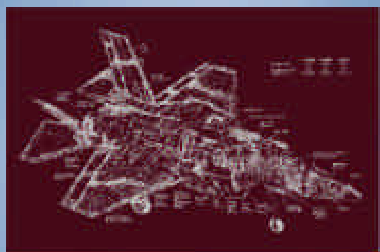
ASQ World Conference, Seattle Washington

Emerging Concepts in Nondestructive Evaluation Imaging Composite on F-35



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Santa Monica, CA 90404
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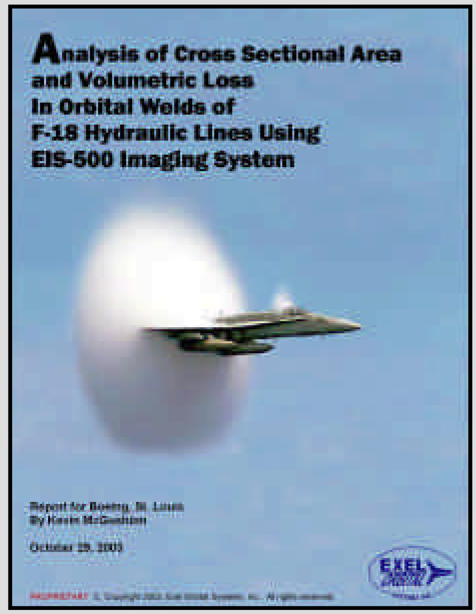
May 17, 2005
Course T304
3:30 PM – 4:45 PM

History of Exel's Imaging System

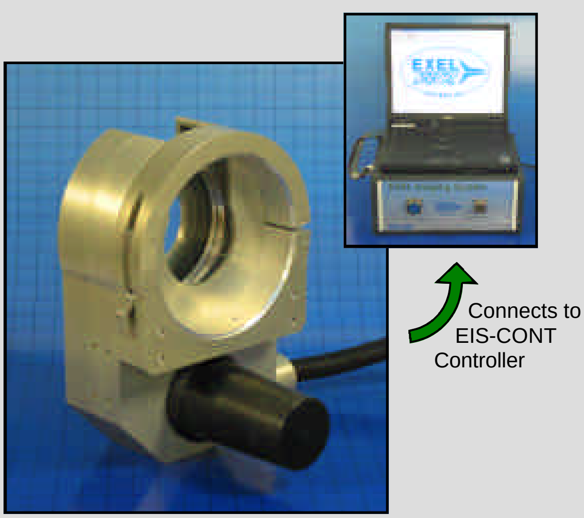
In 2000 Boeing Rocketdyne asked Exel Orbital Systems to develop an imaging system capable of inspecting its engine ducts on the RS68. Development took about 6 months and extensive testing began on the EIS-3000 Imaging System. The imaging system was tasked with scanning tubes of .100” wall 625 Inconnel up to 3.500” in diameter. This testing culminated in successful completion of a 90/95 POD/CL (Probability of Detection/ Confidence Level) analysis on July 27, 2002 and was recommended for use on Boeings RS68 Engine Program.

Soon after Exel began developing its EIS-500 Imaging System for other programs at Boeing ranging from THAAD to Delta 4 to F-18. One such study shown below evaluated the ability of the EIS-500 to calculate cross sectional area loss due to porosity in orbital welds of F-18 hydraulic lines.

90/95 POD/CL Report



Cross Sectional Area Loss Report



EIS-3000 Imaging Systems used for 90/95 POD/CL Report

EIS-500 Imaging System

Programs

The Exel Imaging Systems is currently being either used or evaluated by several customers they are:

RS-68 Rocket Engine Test

Company: Boeing Rocketdyne (Canoga Park Facility)

Program: RS-68 Rocket Engine

Material: 625 Inconnel 1.25” thru 3.50” diameter x .100” wall.

System: EIS-3000

F-18 Fighter

Company: Boeing (St. Louis Facility)

Program: F-18 Fighter

Material: 6-4 Titanium 1/4” thru 1/2” diameter .028 wall.

System: EIS-500

THAAD Missile Test

Company: Boeing Rocketdyne (Desoto Facility)

Program: THAAD (Theater High Altitude Area Defense) Missile

Material: 3-2.5 Titanium, 1/4” thru 5/8” diameter x .028 wall.

System: EIS-500

F-35 Joint Strike Fighter

Company: Northrop Grumman (El Segundo Facility)

Program: F-35 Joint Strike Fighter

Material: Graphite Composite Structures

System: Modified system for large surface imaging.

Delta 4 Rocket Launch

Company: Boeing (Huntington Beach Facility)

Program: Delta 4 Rocket

Material: 625 Inconnel 1/4” thru 1/2” diameter.

System: EIS-500

Imaging Insulators with Eddy Current

It is well understood that eddy current detection operates on the basis of electrical conductivity and magnetic permeability of the material being tested. It has also been well established that metals with their high electrical conductivity or low electrical resistivity make good test subjects because of their ability to induce an electric field or "eddy current" as a result of an induced oscillating magnetic field. The same holds true of insulators, however not to the same degree. Insulators resist the passing on of an electric field however, given enough voltage all insulators eventually break down and become conductors this is commonly referred to a "*break down voltage*". For a semiconductor this may occur at only a few volts however for an insulator this can occur at many thousands or even millions of volts depending on the material and its thickness. In spite of this all insulators have an ability to carry or resist an electric current. This ability to resist commonly referred to as *electrical resistivity* or ρ, denoted by the Greek letter rho.

The term ρ can be calculated by using the following formula:

$$\rho = \frac{R \times A}{L}$$

Where:
ρ is electrical resistivity
R is resistance in Ω's
L is length of the specimen in meters and
A is cross sectional area of the specimen in square meters

Electrical resistivity for some materials is given below:

Material	Electrical Resistivity ρ (Ωm)
Silver	1.59×10^{-8}
Copper	1.673×10^{-8}
Aluminum	2.65×10^{-8}
Sea Water	.2
Granite	1×10^{8}
Glass	1×10^{10}
Vespel SP1	1×10^{12} to 1×10^{13}
Delrin, Acetal ASTMD4181	1×10^{13}
LDPE	6×10^{13}

Chart 1, Electrical Resistivity

Generally materials with a resistivity greater than 1×10^{8} are considered good insulators however, they are still conductors in spite of the fact that they have high electrical resistivity. In fact eddy current detection can be characterized in terms of electrical resistivity with the following formula:

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

Where:
δ is standard depth of penetration in meters
ρ is electrical resistivity
μ is magnetic permeability
f is frequency in Hertz

The variables, according to the equation above that would most affect the output signal of an eddy current sensor are electrical resistivity and permeability. In contrast the equation for depth of penetration when *electrical conductivity* is taken into consideration is:

