB = 8.78mm
TC = 3.966 mm	TC = 7.33 mm
TD = 6.519 mm	TD = 7.34 mm

It is assumed that there will be some deviation in the thickness data with location as well. We can only physically measure the thickness near the edges, so that will result in some deviation in the values.

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Aspect Ratio

- A – W = 26.4mm, T = 5.316mm, AR = 4.97
- B – W = 28.7mm, T = 7.309mm, AR = 3.92
- C – W = 22.6mm, T = 3.966mm, AR = 5.69
- D – W =15.24mm,T = 6.519mm, AR = 2.34

Data vs Measured

AR_A = 4.97 vs 4.36

AR_B = 3.92 vs 2.59

AR_C = 5.69 vs 3.9

AR_D = 2.34 vs 3.63

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SAR 3D ImageDemo

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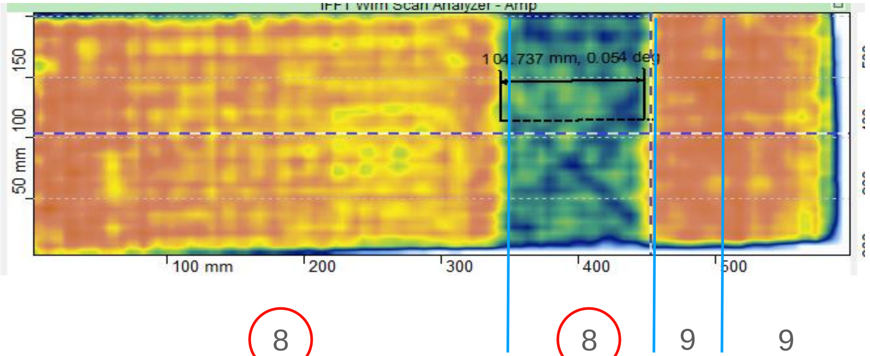
Lagniappe

	material	orentation	length	start	50	100	150	200	250	300	350	400	450	500	550	600
width, no chordw	Gel Coat	N/A	600mm													
	biax	45	600mm													
	ud	0	500mm													
	ud	0	450mm													
	biax	45	600mm													
	biax	45	250mm													
	ud	90	100mm													
	biax	45	150mm													
	BALSA	N/A	N/A													
	biax	45	600mm													
	ud	0	350mm													
	biax	45	600mm													
	biax	45	150mm													



Number of GFRP Layers per Section
(Including Gel Coat)

One item to note is that the ply drops occur, in some cases, in narrow windows of space. For example, some are only 50MM wide. The ability to distinguish these areas through 30MM of balsa wood is difficult because of the beam spread through the thickness. If the poly drops are wider, they would likely be easier to identify.

Image from backside to Gel Coat

The two areas with 8 layers have different reflected signals. This the result of the locations of the layers. The higher dB signal is located in the area where a single layer of UD near the backside is replaced by a single layer of biaxial located on the far side of the balsa.

The two areas with 9 layers are approximately the same because a single layer of bias has changed location on the far side of the balsa.

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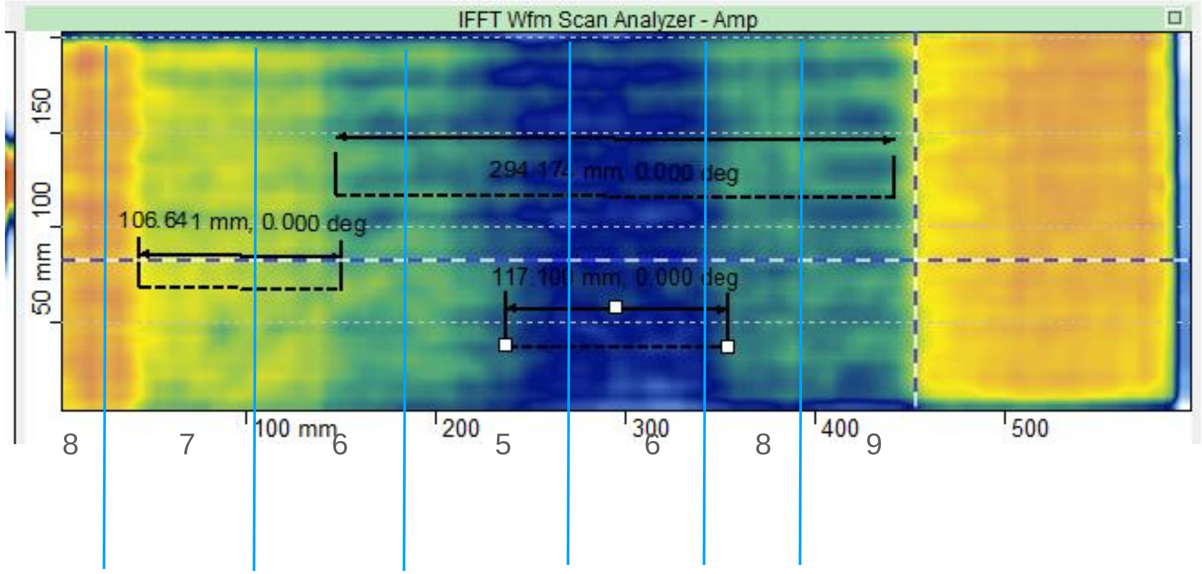
Ply Drop Far Side 30mm Balsa

Pannel with ud plys shifted twords root																
	material	orientation	length	start	50	100	150	200	250	300	350	400	450	500	550	600mm
	Gel Coat	N/A	600mm													
	biax	45	600mm													
	ud	0	250mm													
	ud	0	150mm													
	biax	45	600mm													
	biax	45	250mm													
vidth, no chordw	ud	90	100mm													
	biax	45	150mm													
	BALSA	N/A	N/A													
	biax	45	600mm													
	ud	0	50mm													
	biax	45	600mm													
	biax	45	150mm													



Number of GFRP Layers per Section
(Including Gel Coat)

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Summary

- Microwave inspection is a field or factory deployable inspection method that can detect and measure
  - Flaws through core (Balsa or foam)
  - Delaminations
  - Bond line flaws
  - Wrinkles
  - Ply Drops
  - Porosity including characterizing percent porosity

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Questions?

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