# 6. NON-DESTRUCTIVE EVALUATIONS

## A. Nondestructive Inspection of Adhesive Metal/Metal Bonds

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### Objective

The goal of this project is to identify and develop a nondestructive inspection (NDI) method(s) for adhesive bond evaluation to be used in an automotive manufacturing environment that would foster increased confidence and use in adhesive joining. The primary objective is to identify and validate an NDI method(s) which can; 1) measure the adhesive area 2) measure adhesive thickness and 3) detect weak metal to adhesive bonds (intimate contact but which have reduced strength). Wider use of adhesive joining could result in reduced vehicle weight, increased body stiffness, and improved crashworthiness. Adhesives are also seen as a critical enabler for the joining of dissimilar materials in order to avoid corrosion from dissimilar metals.

### Approach

There are five major attributes which contribute to the strength of an adhesive bond on a metal flange: the width of the adhesive area, the adhesive thickness, the location of the bead relative to the edges of the flange, the state of cure, and the quality of the adhesion. The general approach is to develop a suite of inspection techniques that can be used on the manufacturing floor which allow all the required adhesive characteristics to be measured nondestructively. The chosen methods must be a single-side inspection that can follow a flange, navigate large changes in geometry and have spatial resolution near 1-mm. To accomplish this, there is a two-step validation process: first on flat adhesively bonded specimens, representative of automobile flanges and secondly on production car bodies. The flat specimens vary in adhesive, adherent type and thickness, stackup (2-3 layers), cure state, and surface contaminants. These conditions bound the processing parameters for the adhesive assembly process. A through-transmission ultrasound inspection is performed to characterize the flat specimens and is considered a "gold standard" reference inspection method. Selected samples are also peel tested to measure bond strengths. Multiple automotive bodies in white (BIW) containing a number of adhesive joints were produced by the OEMs to determine whether complex geometries provide any inspection impediments and to develop body-inspection strategies. Three promising single-sided inspection technologies for bond area, location, and thickness were studied this year. They were phased array ultrasonics, laser ultrasonics, and pulsed thermography.

## Accomplishments

- Rapid progress in this first year has produced a novel ultrasonic phased array imaging system that has been validated and already applied to production vehicles to answer real engineering questions. This pulse/echo system uses a custom high-frequency linear array in a novel probe carrier designed by the project team to scan along an adhesive bead. The system includes a position encoder and portable, closed-loop water circulation system. These features allow images of adhesive bonds, registered to markers on the body, to be made on the production floor. The validation included a large test suite of weld-bonded steel and aluminum coupons and a production body subsystem with embedded defects. This system surpassed the design requirements for off-line inspections and can scan at over 5m per minute with 1-mm resolution.

- The project team is currently working on a second generation ultrasonic array system design that will be more adaptable to the complex geometries found on production vehicles. It will be able to inspect regions with stronger radii of curvature, smaller flange widths, and smaller confinements The new probe holder will allow a very high fraction of the bonded area on BIW's to be inspected.

- A new wedge-peel destructive test was developed to provide a high-resolution measurement of the bond strength along an adhesive bead. This uses a standard impact wedge in a fixture designed by the team. This method allows larger engineering joints up to 0.6 m long to be measured quantitatively. This method was combined with ultrasonic thickness maps to determine adhesive strength laws.

- The NDI assessment of pulsed thermography for this application was completed based on the performance on the test coupons. The tests included large sets of both steel and aluminum bonded coupons that were verified..

- A reproducible procedure for constructing weak (kissing) bond samples using a grease contaminant was established. Samples with reduced shear strength were made and evaluated with an ultrasonic inspection. The resulting images could be correlated to the subsequent strength measurements. .

## Future Direction

In the coming year, the second generation ultrasonic array system will be built and evaluated, especially on the BIW structures. A major emphasis of this development will include advanced signal analysis to determine reliably the bead thickness and quality of all adhesive/adherent interfaces. These developments are geared to improve inspectibility, reduce overall system cost, increase reliability and to reach a production-ready system. The second year will also begin the process of identifying methods to detect weak bonds. These are likely to include vibrothermography, angle beam ultrasonic spectroscopy, nonlinear ultrasonics, and laser shock peening. A mid year report will be written addressing the advantages and disadvantages of each technique. The third year is focused on productionizing a weak-bond detection method.