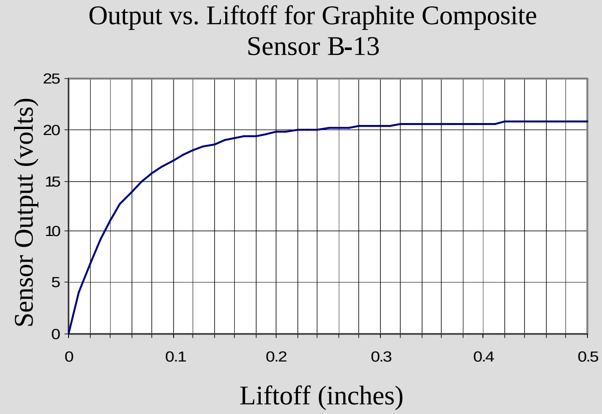
$$\delta = \frac{1}{\sqrt{\pi \mu f \ \sigma}}$$

Where:
σ is electrical conductivity in %IACS

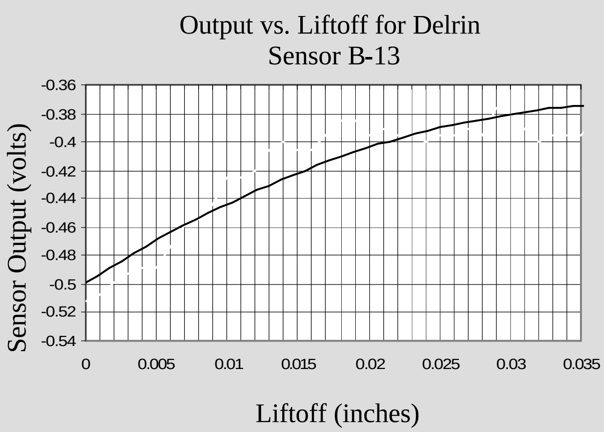
As can be seen through the equations above the ability of an eddy current probe to penetrate conductors or non conductors can be calculated and is a matter of electrical perspective. It can be expected, based on the above equation that the difference in signal or depth of penetration between LDPE and Delrin would actually be greater that that of Copper and Aluminum.

Signal from Plastics Relative to Air

The signal produced by the presence of graphite composite by the Exel Imaging System is large and well understood. The following graph shows how that signal increases exponentially, to greater than 20 volts when liftoff is changed linearly from '0' to .500". Beyond .500" the signal is the same as that in free air. To test the response of the sensor over polymers such as Delrin and LDPE respectively which according to Chart 1 are considered good insulators, output is measured relative to liftoff over each of these materials.

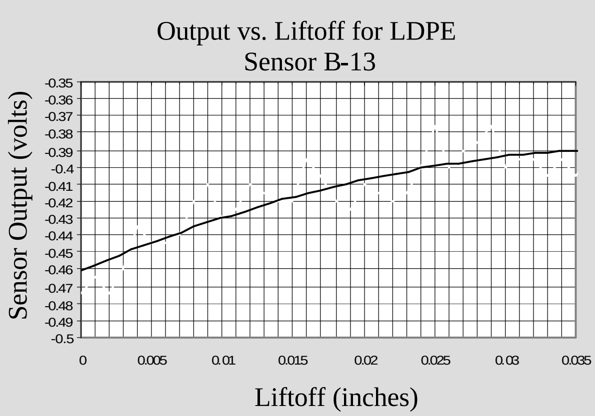


Output vs. Liftoff for Composite



Output vs. Liftoff for Delrin

The first and most important observation is that there is an output change relative to liftoff and even when liftoff is '0'. This directly implies that the presence of both types on insulators with high electrical resistivity affect the sensor. In a more detailed observation the signal output for a given liftoff for each material is different. This means that as the sensor is passed over a sample comprised of 2 different polymers, (in this case Delrin and LDPE) an output signal change can be



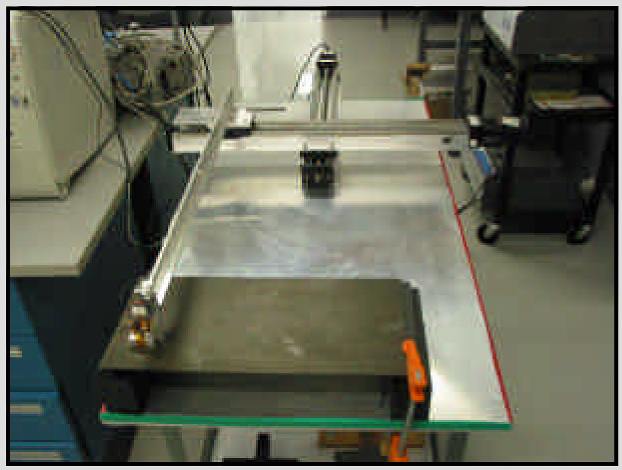
Output vs. Liftoff for LDPE

expected. For instance at '0' liftoff Delrin has an output of –.500 volts and LDPE has an output of –.460 volts for an overall visible difference of .040 volts. A very discernable difference for the Exel Imaging System.

Imaging System Prototype for Composite

Below are photographs of Exel's prototype imaging system for scanning composite. The systems is designed to scan a 24" x 24" area in order to accommodate medium size composite panels. The system is designed to test a number of variables such as data density and travel speed. Data collection densities as high as 1 point every .001 inches and as low as 1 point every .10 inches have been tested to obtain the optimum density to reveal flaws of a critical size for composite. That size is determined to be .250 inches.

Prototype Imaging Systems for Composite



Scan Table of Prototype Imaging Systems for Composite

The prototype system was operated at maximum speed or about 225 in/ minute or 1/4 of a mile per hour. However tests indicate that speed in excess of 100 times faster or greater than 25 mph are possible and the only real limitation is safety based.

Imaging Insulators

To test the ability of the imaging system to differentiate between Delrin and LDPE, two holes, each 1/2" in diameter were drilled in a Delrin block. Two 1/2" diameter plugs of LDPE were pressed into the holes and a fly cut taken, with a milling machine on the face of the sample to ensure that there was not a height difference between the 2 materials. This sample is shown below. The image below shows the relative

1/2 Diameter LDPE Plugs in Delrin Block

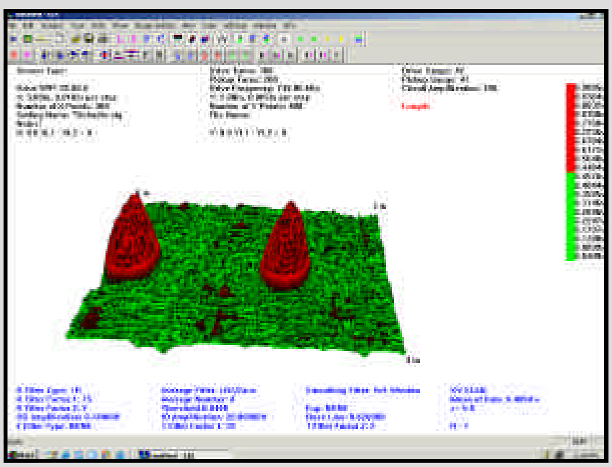
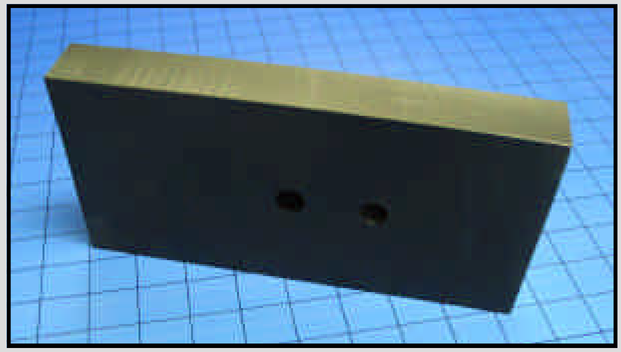


Image of LDPE Plugs in Delrin

ease with which the imaging system can detect the LDPE plugs in the Delrin background.

