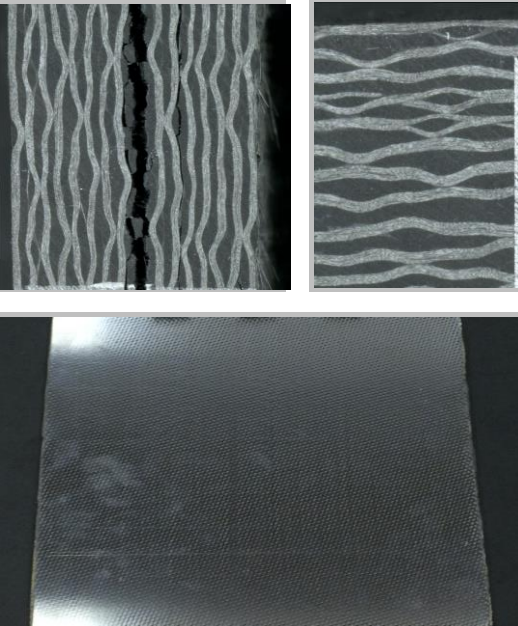# Bond Interface Evaluation of Solid Woven Carbon Fiber Composite onto Aluminum Alloys

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Presented to Professor Peter Cawley
**Head of Department of Mechanical Engineering**
Imperial College London

U.S. DEPARTMENT OF **ENERGY**   **NNSA**
National Nuclear Security Administration

Sandia National Laboratories

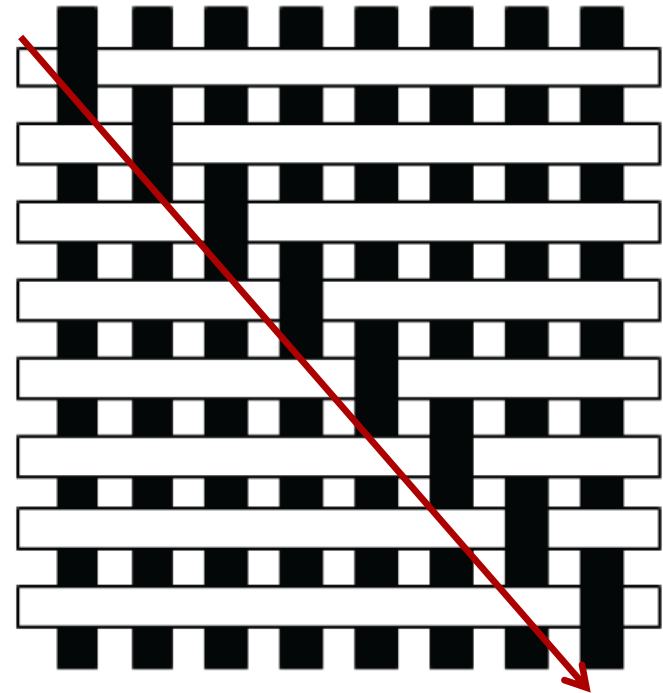*Exceptional*

service

in the

national

interest

Solid Laminate Layup

Specimens are constructed with carbon fiber reinforced plastic (CFRP) $[[0/90]_n]_s$ preimpregnated "prepreg" 8 harness-satin weave with UF3352 TCR™ Resin.
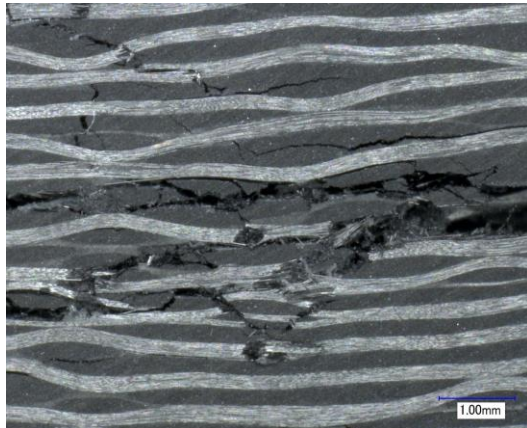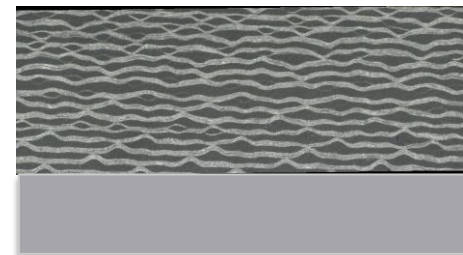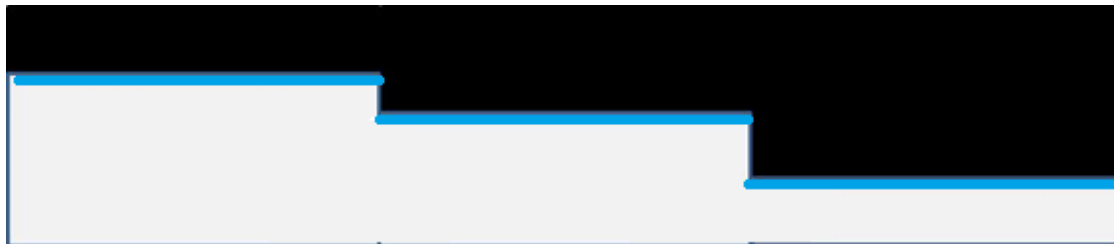
4 ply $[0/90]_2]_s$
8 ply $[0/90]_4]_s$
12 ply $[0/90]_6]_s$

Side view

This weave is resistant to wrinkles and allows for tight radius layups.
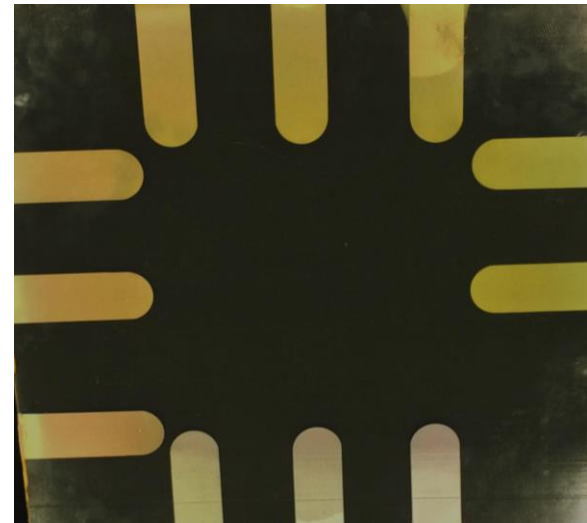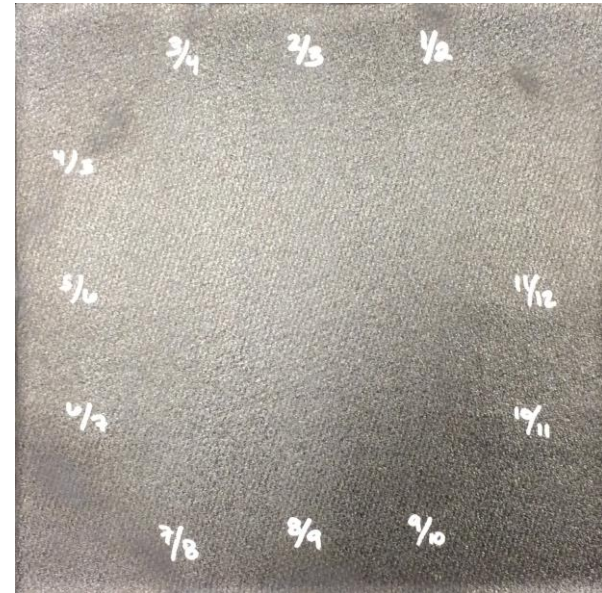
End view

12 plies

Solid Laminate Pull Tab Configuration

Specimens are constructed with carbon fiber reinforced plastic (CFRP) $[[0/90]_n]_s$ preimpregnated "prepreg" 8 harness-satin weave with UF3352 TCR™ Resin. Pull tabs were placed between each ply. Pull tabs are cured in place (Not by choice).

Wave Scatter Theory 1/2

- A wealth of information can be collected on the bondline when one studies the incident wave and preselected incident angles.
- The elastic wave interacts with the materials and its fiber/polymer structure. Scattering is frequency dependent.
- Factors that affect the ability to detect bondline variance are: composite surface texture (random or periodic surface roughness, fiber orientation and binder concentration.
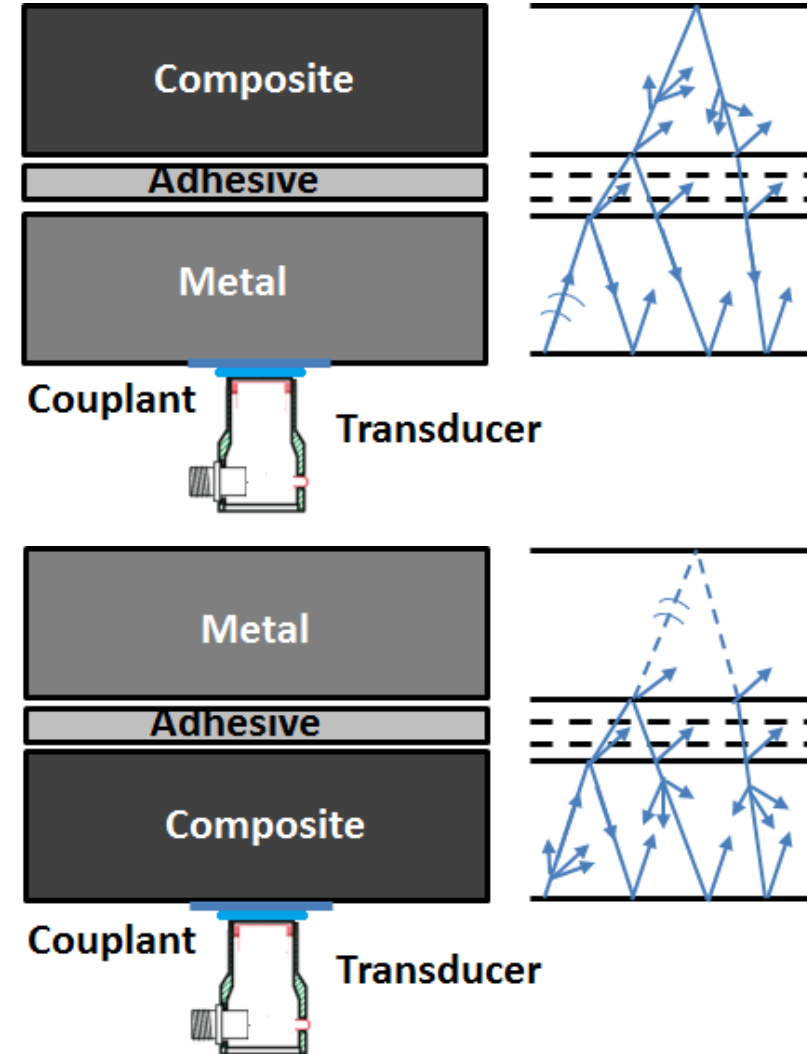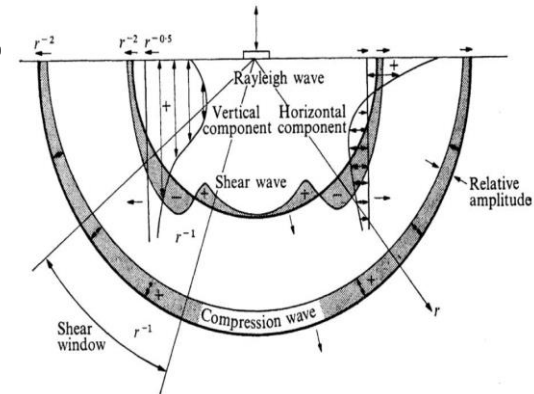
Wave Scatter Theory 2/2

Materials that demonstrate frequency dependent velocity variation are known as dispersive materials. In these types of materials there is a distinction made between the group velocity and the phase velocity.
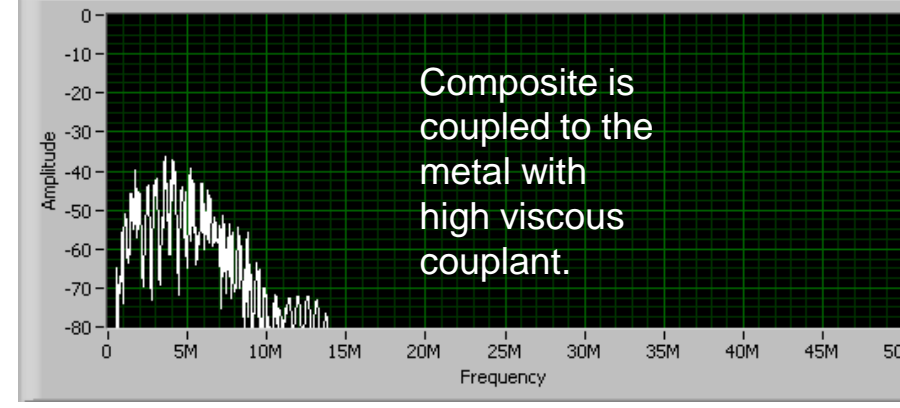
Source "Elastic Wave Propagation in Materials" , Walley, S.M., Field, J.E. Materials Science and Technology, Elsevier 2005.

$$v_g = v_p \ + \ f \ \frac{\delta v_p}{\delta f}$$

Group velocity (v_g) is defined as a rate at which the point of maximum amplitude in the ultrasonic pulse (many frequencies) propagates through the material.