Funding for FY08/09 is a major issue. The continuing resolution within the federal government will only allow quarterly step funding. Deliverables and timing may need to be modified to accommodate the budget.

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## Introduction

Adhesive bonding is increasing every year as automotive manufacturers strive to make bodies stiffer and stronger. Recent applications see as much as 100 meters of adhesive per vehicle being used. Adhesive joining is already widely used in automotive production today for improving body stiffness and durability but is increasingly being used for impact performance. Current manufacturing processes for adhesive joints rely primarily on quality control of the adhesive preparation and application. Controls include machine vision technologies to verify the applied adhesive bead before the mating piece is joined. However, there is no method currently available to test the overall quality of the final assembled joints other than destructive testing.

Adhesive joining is seen as a major-weight saving technology. When adhesives are used in combination with spot welds or rivets, the resulting joints are much stiffer and stronger. Almost a doubling of shear strength has been produced in weld bonded joints when compared with spot welds alone. Moreover, by enabling dissimilar materials to be used in close proximity to each other, assemblies can be constructed with optimized, light-weight materials such as magnesium and aluminum.

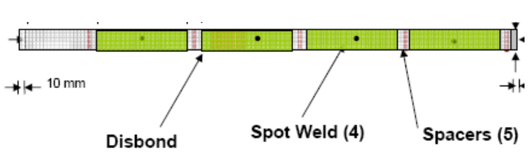
A major strategy of this project is to leverage the decades of development in the aerospace sector devoted to the nondestructive inspection (NDI) of adhesive joints. NDI is now commonly used in aerospace manufacturing of adhesive joints, especially for composite panel joining. Entire load bearing structures are inspected. Portable NDI methods are also used in routine, in-service aircraft inspections.

Within the automotive prototype development sector, increased inspection capability is needed. The major area of need is within the body shop before the adhesive is cured. This is the most likely place in the manufacturing steps where discrepant joints would be repaired. Additionally, inspections are also needed at the end of line to ensure the quality of the entire assembled, cured, and painted product. NDI inspections are also seen as a major cost savings for accelerating engineering and environmental testing, ramp-up to production, and monitoring the long term performance of the joints.

## <u>Coupon Preparation and Characterization</u>

Several sets of flat adhesively bonded specimens, representative of automobile flanges, have been generated by the automotive OEMs and adhesive suppliers to test the feasibility of NDI techniques to assess bond area and bond-line thickness. The specimens include aluminum and mild steel adherents, several production adhesives, a range of adhesive spread and thickness under compression, and both cured and uncured conditions. These were designed to include many of the variations that can occur in production. These coupon sets allow parallel nondestructive and destructive testing.

Figure 1: Joint Layout Prior to Assembly.

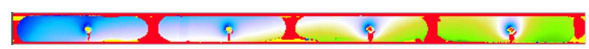



An example of the coupons prior to assembly is shown in Figure 1 showing the wire spacers used to control the adhesive thickness, intentional skips, and a section of Teflon tape to simulate a kissing bond. Most of the specimens have also been spot welded using typical production welders and standard welding parameters.

All the manufactured test specimens were nondestructively inspected using high frequency immersion ultrasonic through transmission inspection method. The transmitted signal strength allows the areas where all interfaces in the stack are in contact with each other to be imaged (Figure 2a). Using the experimentally measured speed of sound for each adhesive in its state-of-cure, a map of the adhesive thickness is simultaneously measured (Figure 2b). Using image analysis, the bead-width and average bead-thickness at each flange location can be determined. This data provides the reference for the evaluation of the other inspections.