According to the liftoff tests on the previous page there is a distinct difference between air and Delrin. To test the imaging systems ability to resolve this, 2 holes, each measuring 1/2" in diameter and having a wall thickness from breaking through of .031" and .062". The sensor was placed on the side opposite the holes so that a .031 and .062 wall would need to be scanned through to detect the holes. It can be seen that the difference between air and Delrin is very detectable.



1/2 Diameter Holes in Delrin Block

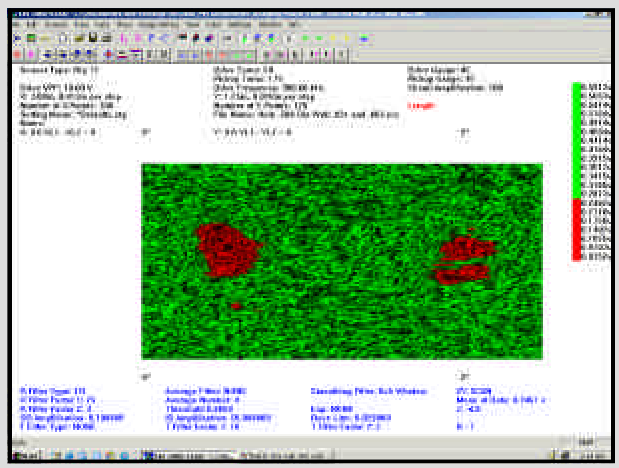
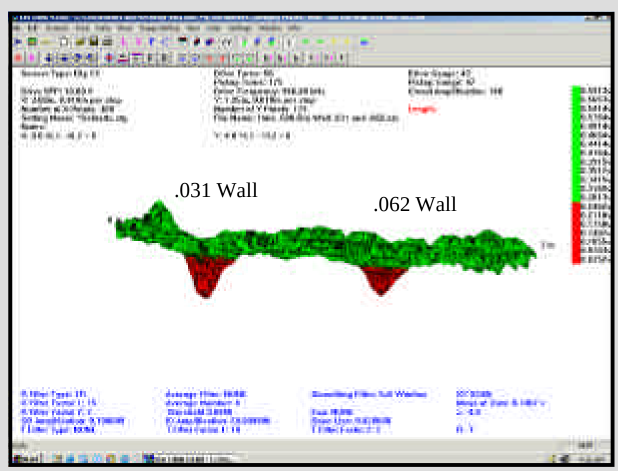


Image of 1/2 Diameter Holes in Delrin Block



Profile Image of 1/2 Diameter Holes in Delrin Block

Imaging Coatings on Composite

It would be desirable to detect both the difference between the thickness of insulating coatings and to measure the thickness of that coating relative to sensor output when that coating is placed on graphite composite. To test this Kapton tape was used as the insulating coating. A 1/2" x 3/4 rectangular piece of Kapton measuring .0035" in thickness was place on a piece of graphite composite and a larger piece of Kapton (of the same thickness) placed over the rectangle such that it was completely covered. An area measuring 1.25" x 2.00" was scanned such that the sensor was always on the larger layer of Kapton and translating over the small Kapton rectangle.

2 Layers of Kapton on Composite

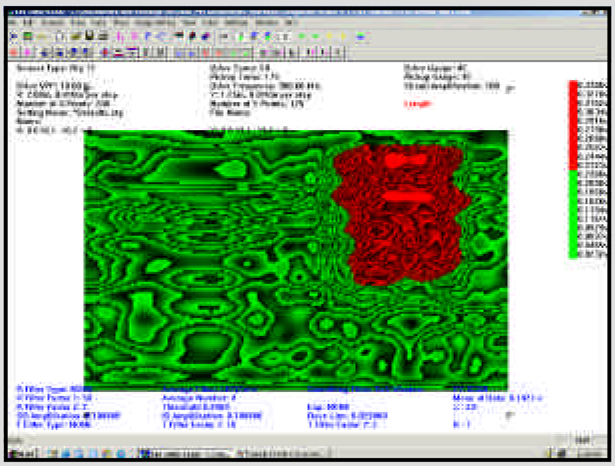


Image of Kapton Rectangle on Composite, C-Scan

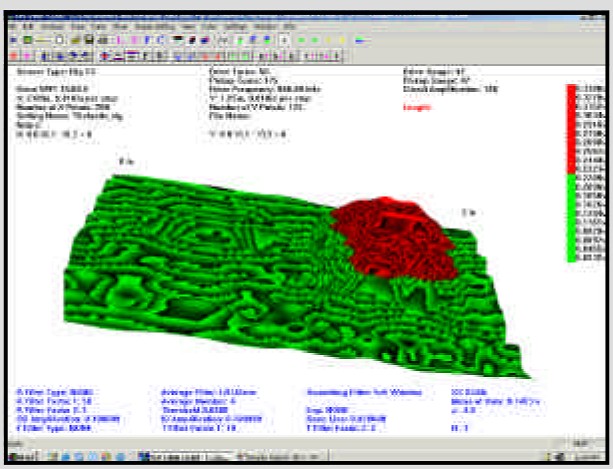
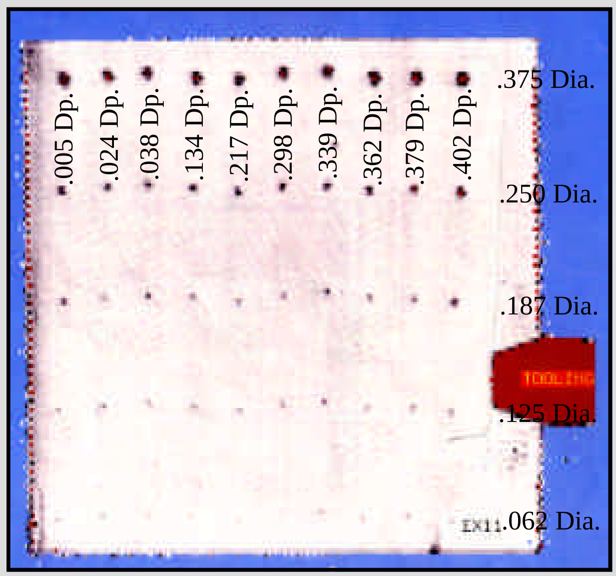


Image of Kapton Rectangle on Composite, Iso View

It is apparent that the imaging system can detect the difference between insulating coating thickness' varying by .0035". The C-Scan and Iso images clearly show this.