Phase velocity (v_p) is defined as the velocity of a continuous sinusoidal wave (one frequency) in the material.

These two velocities are related to each other through dispersive properties (frequency dependence of the phase velocity).
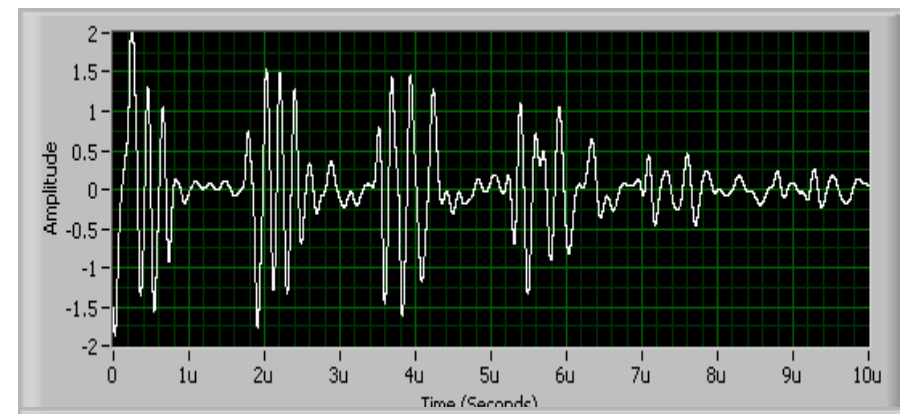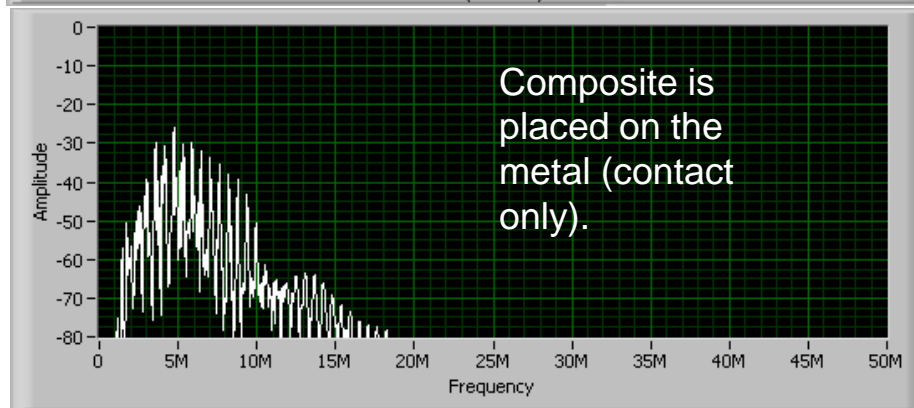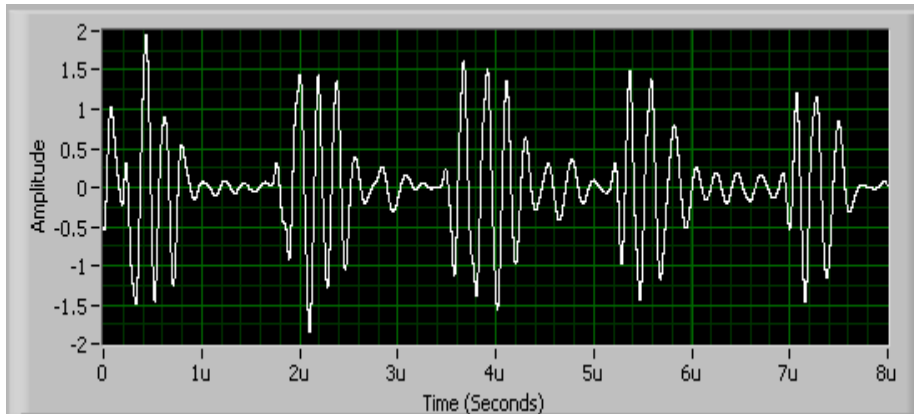
Source: Horizontal Transverse Isotropic axis defination, MIT OpenCourseWare http://ocw.mit.edu/terms/

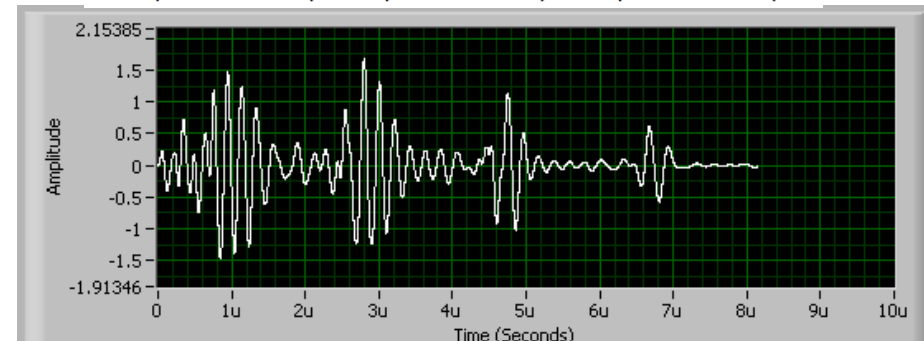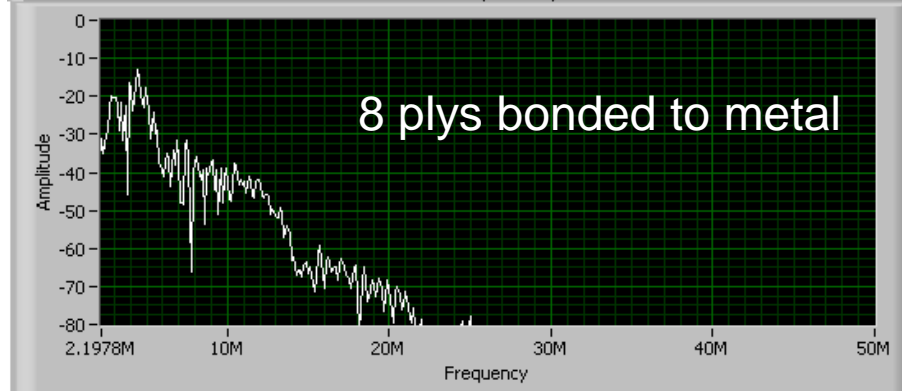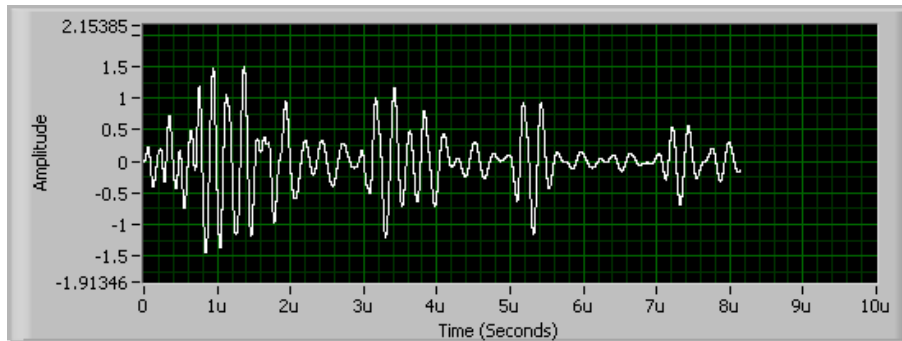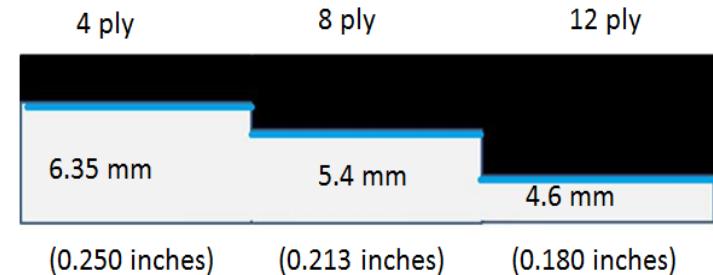# Metal to Composite - Conventional Ultrasonics

Contact: 5 Mhz A-Scan of 6.30 mm thick aluminum and composite placed below.

Composite is placed on the metal (contact only).

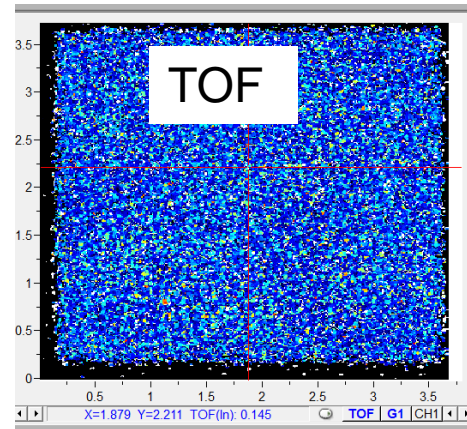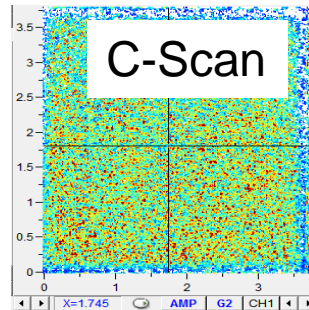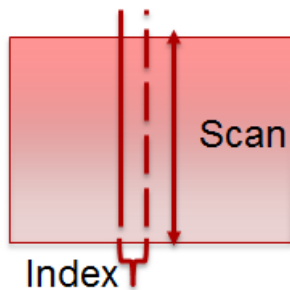Composite is coupled to the metal with high viscous couplant.

Composite to Metal - Conventional Ultrasonics

Contact: 5 Mhz A-Scan of (8 ply) 1.68 mm thick composite bonded to aluminum.

4 ply   8 ply   12 ply

6.35 mm   5.4 mm   4.6 mm

(0.250 inches)   (0.213 inches)   (0.180 inches)
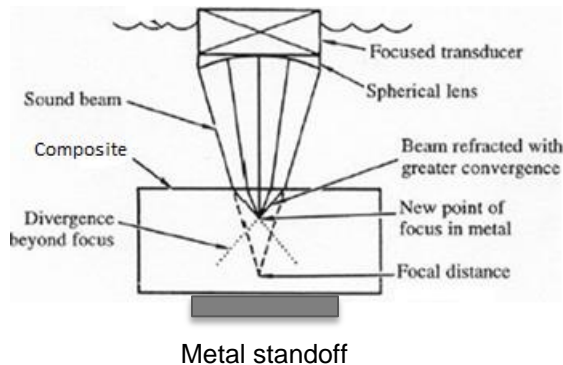

8 plys bonded to metal

8 plys unbonded
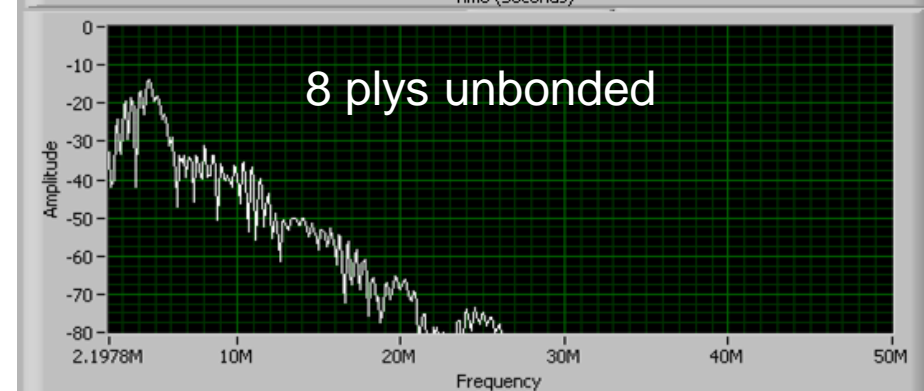
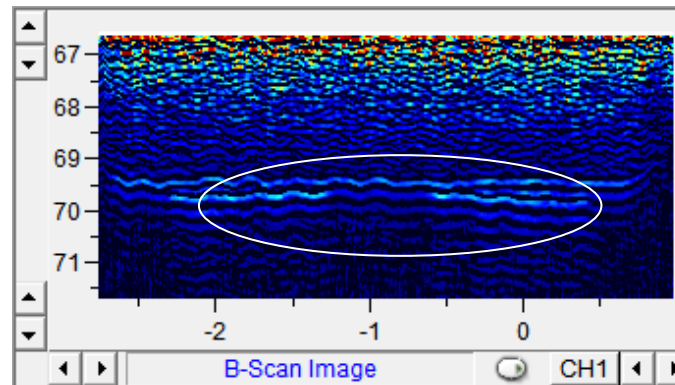# Interface Detection with Immersion Ultrasonics (1 of 3)