Figure 2: Ultrasonic Characterization of a 600-mm long weld-bonded coupon.

a) Ultrasonic Transmission Intensity

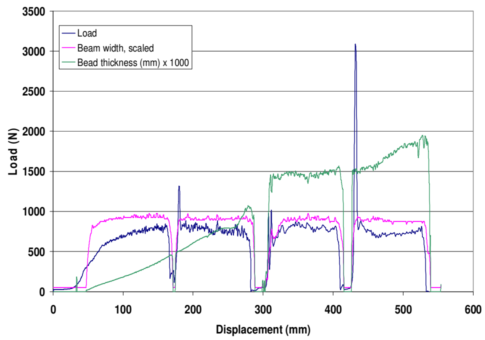


b) Ultrasonic Thickness Measurement

A new wedge-peel destructive test was also developed. This method uses an instrumented load frame to pull a standard wedge (ISO11343) through the adhesive bond. This produces a load vs. displacement curve. This method was selected after evaluating three alternative peel methods including the standard floating-roller peel, a multi-roller peel test, and a thin-slicer peel test. As seen in Fig. 3, the load-versus-displacement curves have been combined with the ultrasonic bead-width and average bead thickness measurements to determine strength laws.

The combination of nondestructive imaging with destructive tests has driven our emphasis on bead-width measurement and minimum bead-thickness detection.

Figure 3. Wedge-peel Strength Measurements Compared with Ultrasonic Bead-width and Thickness Measurements.




## Ultrasonic Pulse/echo Imaging

**Basic Description**:

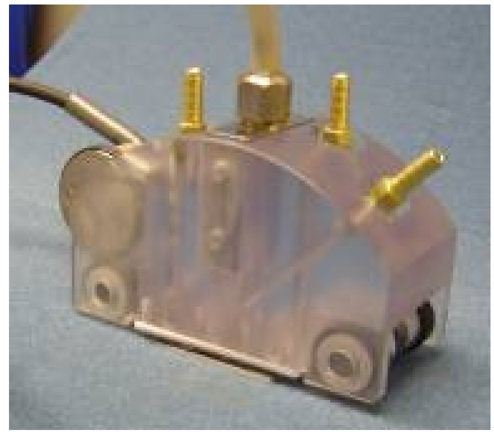
Ultrasonic pulse/echo imaging has been a standard inspection tool for adhesive inspections for many decades. A short ultrasonic pulse is launched through the outer adherent and the train of echoes from the various adhesive-adherent interfaces is detected. Typically, the ultrasonic beam is raster-scanned over the bond area and variations of the interface reflectivity are used to determine the joint condition. The primary barriers to introducing this to the plant floor have been the complex joint geometries and the difficulty of analyzing the echo train. During this year three different pulse/echo inspections have been used. Traditional raster scans in an immersion tank provided high-quality data on flat samples for signal analysis development. For a manufacturing tool, both a phased array scanner and a laser-ultrasonic scanner have been under development.

**Phased Array Ultrasonic Scanner**

Basic Description:

Phased array probes are comprised of many small piezoelectric elements embedded into a polymer base material. Each ultrasonic element is individually wired, allowing individual delays (phasing) to be applied to each element. This delay allows the ultrasonic beam to be steered and focused and for the reflected signals from each element to be coherently added. Linear arrays with 16 to 128 elements are commonly available, but square and circular arrays have been made for special applications. This technology also has the ability to introduce both longitudinal and shear waves simultaneously into a specimen.

Figure 4: High Frequency Phased Array Embedded in a Custom Probe Holder (Vesion 1) with water tubes removed.

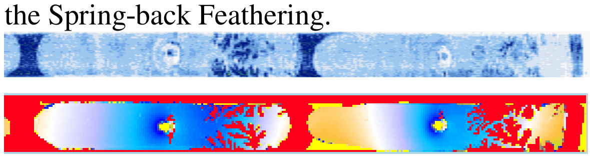


A phased array holder/scanner was designed by Sandia National Laboratories and the USCAR Design Team. The probe holder has been designed specifically to rapidly inspect long and narrow flanges that may be flat or have tight radius of curvatures. The unit uses a high-frequency linear array that spans the flange width and produces a focused ultrasonic beam that is rapidly scanned electronically at up to 10,000 points per second. This probe is manually scanned along the flange or inspection area. The probe holder incorporates a position encoder so that a two-dimensional image is obtained. Figure 4 shows the version 1 prototype that generated the images below. .

Figure 5: The Phased Array Probe Holder on a Test Coupon Showing the Controller and Closed-loop Circulation System.

The holder uses a closed-loop water circulation system to maintain a water column between the array and the flange surface. The angled inlet port (Figure 4) supplies the water below the array while the two vertical ports vacuum excess water from the part. The closed-loop circulation system was designed and built to include a filtered water supply, return pump and coupling gages in a self contained shipping case (Figure 5).