Sample EX11

Sample EX11 contains Teflon disks .006" thick, varying in diameter from .062" to .375" and placed at increasing depths from .005" deep to .402" deep.



AUS Image courtesy of Northrop Grumman

Based on the data collected in imaging insulators it is reasonable to assume that the presence of Teflon disks can be detected especially since the resistivity difference between Teflon and graphite is so large.

Analysis of Sample EX11

Studying the .375” diameter Teflon disks, it can be seen that the first 3 disks from left to right diminish in a uniform exponential manner. However, disks 4 on appear to have a low and comparatively uniform height. This phenomena can be explained by referring to a previous graph of Output vs. Liftoff for Graphite Composite. In this graph it is obvious that anomalies

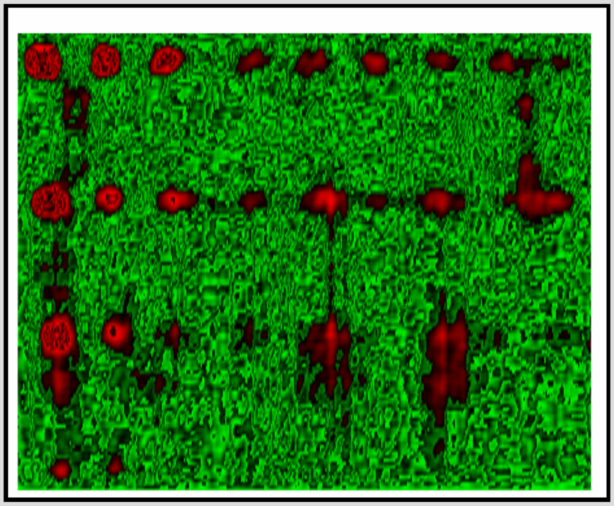


Image of Teflon Disks in Composite C-Scan View

Photograph of Sample EX11

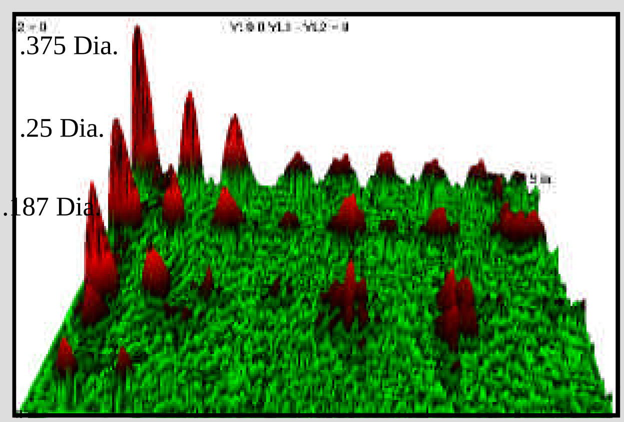


Image of Teflon Disks in Composite Iso View

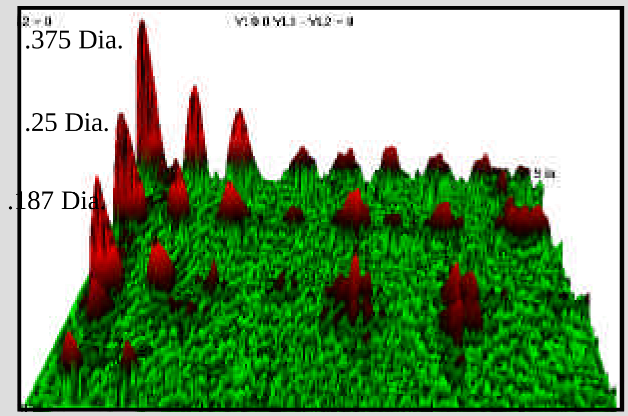
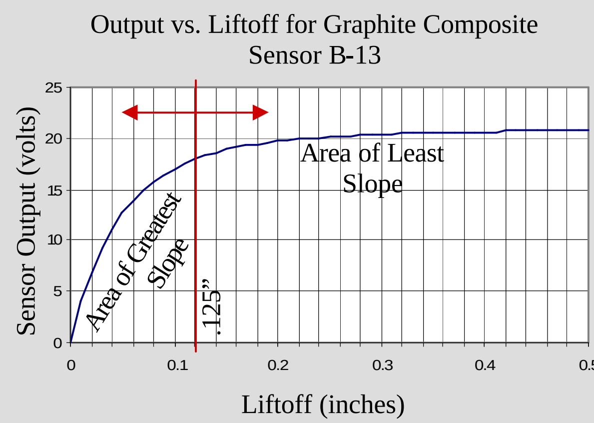


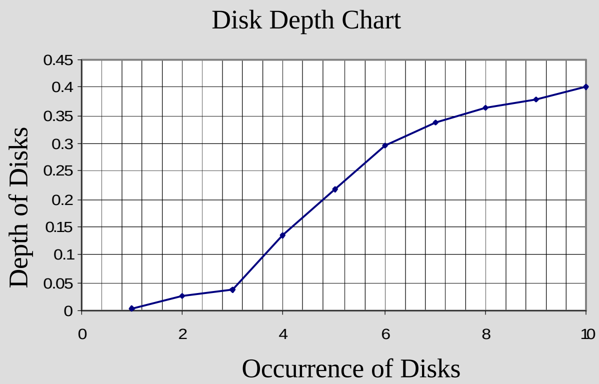
Image of Teflon Disks in Composite Iso View

between ‘0’ liftoff or depth and .125” lie in the area of greatest slope. In this area slight differences in size or depth of an anomaly have a large affect on the output signal. Beyond .125” anomalies are still visible however, the differences related to depth or size are comparatively small. On the Disk Depth Chart it can be



Graph of Slope

seen that flaws 1,2 and 3 lie at depths of .005”, .024” and .038” respectively, depths which are in the area of greatest slope thus yielding very obvious signal changes. Flaws 4, 5, 6, 7, 8, 9 and 10 lie at .134, .217, .298, .339, .362, .379 and .402 respectively, a depth which is visible to the sensor but in a range that yields very little discriminating signal difference. Also the

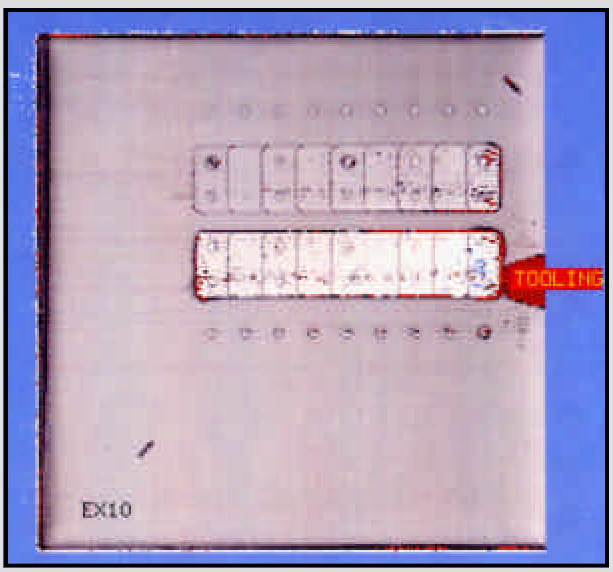


Graph of Disk Depths

Disk Depth Chart shows a sudden change in depth between flaws 3 and 4 expediting the excursion into