In immersion testing, the part and the transducer are placed in a tank filled with water. This allows for better movement of the transducer while maintaining consistent coupling. Its disadvantage is that the part must sit in water for long periods of time. Immersion testing can also measure backwall signals changes, small amplitude changes and variation in the time of flight measurement from the front to back surfaces.
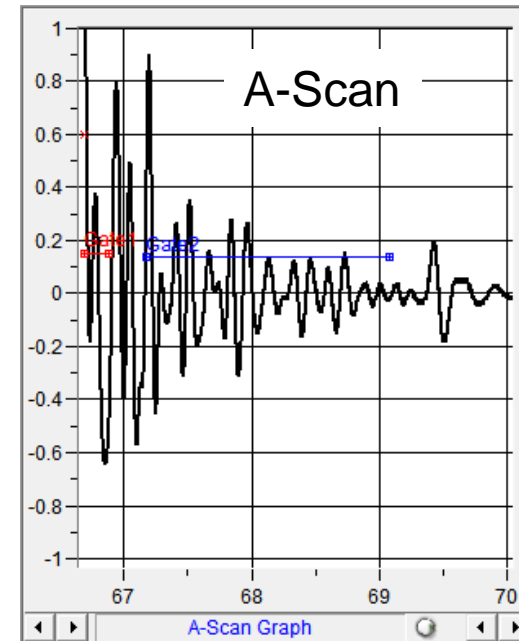

Scan

Index

C-Scan

TOF

X=1.745   AMP G2 CH1

X=1.879 Y=2.211 TOF(ln): 0.145   TOF G1 CH1

Immersion:10 Mhz
12 ply composite only
thickness 4.60 mm
V_c = 2.85 km/sec

A-Scan

A-Scan Graph

Focused transducer
Spherical lens
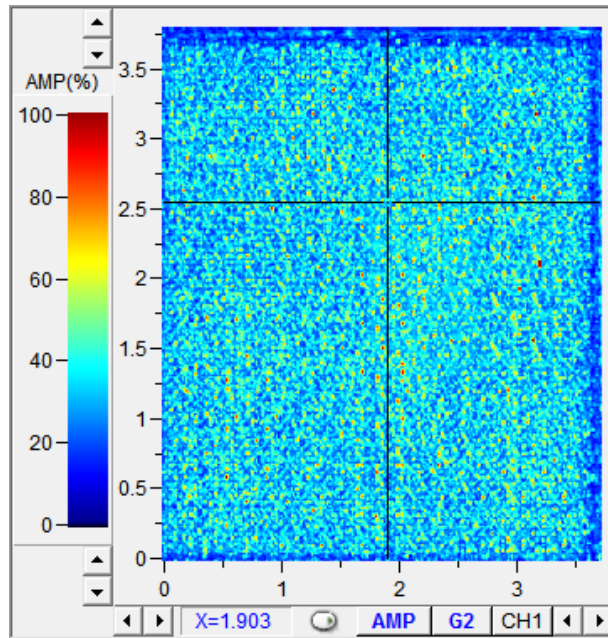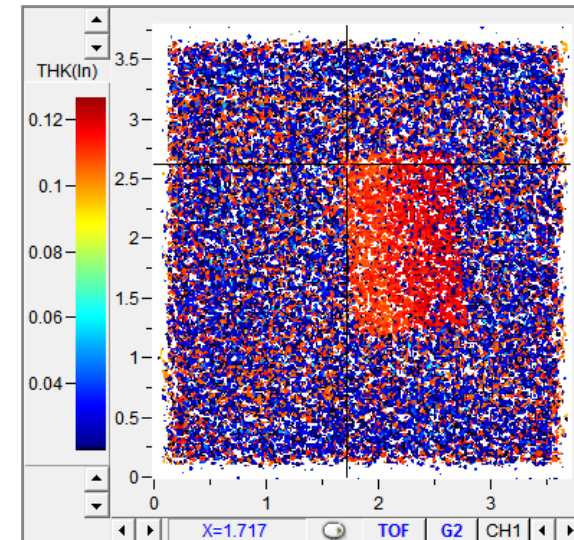Sound beam
Composite
Beam refracted with greater convergence
Divergence beyond focus
New point of focus in metal
Focal distance

Metal standoff

B-Scan

B-Scan Image   CH1

Immersion: 10 Mhz
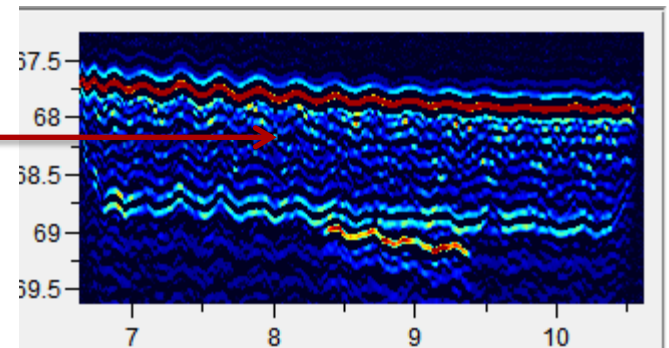**8 ply** composite only
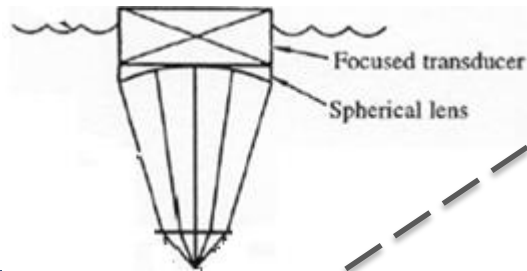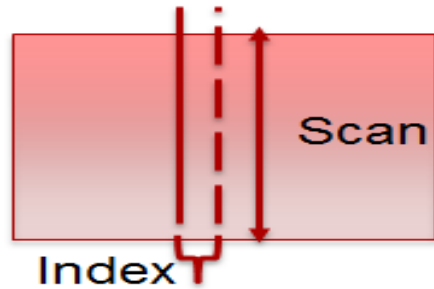thickness 3.11 mm
V_c = 2.93 km/sec

Time of flight

Immersion:10 Mhz **4 ply** composite only thick 1.53 mm
V_c = 3.23 km/sec

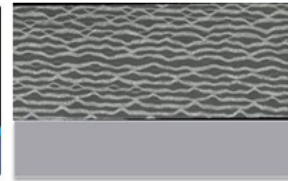High noise signal within the thickness of the composite is due to porosity and weave pattern
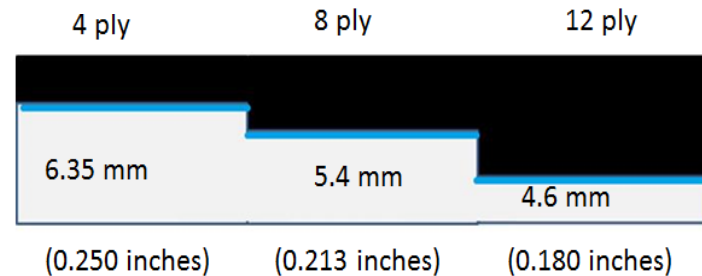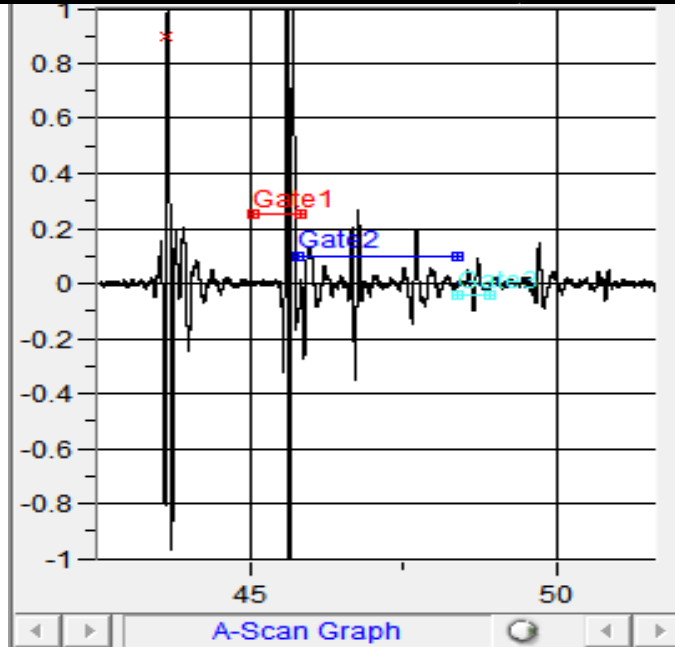
As thickness increases the wave speed decreases.

10

Inspection Scan Plan for Bonded Sample

Part is scanned from both sides

4 ply	8 ply	12 ply

6.35 mm

5.4 mm

4.6 mm

(0.250 inches)   (0.213 inches)   (0.180 inches)

Scan

Index

Focused transducer

Spherical lens

A-Scan Graph

Gate1

Gate2

4 Plys ~ 0.86 mm (0.034 inches)
8 plys ~ 1.68 mm (0.066 inches)
12 plys ~ 2.91 mm (0.115 inches)

Warp 0°

Weft 90°

11
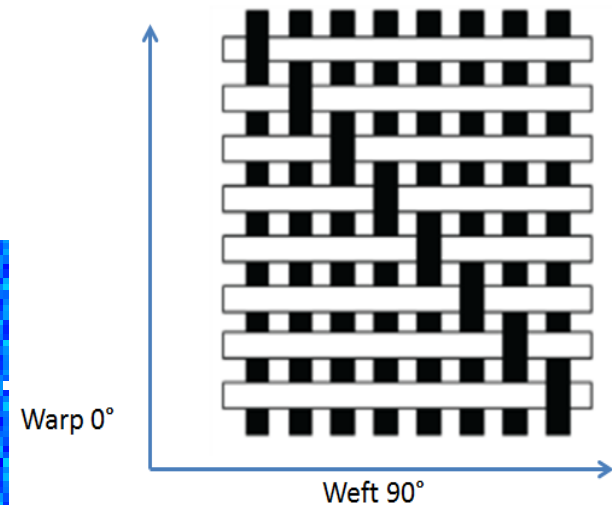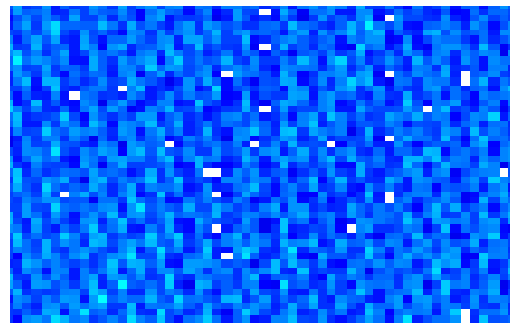
Bondline Detection Aluminum Over Composite

10 MHz; W.P. = 4.6 cm

FL = 5.4 cm (Focus into part 1.19 mm)