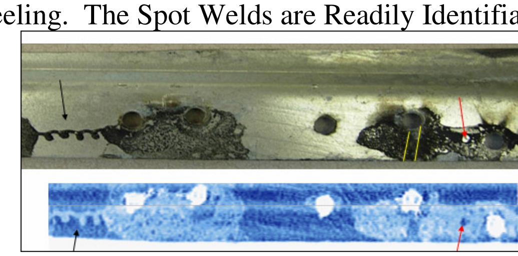
Figure 6: Phased Array Image (top) of a 300 mm x 25 mm Section of a Coupon is Compared to the UT-TT Reference Thickness Map (bottom). Note the Spring-back Feathering.



The system has been validated in a C-scan mode using simple time gating in order to inspect the first adherent/adhesive interface. This provide a rapid, high resolution scan of the adhesive bead position and area. The system can scan at up to 10 m/min with 1-mm resolution. This is more than enough to inspect 100-m of adhesive in an off-line, 2-hr inspection window.

The system performance was validated on flat test coupons and large BIW sections. Images demonstrating the high-resolution performance are shown in Figures 6 and 7. The phased array resolution is comparable to that obtainable in an immersion tank, i.e. about 1-mm.

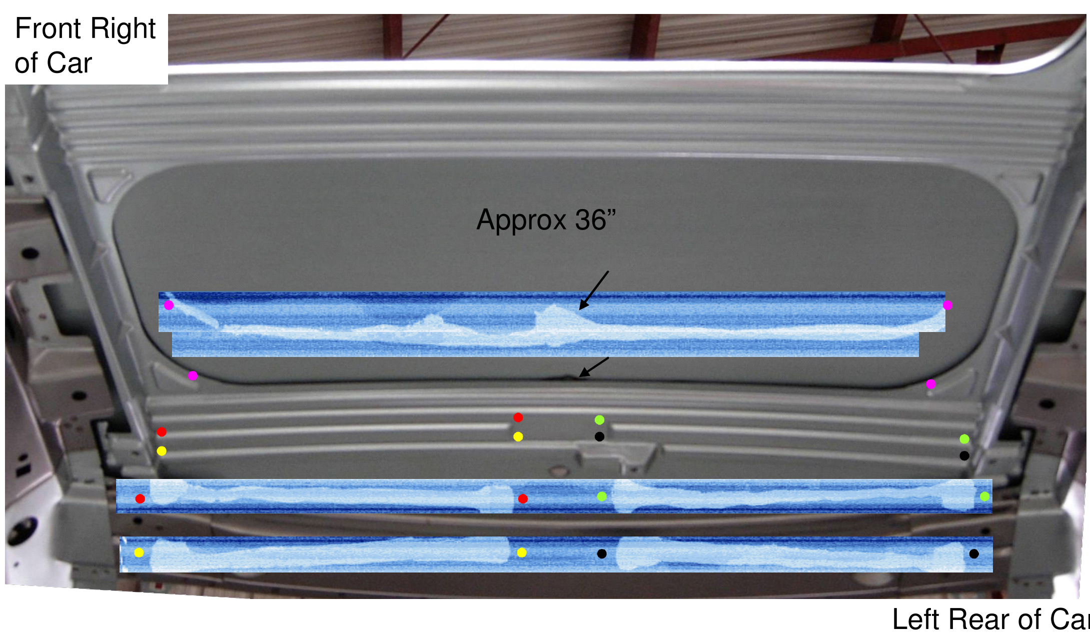
Figure 7. Section From a Vehicle (30 mm x 100 mm) with Embedded Skips. Top Image is After Peeling; Lower Phased Array Image is Before Peeling. The Spot Welds are Readily Identifiable.



<u>Deployment of the Phase Array Probe on BIW Test Samples:</u>

After tests of embedded discrepancies such as shown in Figure 7, the scanner was deployed to BIW vehicles as shown in Figure 8. This shows multiple adhesive maps taken of the adhesives beads between the roof-bows and the roof. This is shown for illustrative purposes since features can be readily identified. The scanner has now been demonstrated on a variety of different bodies and

Figure 8: Maps of the adhesive area on a roof bow using the phased array probe holder. The colored PA images were obtained on the roof and are superimposed on a picture of the roof bow taken from the vehicle interior.



joint designs.