Sample EX10

Pockets and Flat Bottom Holes



AUS Image of Sample EX10 Courtesy of Northrop Grumman

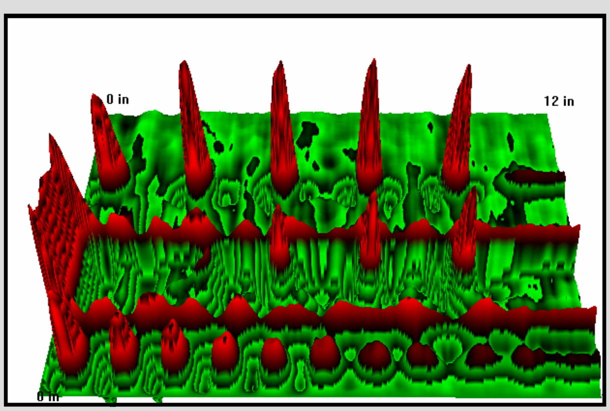


Image Sample EX11 Iso View

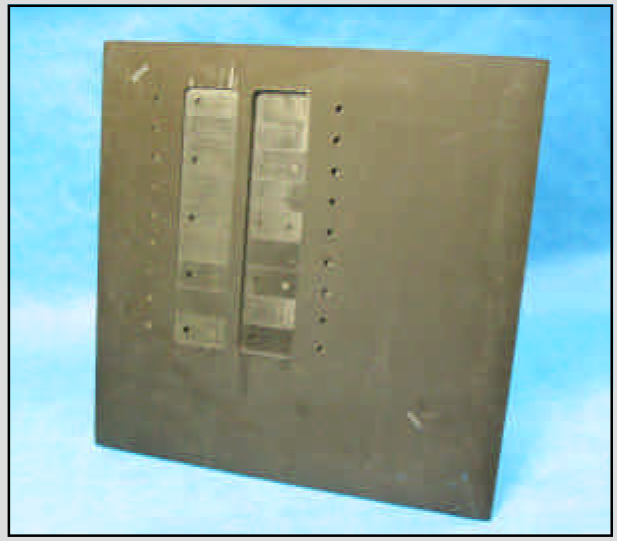
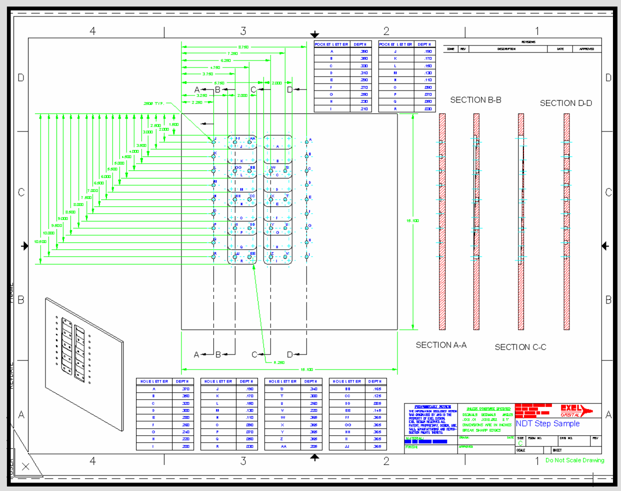


Photo Sample EX11



Drawing Sample EX11

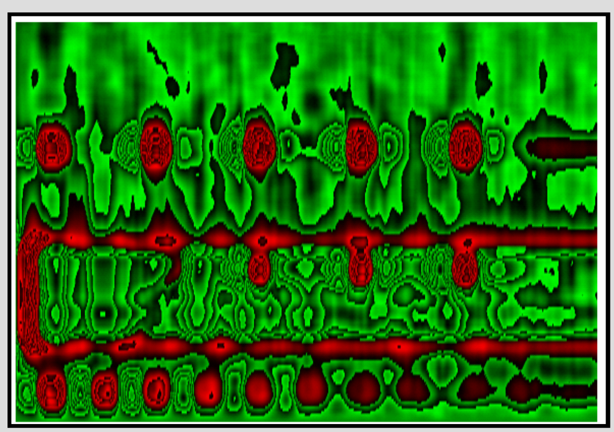
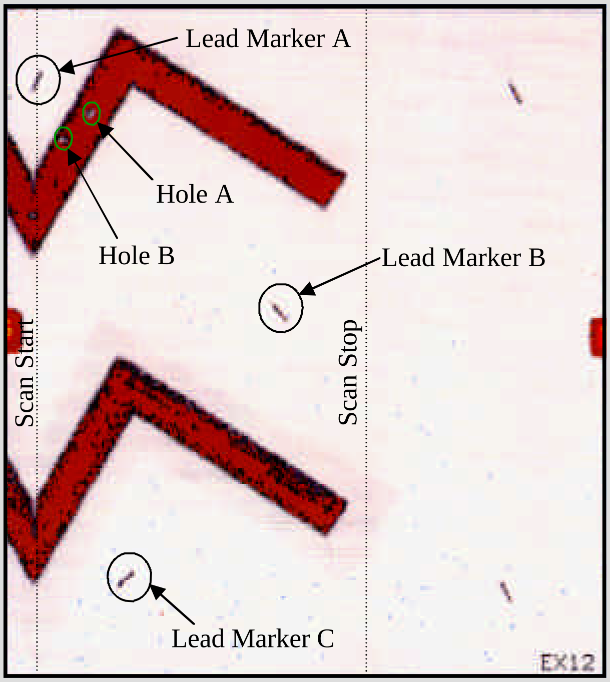