12 Ply 2.91 mm

Bonded area

Acoustic Impedance Mismatch

In well bonded areas the sound transmits through the aluminum and into the composite (yellow, green and blue thickness change in aluminum) and returns a lower amplitude signal. Poorly bonded areas return higher signal amplitude.
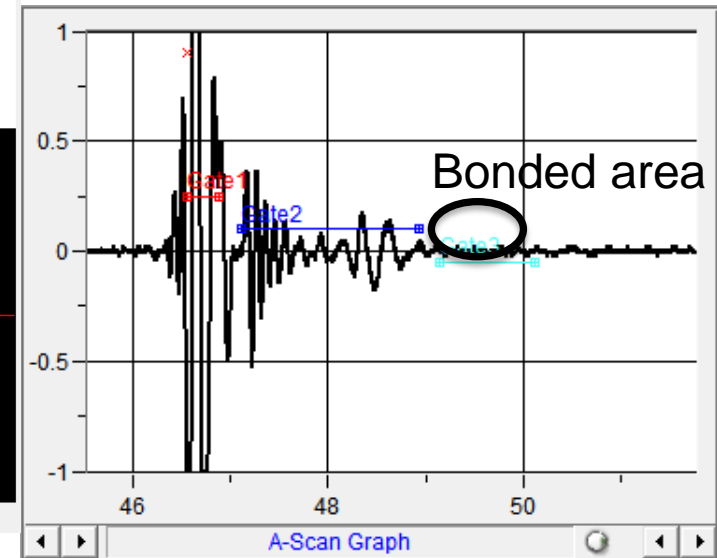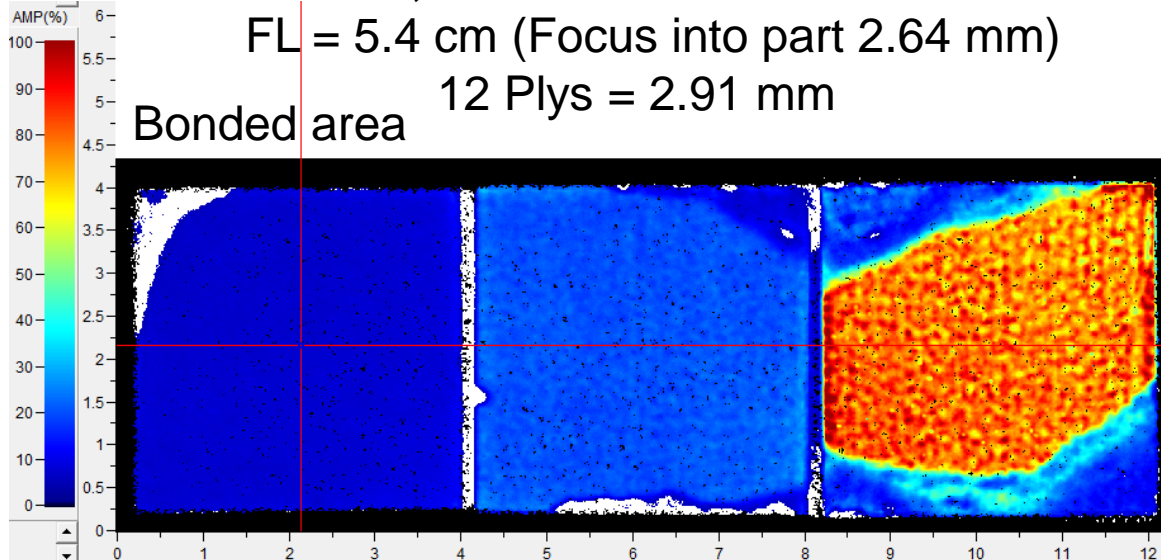
Unbonded area
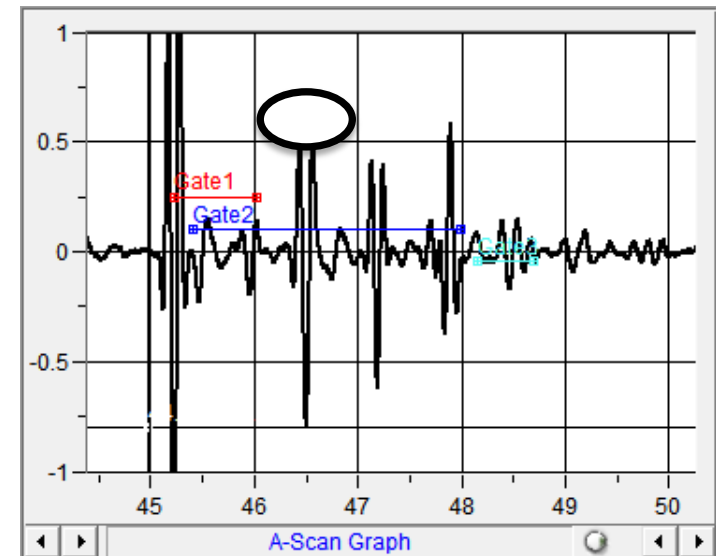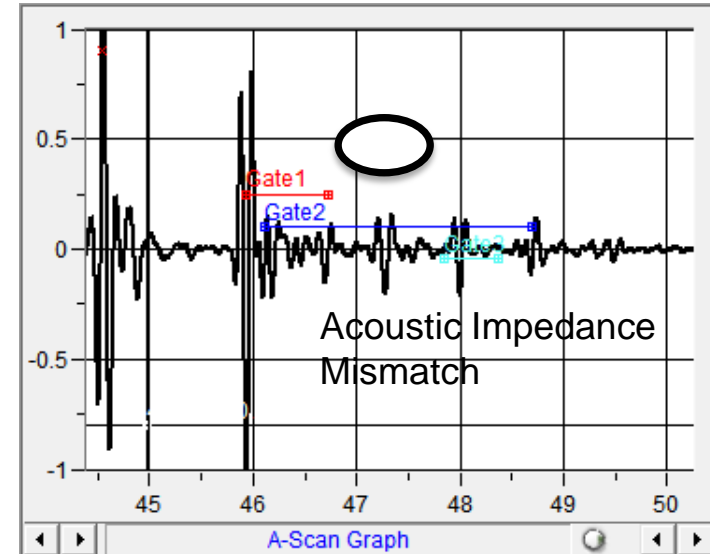
12

10 MHz; W.P. = 4.6 cm

FL = 5.4 cm (Focus into part 2.64 mm)

12 Plys = 2.91 mm

Bonded area

Bonded area

12 Plys   8 Plys   4 Plys

Unbonded area
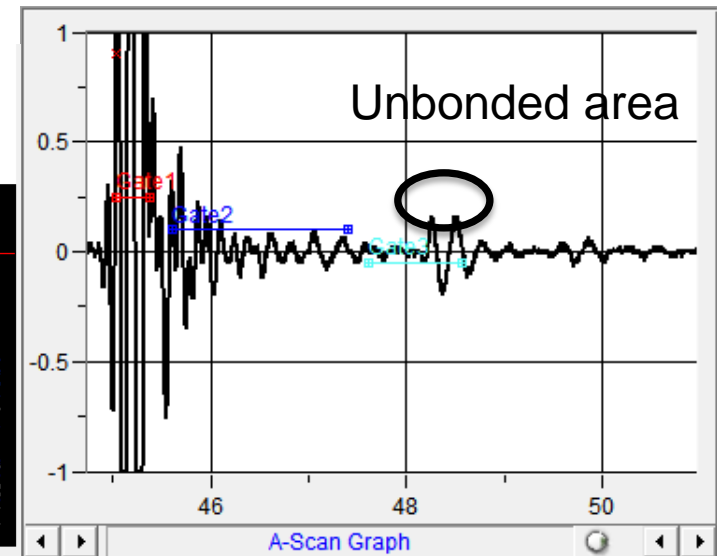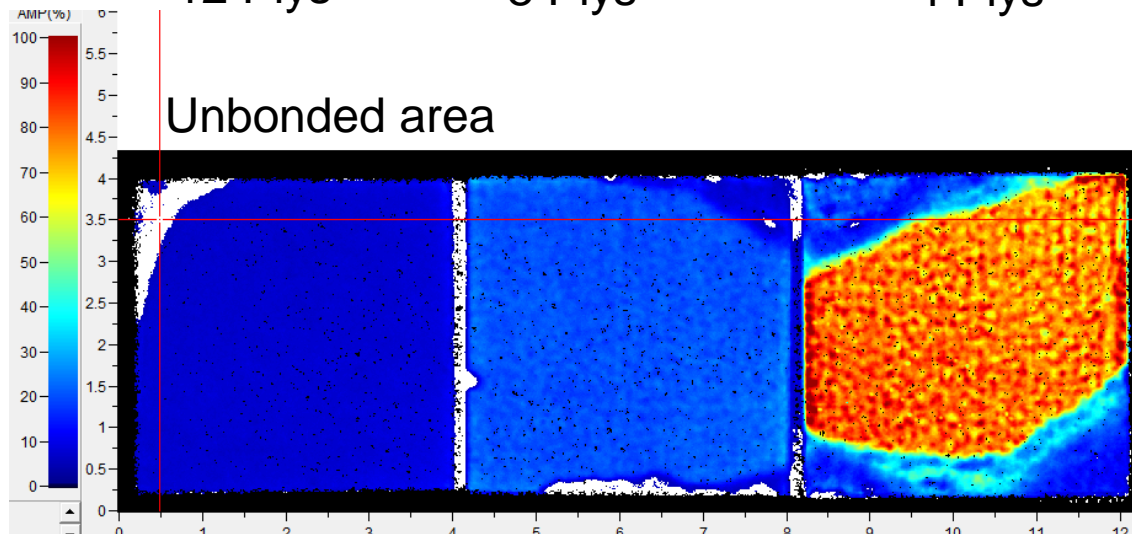
Unbonded area

Bonded area reflects sound from the aluminum and sends a stronger reflection back to the probe.

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10 MHz; W.P. = 4.6 cm
FL = 5.4 cm (Focus into part 2.64 mm)
4 Plys = ~ 0.86 mm

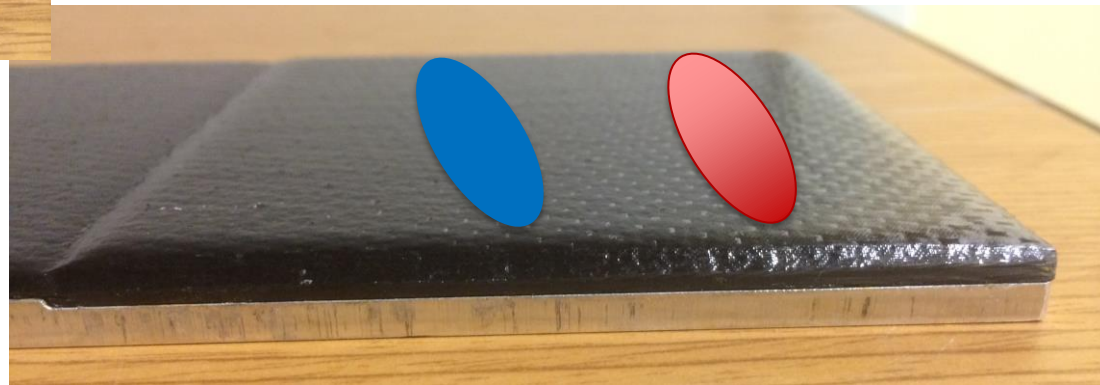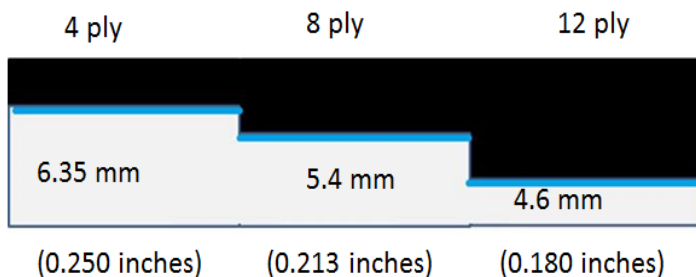X=9.510 Y=2.278 AMP(%): 87.5