While already of engineering usefulness, the amplitude C-scans are incomplete. They only register the location of adhesive on the outer adherent. Only with signal analysis can the other interfaces and the thickness be imaged.

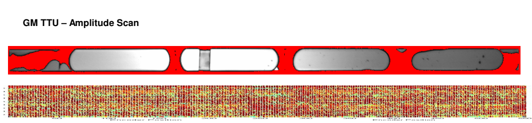
The C-scan images are easily interpreted and oriented relative to features on the surface. Furthermore, they can be obtained with simple controllers without signal processing

Similar images on coupons have been obtained with laser ultrasonics. While laser ultrasonics do not require water-couplant and have much better echo separation, the scan rates are currently much lower.

Preliminary Pulse/echo Signal Analysis

The short burst of high-frequency sound waves travel through the material with some loss of energy and is reflected at any interface. The reflected signal is captured and then analyzed to define the presence and location of reflected surfaces. Variations in reflectivity or scattering can be used as the basis of flaw detection. Transit times of the echoes can be used to assess bond-line thickness. Sandia National Laboratories contracted with Lawrence Livermore National Laboratories (LLNL) to determine if there was any unique signal processing and analysis that could determine adhesive thickness. The LLNL algorithm processes an ultrasonic echo that has many cycles and yields an output that is narrower with respect to time. The ideal output is to reduce multiple complex echoes to a series of delta functions. This would allow small echoes from secondary adhesive interfaces to be resolved. This LLNL algorithm has been used successfully on single interfaces, but not on layered structures with multiple echoes. Figure 9 displays the "golden standard" data to the LLNL algorithm and shows that adhesive thickness is not resolved. There is no uniformity in the data.

Figure 9: Comparison of UT-TT Data to the LLNL Algorithm.




Phase Array Signal Analysis and Data Processing:

A second more successful algorithm repeatedly subtracts a model waveform from a data waveform in a least-square fashion to remove the primary echoes from the first interface. The subtraction attempts to extract the relatively weak echoes associated with the secondary interfaces. Particular care was given to develop an algorithm that uses as few computations as possible and being, applied thousands of times in only a few seconds.

The algorithm assumes the primary echoes have a single reflectivity, a fixed round-trip delay time, and minimal frequency dispersion. With these assumptions made, two signals are considered. The first is called the "model" signal, which is the waveform acquired when it is known that no adhesive is present (Figure 10). The second is called the "data" signal, which is associated adhesive is present (Figure 11). These example signals are from an immersion tank scan. The overlapping signals represent the peak values of multiple echoes from model and data waveforms. When adhesive is present, peak values are reduced due to the lower reflectivity when adhesive is present. Secondary echoes are typically 10-25% of the peak echoes depending on the adherent.

Figure 10: Representative Pulse/echo Signals on a Test Specimen – No Adhesive Present.

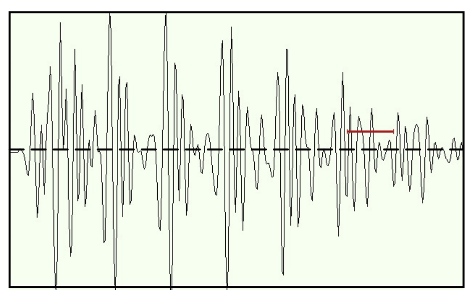
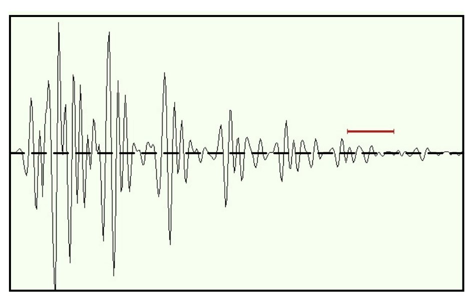


Figure 11: Representative Pulse/echo Signals on a Test Specimen – Adhesive Present.