Image Sample EX11 C-Scan View Close –Up

Sample EX10



AUS Image of Sample EX12 Courtesy of Northrop Grumman

Photo Sample EX12

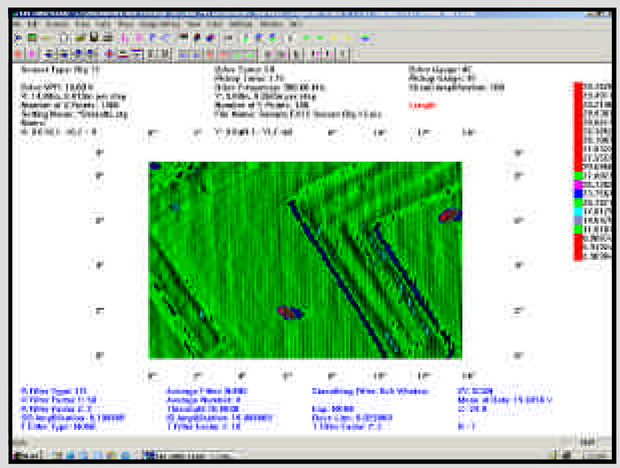


Image Sample EX12 C-Scan View

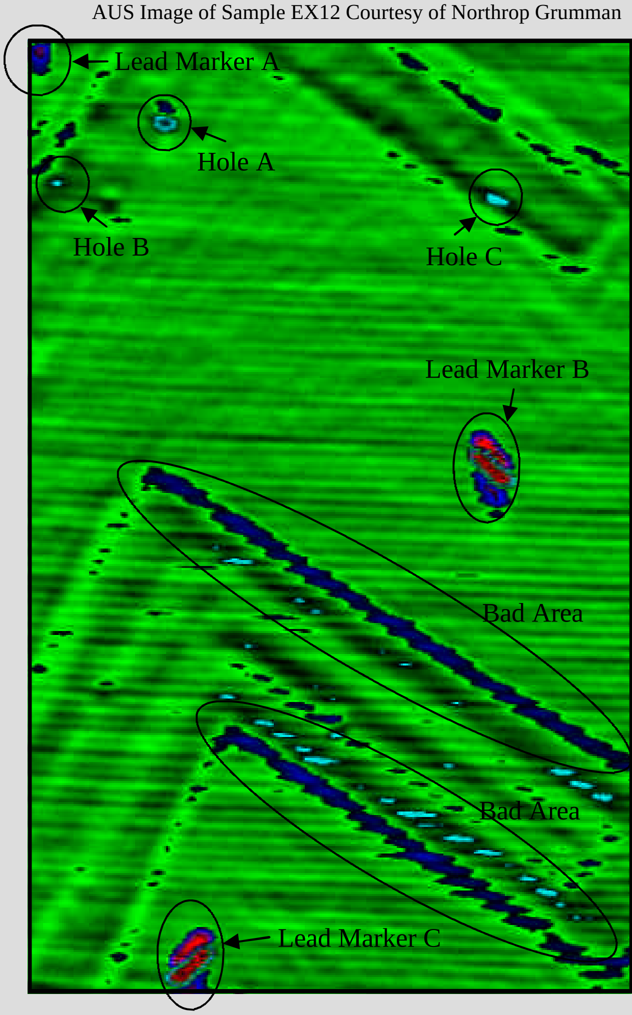
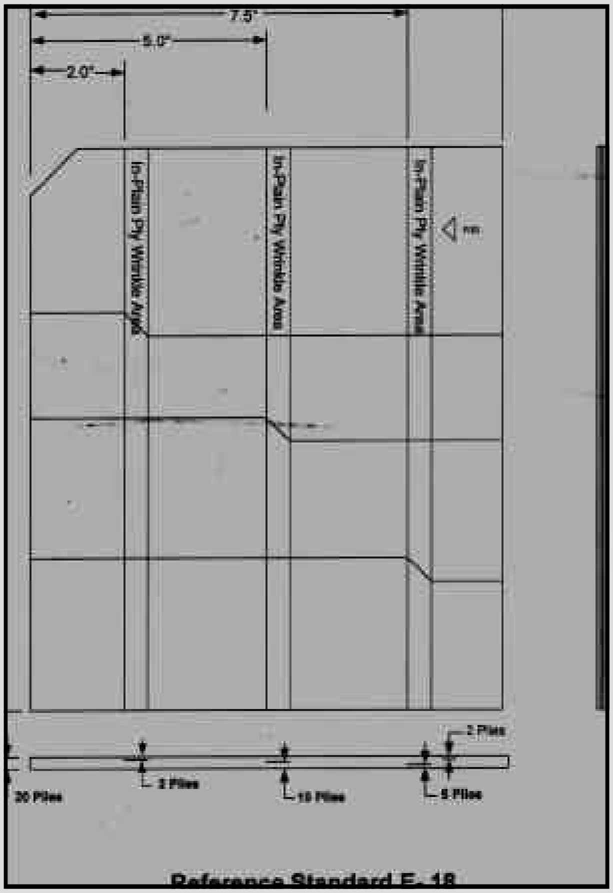


Image Sample EX12 C-Scan View, Close-Up

Sample EX18



Drawing Sample EX18

Ply shifting and folding is a concern as both effect the strength of composite. Above is a drawing showing known ply shifting induced in a composite sample. In each of the 3 cases the ply's were shifted by 45 degrees. The Exel Imaging Systems appears to be sensitive to this anomaly however, the threshold of detection must be lowered to a point where other benign conditions would be rejected. More development is needed to be selectively sensitive to ply shifting.

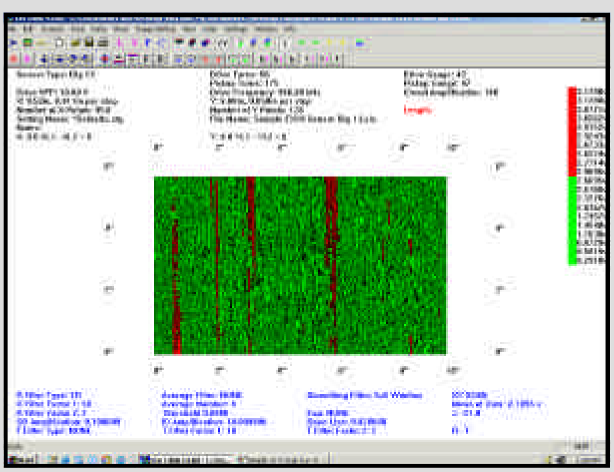
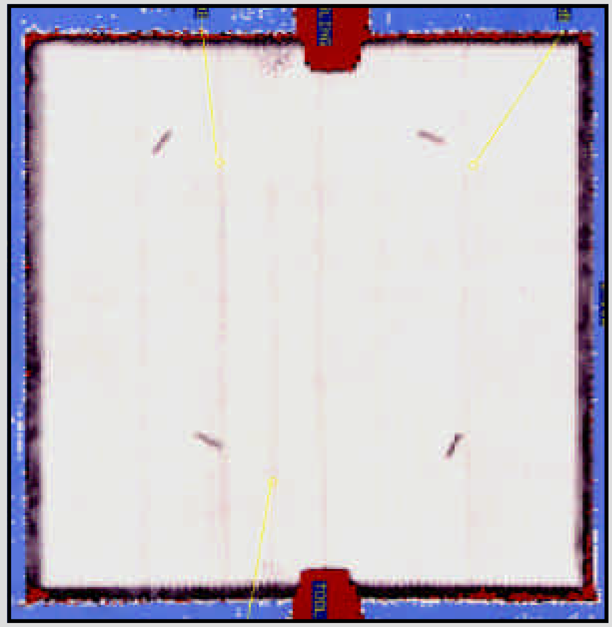


Image Sample EX18 C-Scan View

Sample EX16B



AUS Image of Sample EX16B Courtesy of Northrop Grumman

The sample above contains folds in ply lay-up. These folds are either extremely difficult to detect or impossible. In the AUSS image above light shadows can be seen where these folds exist. To the right is the Exel Image clearly showing the presence of these folds.