Bonded area

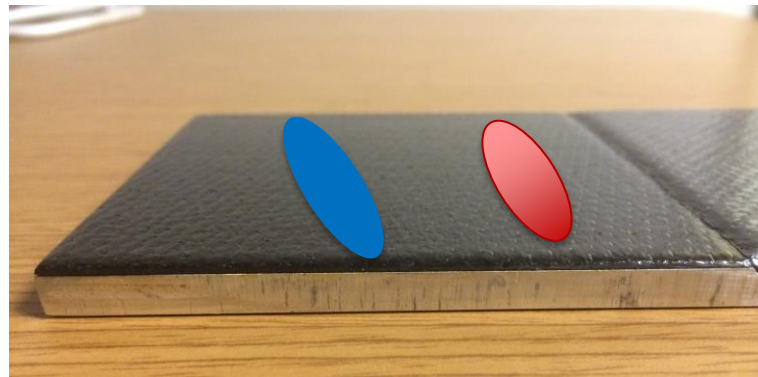4 Plys
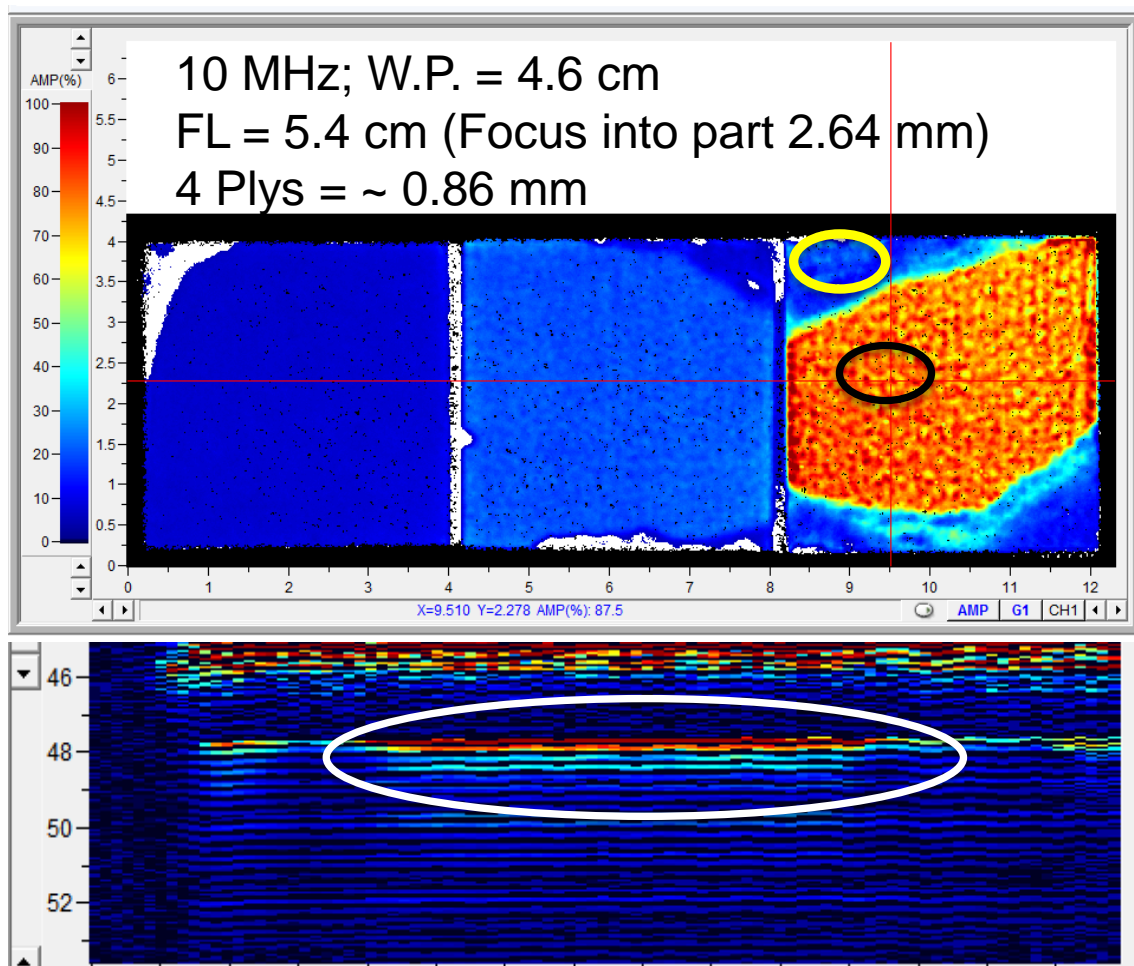
Unbonded area

Poorly bonded areas return no interface signal from the aluminum this results in a lower amplitude signal.
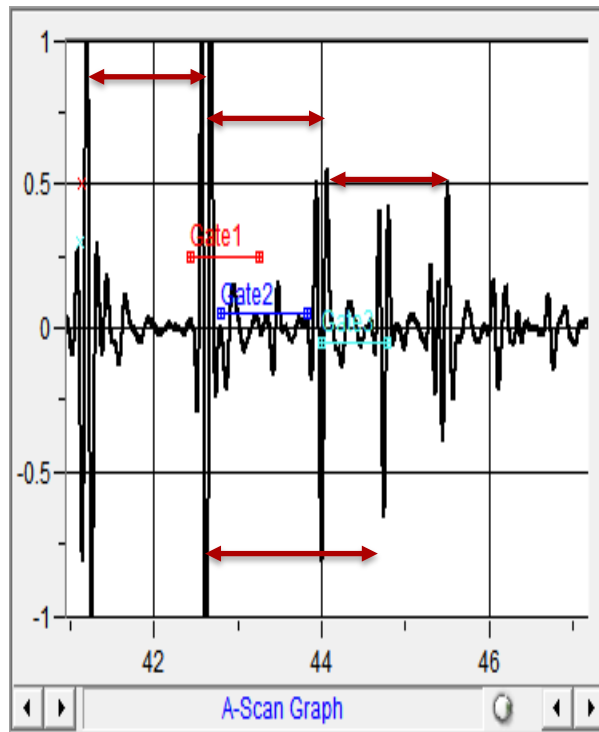
14

Interface Detection Using Couplant on Dissimilar Materials

High viscous v_c = 0.203 km/sec

Glycerin Oil v_c = 0.192 km/sec

4 ply   8 ply   12 ply

6.35 mm   5.4 mm   4.6 mm

(0.250 inches)   (0.213 inches)   (0.180 inches)

4 ply   8 ply   12 ply

6.35 mm   5.4 mm
               4.6 mm

(0.250 inches)   (0.213 inches)   (0.180 inches)
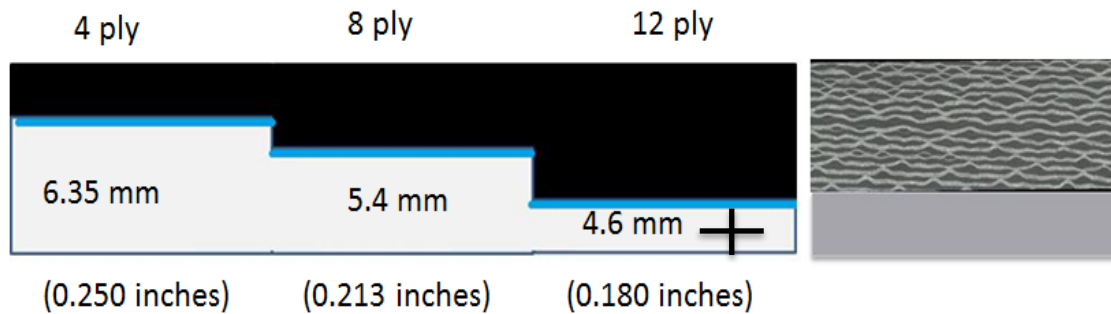
No bond
aluminum side up
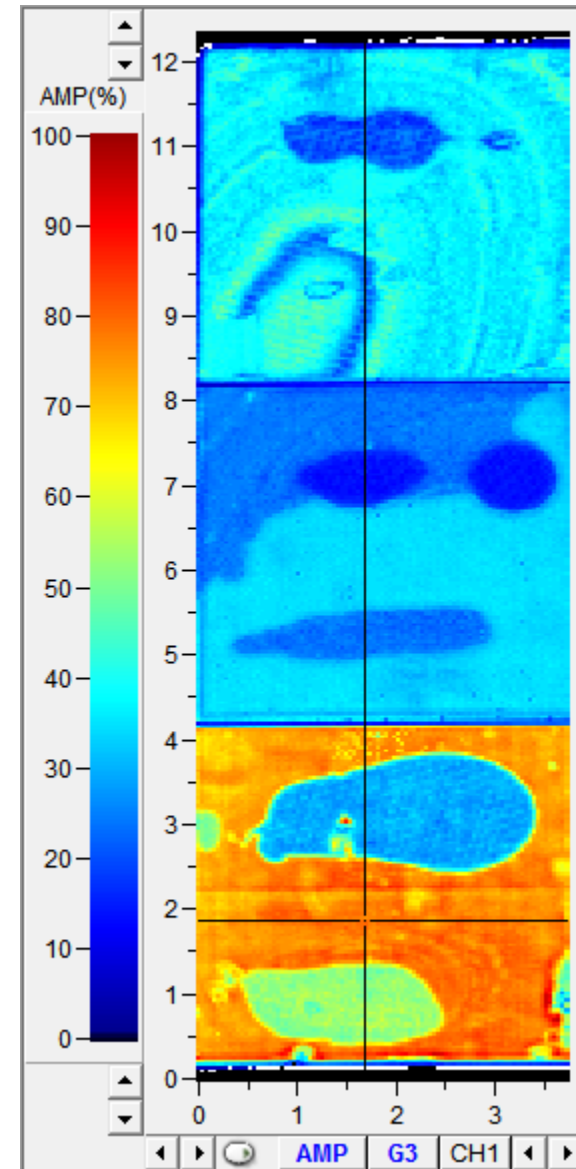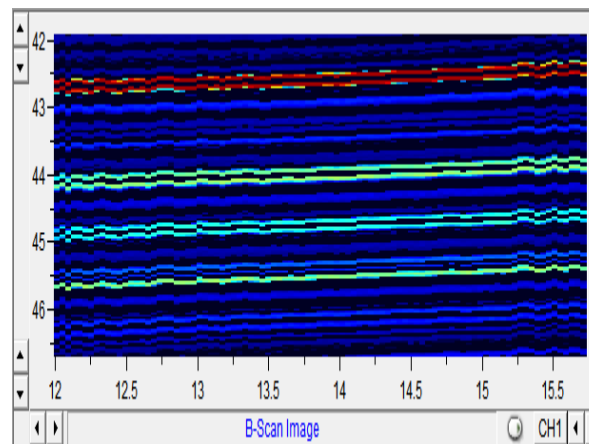
AMP(%)

Gate1
Gate2

A-Scan Graph

B-Scan Image   CH1

AMP   G3   CH1

4 ply   8 ply   12 ply

6.35 mm   5.4 mm   4.6 mm

(0.250 inches)   (0.213 inches)   (0.180 inches)

No bond, interface detected (aluminum up).

A-Scan Graph

B-Scan Image   CH1

AMP(%)