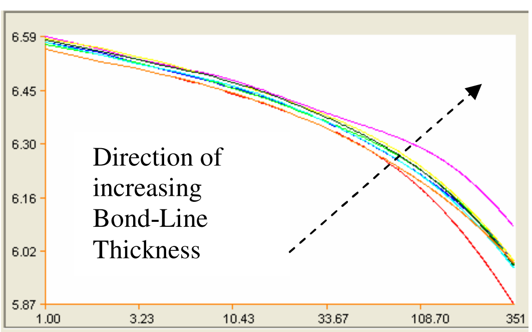


Finally, the third year of the project will analyze all the inspection data to determine if any data fusion (combining inspection data from two types of inspections) will be possible. Figure 11 displays two types of inspection data uncured adhesive applied over a thin metal.

## Completed Assessment of Pulsed Thermography

This technology uses thermal gradients to analyze the physical characteristics of a structure for internal non-uniformity. Flash lamps heat the surface of the structure and the heat diffusion is measured by imaging the surface temperature with a fast infrared camera. Areas that appear hotter or cooler may indicate the presence of a flaw beneath the surface that is affects the heat diffusion into deeper layers. By analyzing the time-history of the infrared signal, subtle variations can be enhanced in the image. By plotting the log of temperature versus log of time, quantitative adhesive bond-line thickness measurements were obtained (Figure 12).

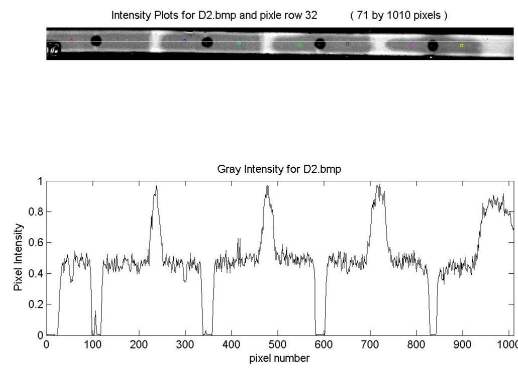
Figure 12: Log of Temperature vs. Log of Time Depicts Thickness Variations on an Uncured Steel Stackup.




While Sandia National Laboratories was conducting pulsed thermography inspections on BIW vehicles, similar inspections on the flat adhesively bonded specimens were being conducted concurrently at Thermal Wave Imaging Incorporated. Unfortunately, the high optical reflectivity and low infrared emissivity of aluminum and steel typically prohibit a successful pulsed thermography inspection without adding a black paint to the inspection surface.

New Mexico State University (NMSU) was sent IR data files to analyze. C-scans optimized for adhesive/no adhesive contrast were processed to extract relative intensity of the pixels along a data line as seen in Figure 13. The spot welds, adhesive and skips can be distinguished in the data. Unfortunately, adhesive thickness could not be easily extracted without reanalyzing the entire time-history datasets.

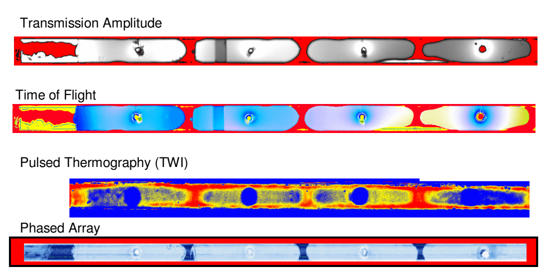
Figure 13: Pixel intensity versus Pixel Number along the mid-line of an uncured steel stackup.




## Inspection of Uncured adhesives

To date there has been no difficulty imaging uncured coupons. While the uncured adhesives have a significantly lower speed of sound and are more attenuative, this has not presented a problem so far. In Figure 14, results from the reference UT-TT measurements are shown in comparison with the pulsed thermography and phased array pulse/echo measurements. While the thermography results have poorer contrast, the skips, welds, and bead-spread are discernable.

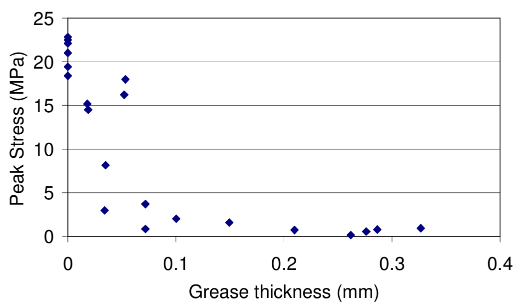
Figure 14: Comparisons of three inspection methods on an uncured adhesive coupon.