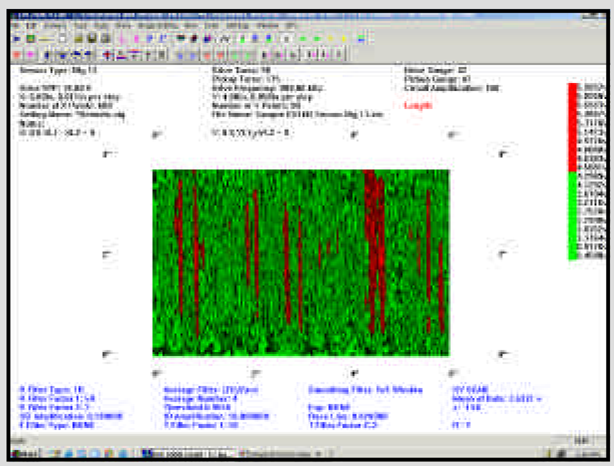
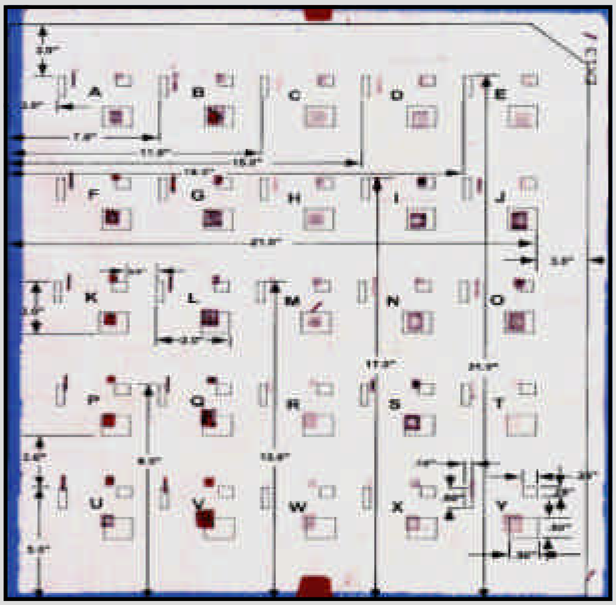


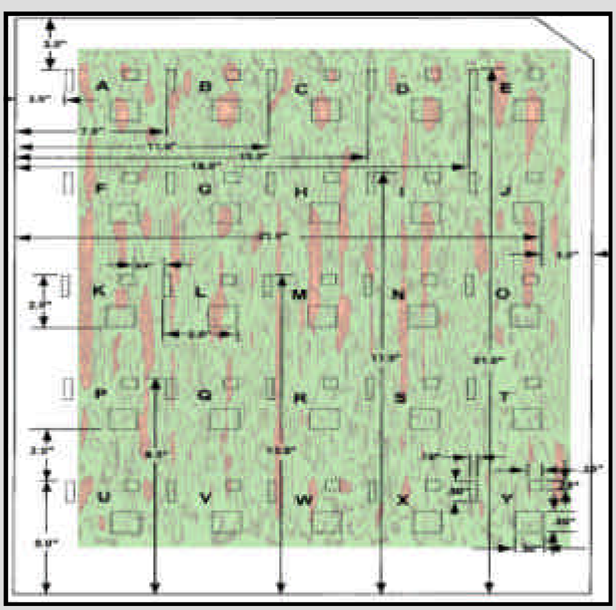
Image Sample EX16B C-Scan View

Sample EX13

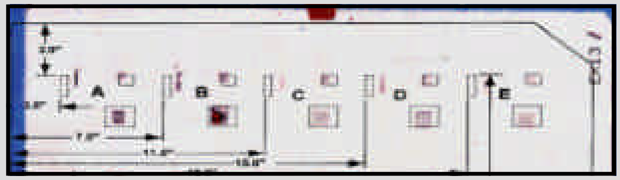
Below is a sample created to evaluate the detectability of various types of backing material or FOD that can be expected in the processing of composite. In this case the composite is MMS 5024. This sample is an 18 ply lay-up that is .133" in overall thickness. While not all of the flaws were visible the first row of flaws had very good correlation as can be seen in the detail views to the right. The table to the right defines the type of FOD tested as well as the respective thickness.



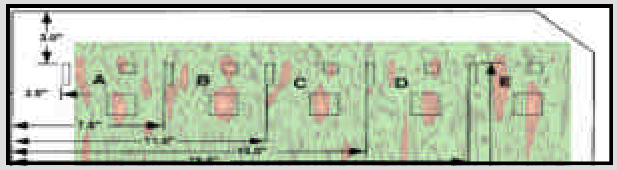
AUS Image of Sample EX13 Superimposed on FOD Drawing



Exel Image of Sample EX13 Superimposed on FOD Drawing



Detail of AUS Image FOD Area A through E



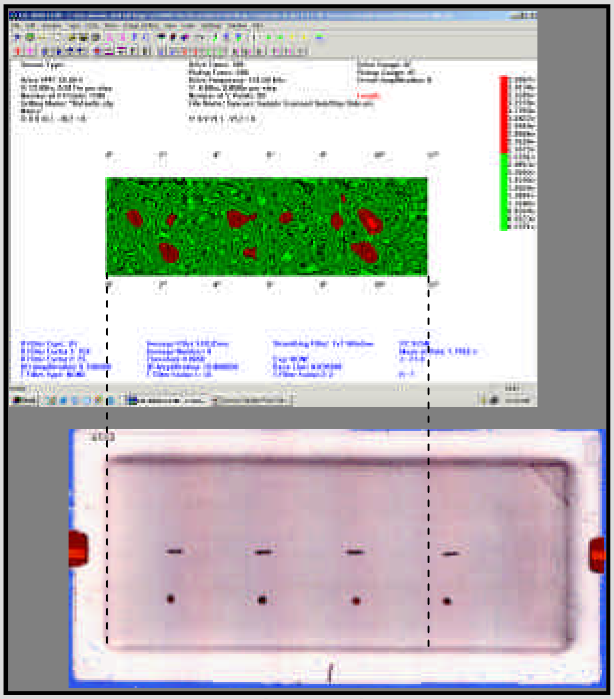
Detail of Exel Image FOD Area A through E

Flaw Group	Backing Type	Flaw Thickness
A	White Backing Paper	.008
B	Transparent Adhesive Backing	.047
C	Brown Backing Paper	.070
D	Yellow Backing Paper	.007
E	Red Backing Paper	.070