AMP   G3   CH1
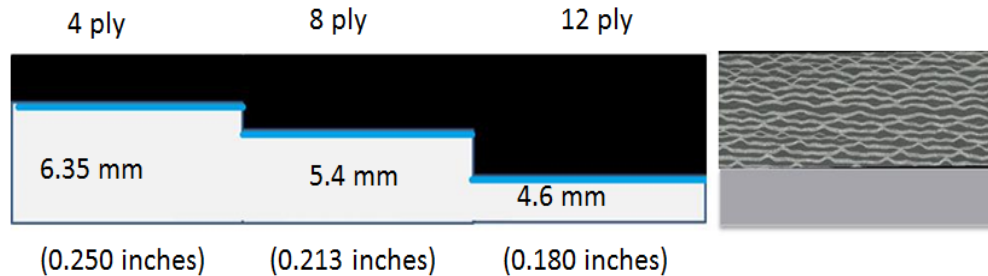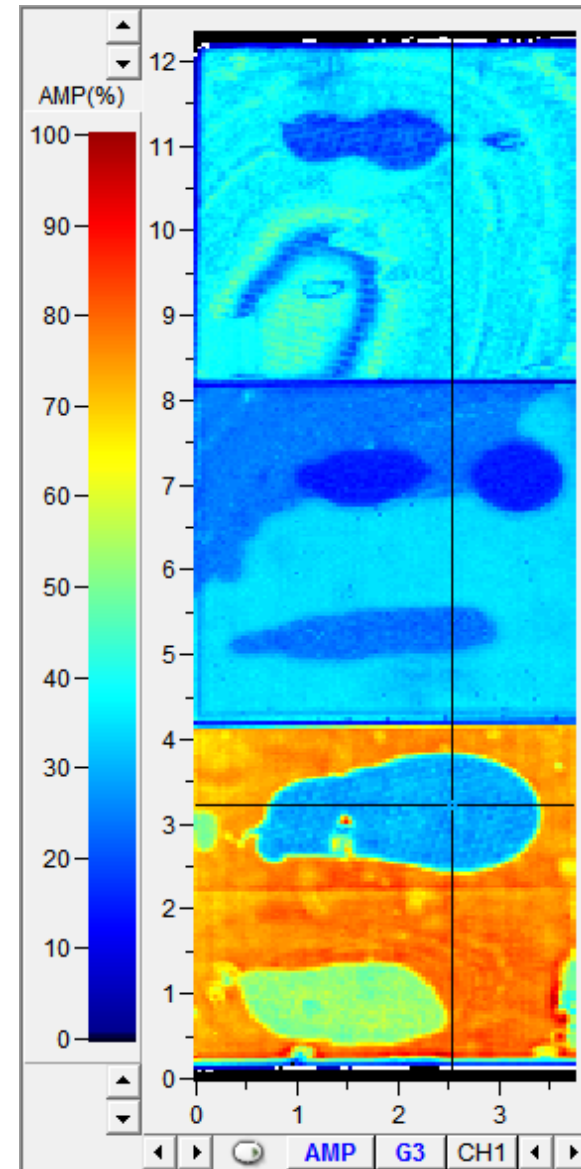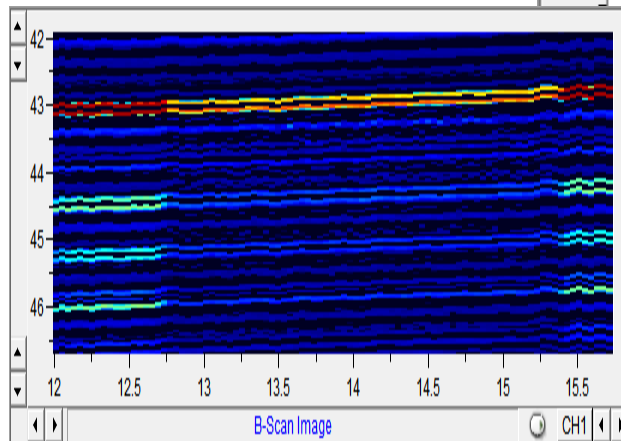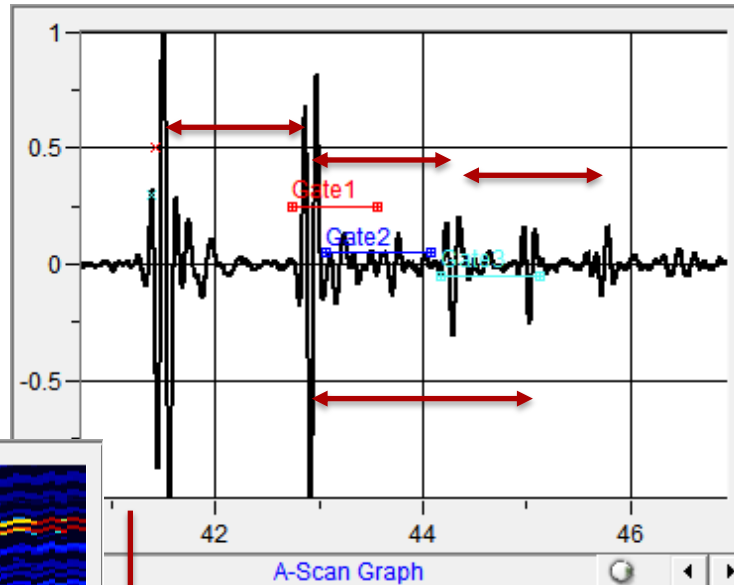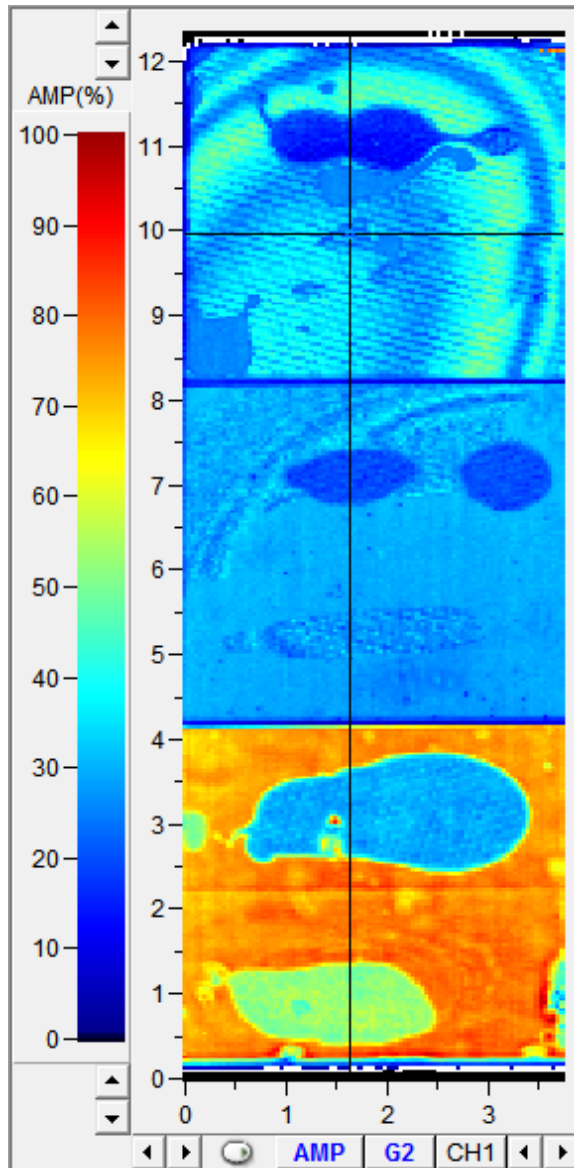
No bond, interface detected (aluminum up).
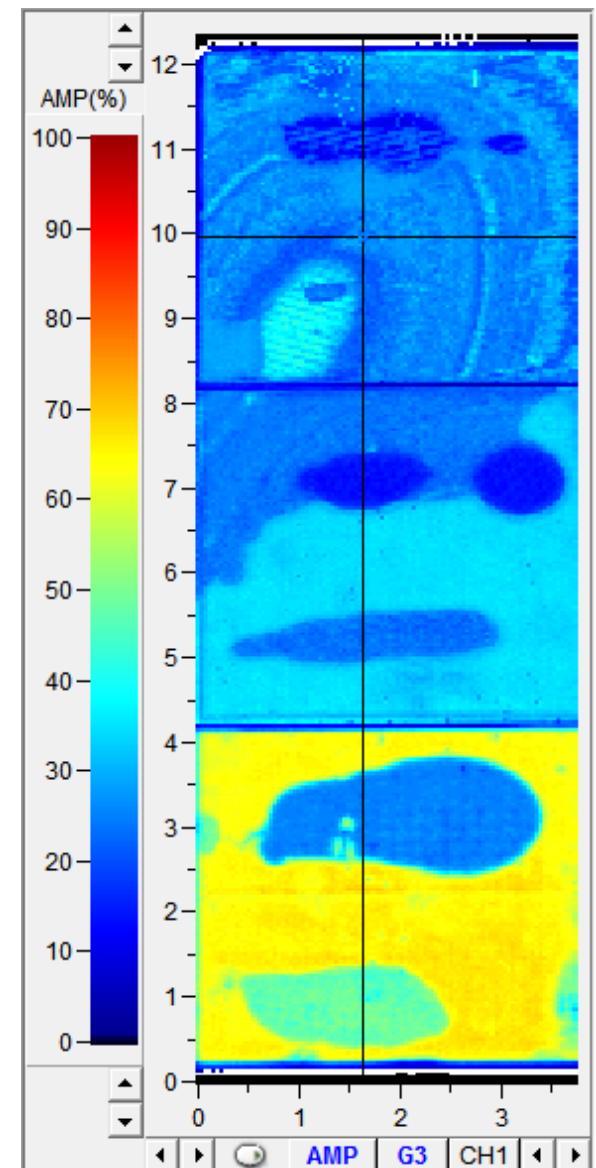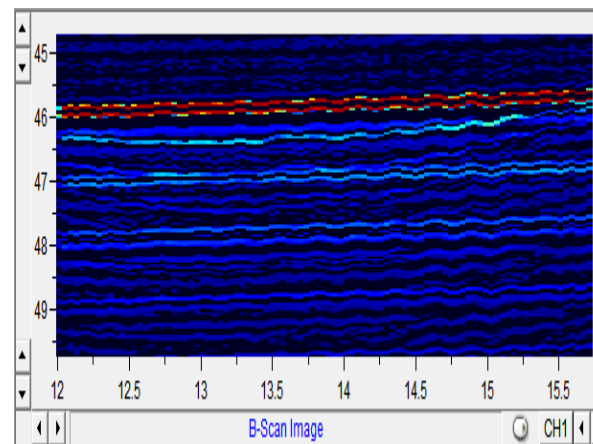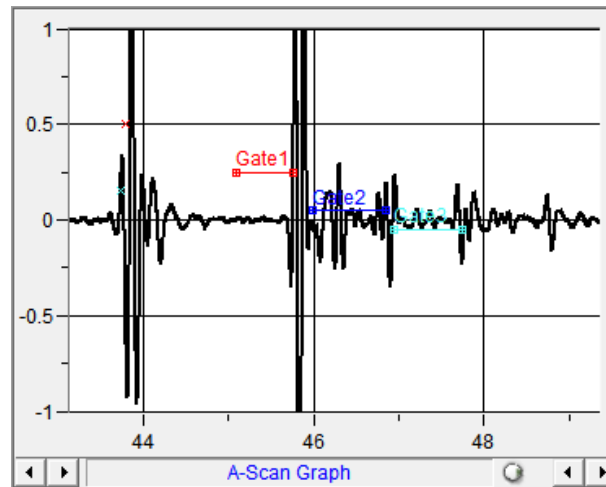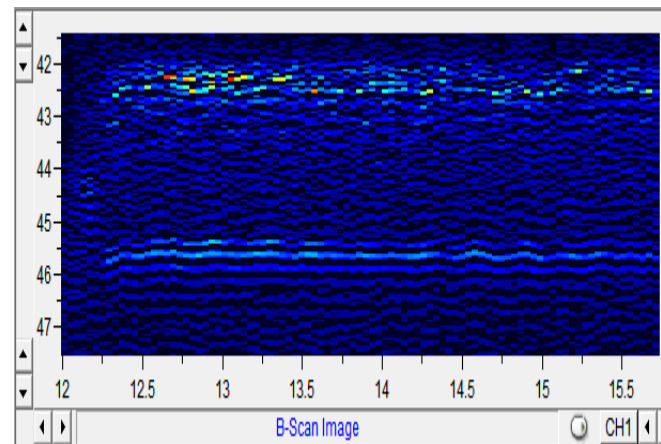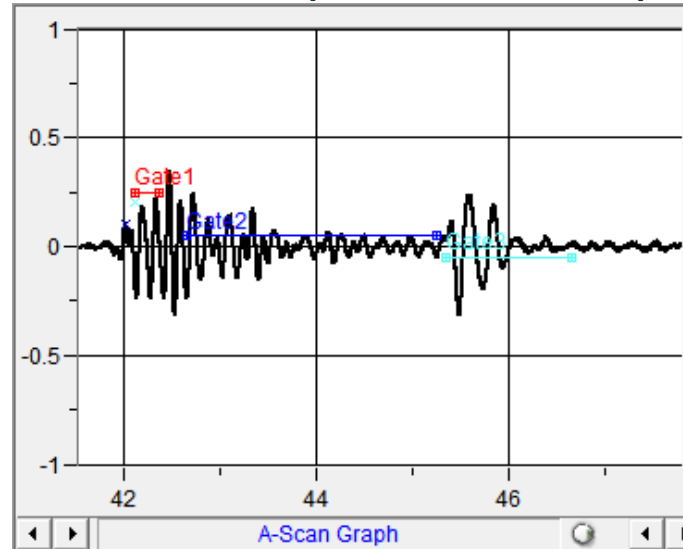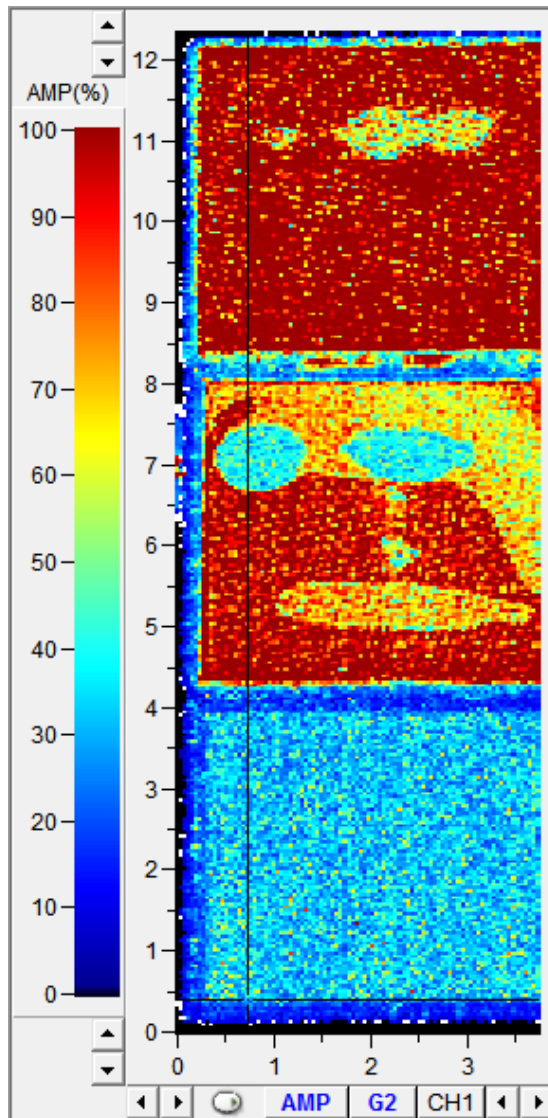
No bond composite side up
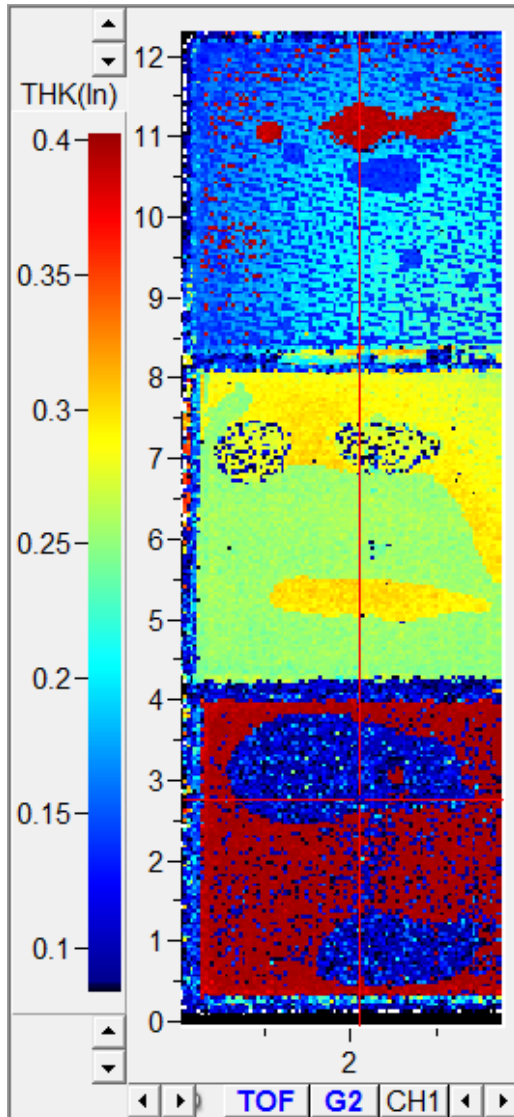
No bond composite side up
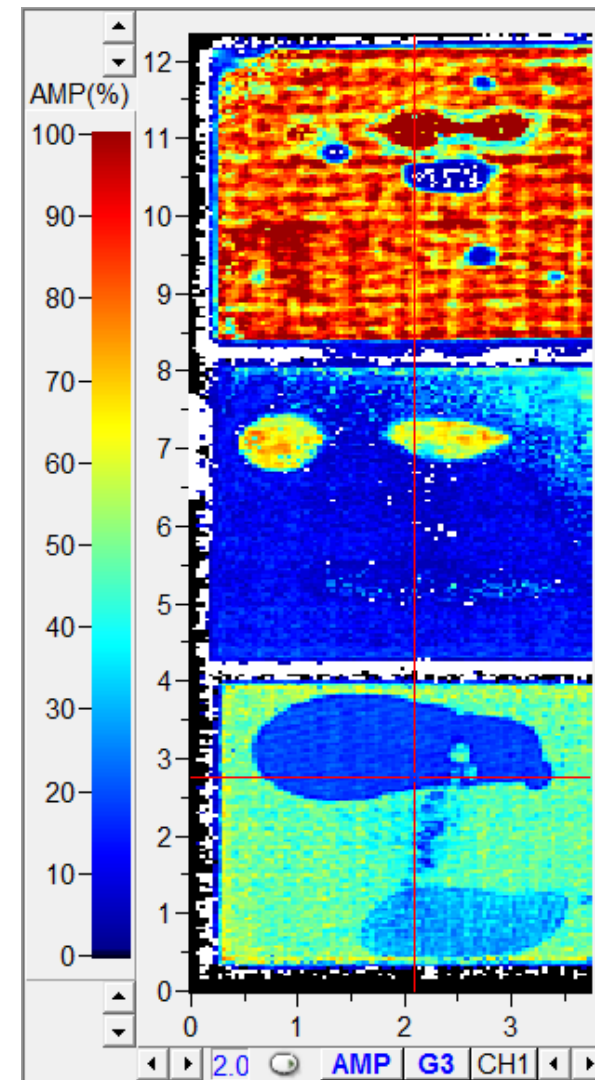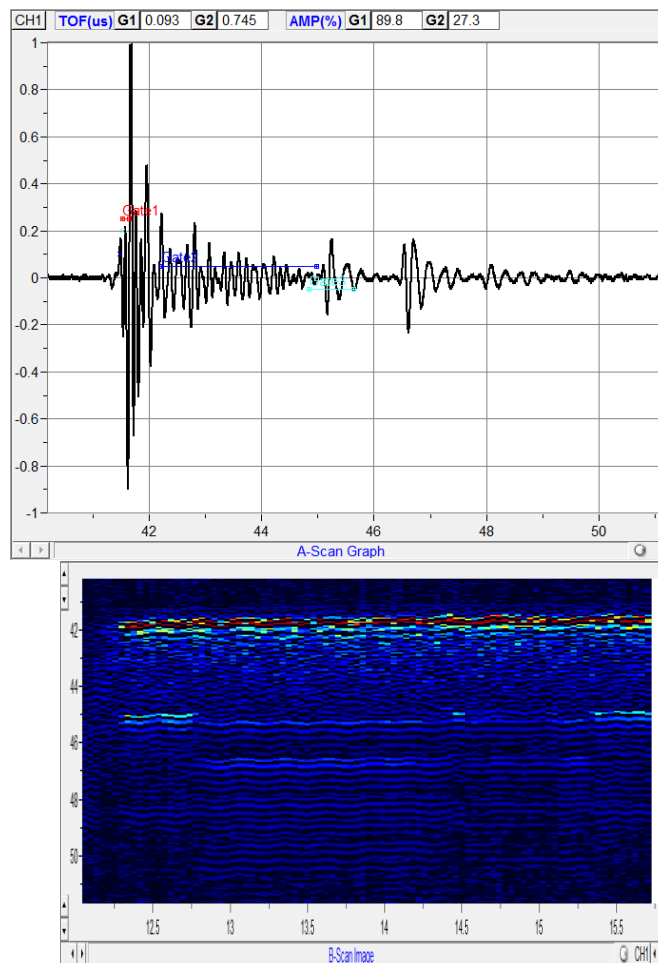
Roller Scanner Evaluation