## Weak (Kissing) Bond Samples

A procedure to make weak bond samples reproducibly was developed. These used a bearing-grease as a model surface contaminant. Figure 15 shows the range of lap-shear strengths obtainable for different thicknesses of grease. These adhesives are designed to adhere and cure on greasy surfaces. Significant contamination is needed to affect the strength. These samples were also ultrasonically imaged. The ultrasonic data could be processed to predict the strength with good confidence.

Figure 14. Bond Shear-strength Dependence on Thickness of a Grease-contaminant.




## Conclusions

Good progress was made on the project objectives during this first full year. An effective inspection tool for off-line inspections was designed, verified, and tested on production vehicles. While this ultrasonic array system is currently only able to inspect the wet-out on the outer skin, the system performance appears to be adequate to allow the adhesive thickness and second interface inspection of 2-layer stickups as signal processing improves. A second-generation version of this ultrasonic array scanner is in process and should be production capable. A new, high-resolution wedge-peel test and procedures to make reproducible coupons are essential ingredients for the weak-bond detection tasks of the project.


## Acknowledgements

This project team included Ciji Nelson, Kirk Rackow, Steve Younghouse, Kim Lazarz, Dan Ondrus, Dave Biernet, Jessica Schroeder, John Fickes, Ray Bis, Mike Golden, Dave White, Rajat Agarwal, Bill Brown, Kent Wen and Marvin Klein. We also would like to thank IOS and Olympus NDT for their input and Metal Steel and Novellis for supplying metal blanks.


## Presentation/Publications/Patents


1. NDE601-FY2006 Annual Progress Report for DOE ALM, J. DiMambro and D. P. Roach, Sandia National Laboratories, and C. J. Dasch General Motors R&D, December 15, 2006.

2. "Preliminary Report of Sample Preparation and Ultrasonic Through-Transmission Images of Flat, Mild Steel Coupons for USCAR /USAMP Project NDE 601 – NDI of Adhesive Metal Bonds", *C. J. Dasch, A. Terry, W. Brown, R. Bis, D. White, and D. Sigler* , January 31, 2007.

3. "Preliminary Report of Sample Preparation and Ultrasonic Through-Transmission Images of Flat, Aluminum Coupons for USCAR /USAMP Project NDE 601 – NDI of Adhesive Metal Bonds", *C. J. Dasch, A. Terry, W. Brown, R. Bis, D. White, and D. Sigler*, February 14, 2007.

4. Disclosure of Technical Advance, "*Probe Deployment Device for Optimal Ultrasonic Wave Transmission and Area Scan Inspections*", J. DiMambro, D. Roach, K. Rackow, C. Nelson, Sandia National Laboratories and C. Dasch General Motor Corporation, February 20, 2007.

5. "Automotive Lightweight Materials: the Roles for NDE in Bringing New Materials into Production", C. J. Dasch, Plenary Lecture, Conference on Quantitative Nondestructive Evaluations, Golden, CO, July 2007.

6. "Nondestructive Inspection of Adhesive Bonds in Automotive Metal Joints (NDE 601)", *C. J. Dasch*, USAMP Off-site Review, Oct. 25, 2007.

7. "Correlating Adhesive Bond Strength with Non-Destructive Test Methods", *K. Lazarz, C. Dasch, R. Agarwa*l, to be presented at the Annual Meeting of the Adhesion Society, Austin TX, Feb. 2008.


**List of Acronyms Used**

(NDI) Nondestructive Inspection
(OEM) Original Equipment Manufacturer
(BIW) Body in White
(UT-TT) Ultrasonnic testing using through-transmission

## Key Words

Nondestructive testing, adhesives, weld-bonding, manufacturing, lightweight materials.

**Brief Description of Report**

Progress in developing nondestructive inspection tools for automotive adhesive bonds on metals is described. A novel ultrasonic phased array scanner for manual inspection has been developed specifically for the complex geometries of automotive structures. This has been successfully applied to many sections of a variety of body-in-white structures. Both cured and uncured adhesives can be imaged.