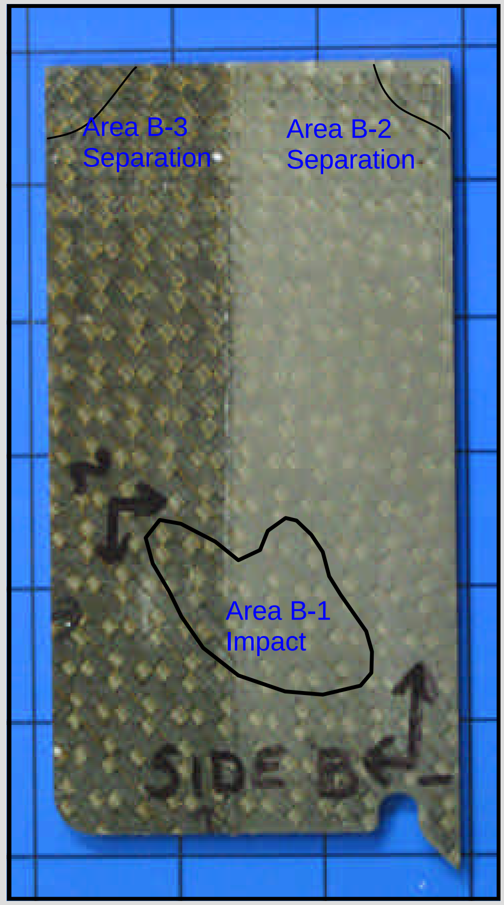
Table of FOD Type and Thickness

Sample EX15

Syncore is dramatically different from composite in terms of electrical conductivity. Even though it is covered with a composite layer, the Teflon disks are suspended in a layer of dense foam which is substantially and insulator. Because of the apparent slight difference in electrical conductivity between Syncore and Teflon it was not clear if it would be detected by the imaging system.



Exel Image and AUS Image, Sample EX15

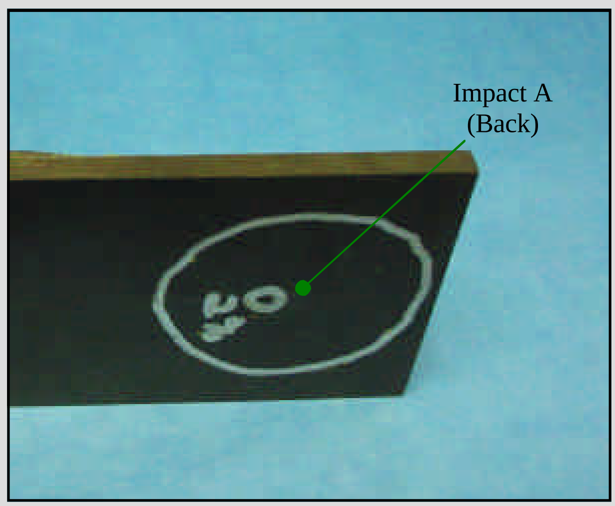


Photo, Sample 1 Side B

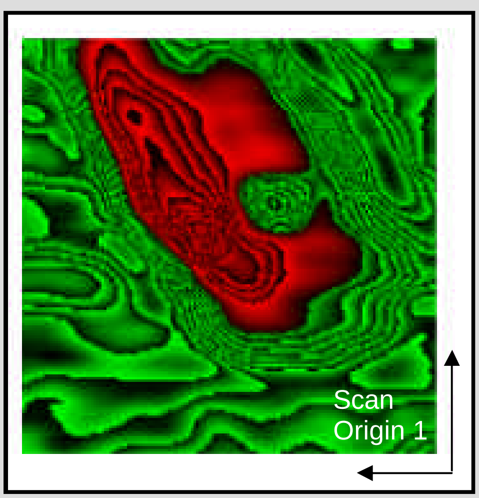
As can be seen in the image above both the Teflon rectangles and disks are visible.

Sample 1 & 2 Impact

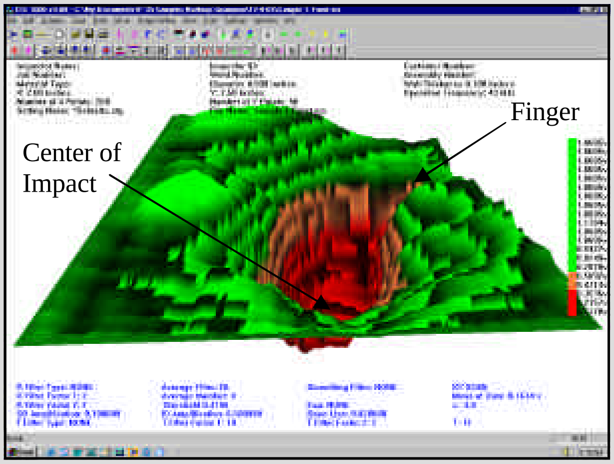
Sample 1 is a small composite section measuring about 4 $^3/_4$" x 2 $^1/_2$" being .187" thick. The bottom center portion of the panel was struck with a ball peen hammer while being supported from behind by a table. Two corners were cleaved in order to simulate fiber separation.



Photo, Sample 2 Impact A Back Side



Exel Image, Impact Area B-1

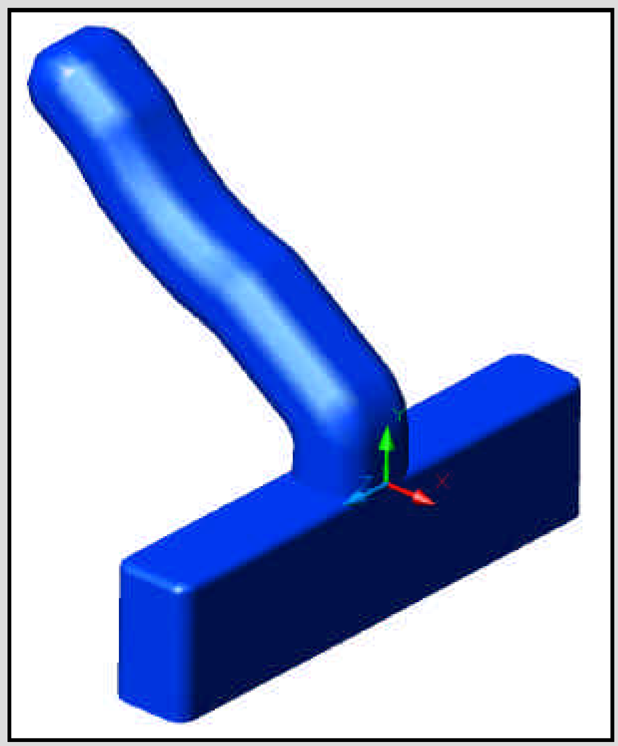


Exel Image, Sample 2 Impact A Back Side

Sample 2 is an impact produced similarly to Sample 1. The impact is very visible by the Exel Imaging System which identified a finger extending from the impact center, later confirmed with a UT scan.

Hand Held Imager

The next phase of development will be to build a mouse type hand held imaging wand. With the information and success to date it will be possible to place a floating sensor array within the wand so that with a single pass an area as wide as 12” can be scanned at high speed. The wand will have an encoder system that measures the length of the path scanned or curve induced in the path. With this wand system very large parts could be scanned very rapidly and it could be used in both a production and service environment. Because no coupling liquid is needed the system is clean and can be used to scan uncured composite.



Hande Held Imaging Wand