Tool Side Down (with Pull Tabs)

Tool Side Up (with Pull Tabs)
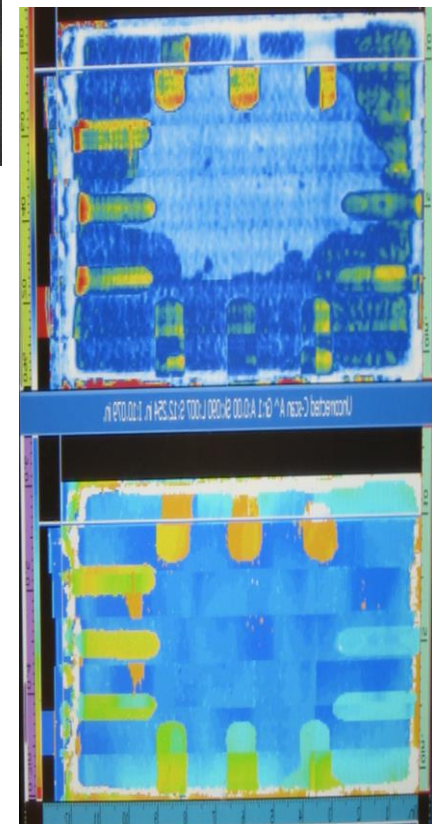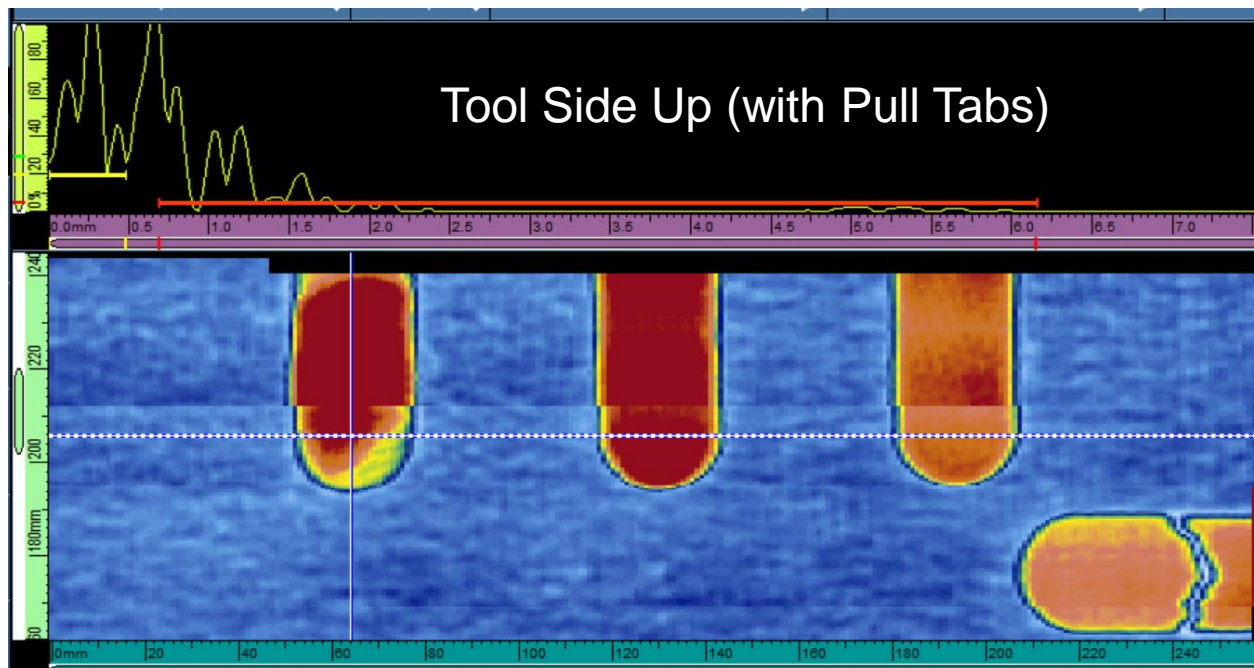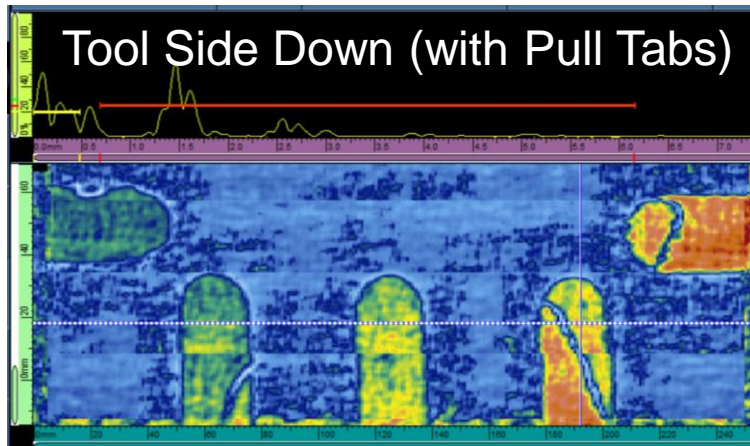
Semi-automatic Scanner

Tool Side Down (with Pull Tabs)

Amplitude

Depth Gate

1/2

11/12

Tool Side Up (with Pull Tabs)

Front Surface Echo

Pull Tab and Back Surface Echo

Amplitude

Depth Gate

11/12

1/2
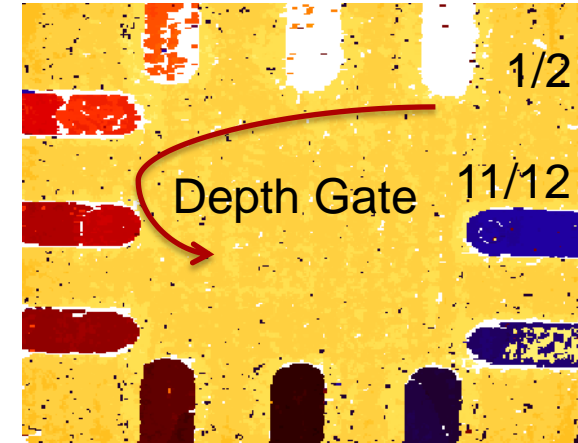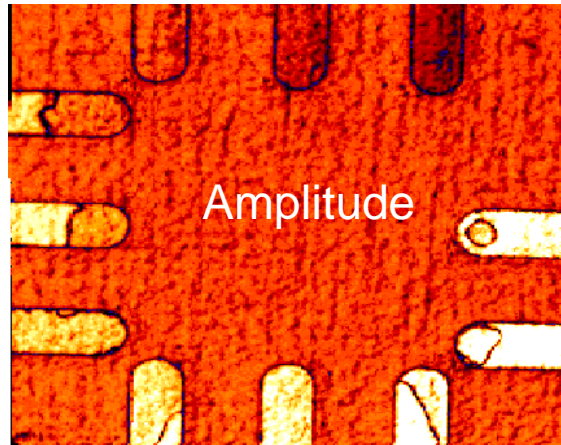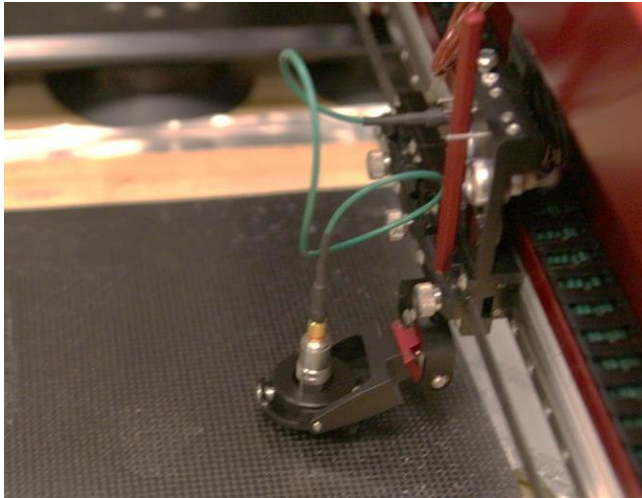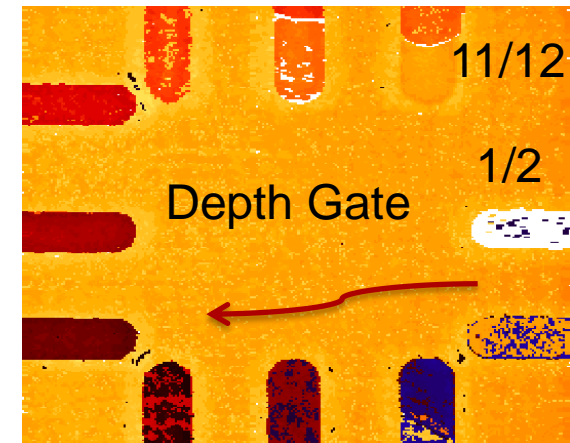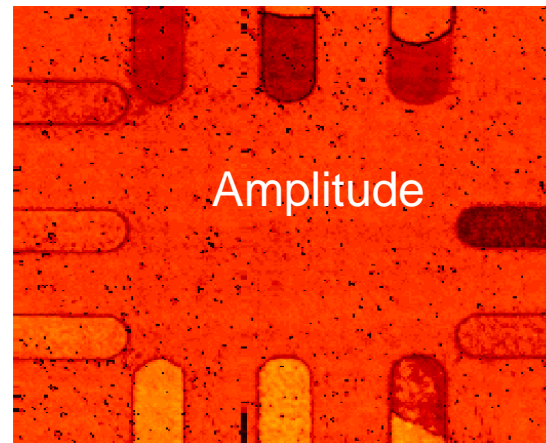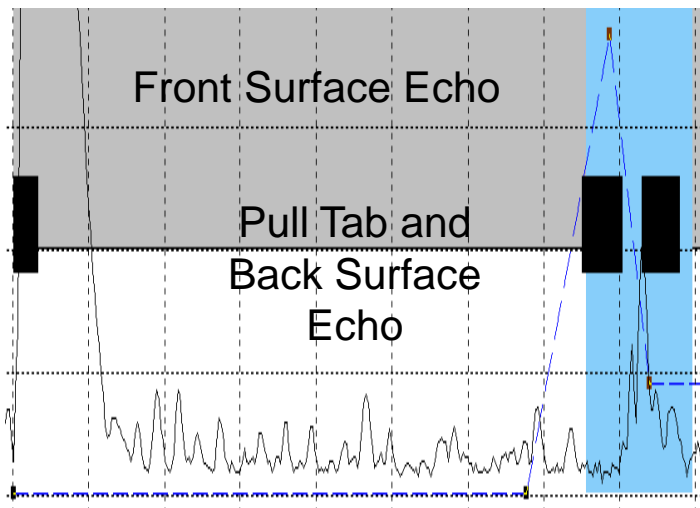
Conclusions

- Contact, immersion and array methodologies can identify wave scattering. If the composite layer is thin enough acoustic wave techniques can analyze the bondline. Both conventional and advanced ultrasonic methods can detect interfaces between the m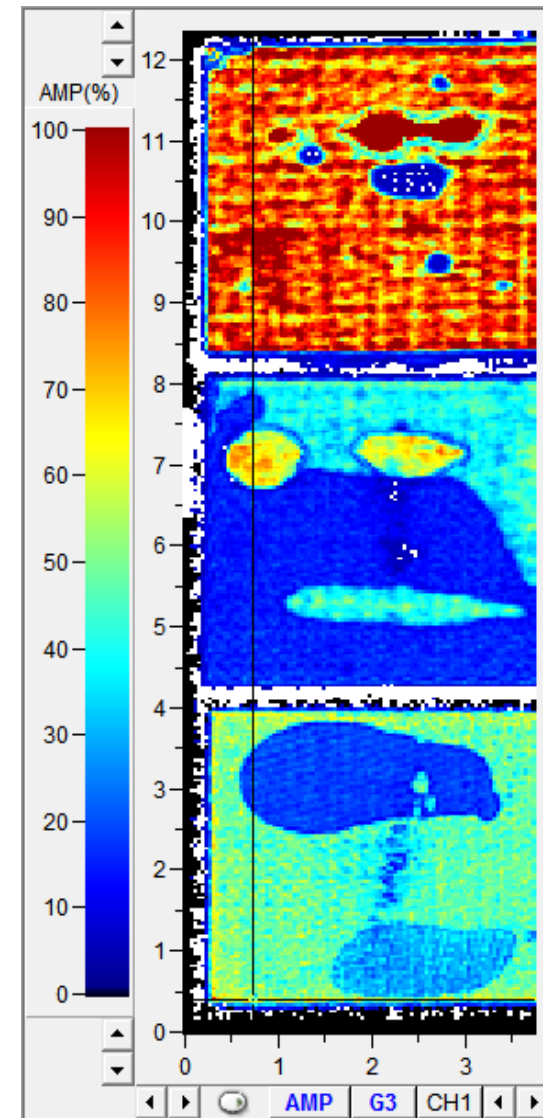etal and composite. This comparison of the pulse-echo signal measured is based at the point of interest (the bondline interface).

- It is difficult to correlate ultrasonic signal to the strength of a bond. Bond strength is not a physical property but a structural parameter. The inspection methods described in the paper are not designed to find the weakest of the weakest area (i.e. highest stress in the weakest specific area of failure). Understanding the behavior of bonded interfaces with the use of ultrasonic inspection will ensure safety and reliability of designs.

- Ultrasonic techniques described above can detect most discontinuities types that are required. However, a high variance in the material properties or surface roughness may not allow for a reliable assessment. The most important variable to understand for all composite inspection is the role of attenuation and the frequency selected.

Future Work

- Develop equations for wave scattering in the 8 satin weave material.

- Create new samples at varying thickness and determine the optimal frequency.

- Measure elastic wave speeds and calculate elastic constants.

- Characterize different material interfaces.

Back up Slides

Plane Sound Waves at Boundaries

A sound waves **always require** particle movement. When the sound hits a boundary, it will either be reflected back toward the source (the probe) or scattered (smooth versus rough surfaces). If two materials are "bonded" the boundary becomes a point of interest. Strong bonds allow the forces to be transmitted into the second material and the wave will continue to propagate.

Sound intensity, direction and/or mode change occur when a boundary is encountered. Material boundaries have a strong influence on the propagation of sound. Defects within a material are detected by the change in wave propagation (reflected or transmitted). If we consider our case: aluminum to composite; the acoustic impedance of the first two materials is the driving condition

$Z_{water} = 1.48$ (Pa s/m) $= \rho_1 c_1$ water;
$Z_{aluminum} = 17.06$ (Pa s/m) $= \rho_2 c_2$
$Z_{air} = 0$
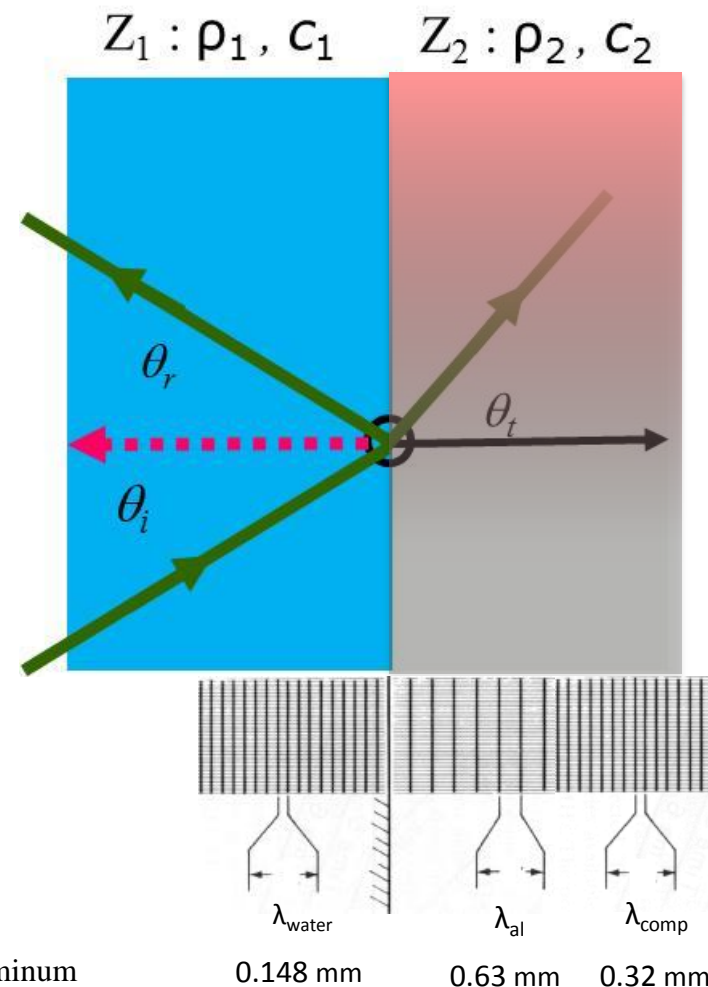$Z_{composite} = \sim 5$ Pa s/m

Coefficient of reflection 80% water to aluminum
20% of sound energy enters aluminum
Coefficient of reflection 55% aluminum to composite
Coefficient of reflection 54% water to composite

$Z_1 : \rho_1 , c_1$ $Z_2 : \rho_2 , c_2$

θ_r θ_t θ_i

λ_{water} λ_{al} λ_{comp}
0.148 mm   0.63 mm   0.32 mm

Gate Adjustments

- Slide 22 Thin composite al up

- Gate 1: Start 1.304 width 0.033 usec 50% thres 25% Detection Max Peak Amp

- AMP Gate 2: 2.26 width 0.847 usec 15% threshold 5% Detection Threshold

- Gate 3 – side start 3.217 Width 0.792 15% thres 5% Detection Threshold

- Slide 21 Thick composite al up

- Gate 1: Start 1.304 width 0.0821 usec 50% thres 25% Detection Max Peak Amp

- AMP Gate 2: start 1.68 width 1.021 usec 30% threshold 5% Detection Threshold

- Gate 3 – side start 2.782 Width 0.966 30% thres 5% Detection Threshold