LA-UR:04-7889

Optimizing Ultrasonic Imaging for Adhesively Bonded Plates

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Los Alamos Dynamic Summer School
2004

Abstract

Bonded materials are used in many critical applications, making it important to determine the state of the adhesive during service or aging. It is also of importance, in many cases, to determine if the adhesive has uniformly and completely covered the area to be joined. Through dual transducer scanning, focused and unfocused transducers, and immersion scanning, the uniformity and adherence of a visco-elastic material can be evaluated. In this report, ultrasonic scanning parameters will be optimized experimentally with guidance from simulation tools including Wave 2000 pro and Imagine 3D. We explored optimizing the contrast ratio by varying the interrogation frequency and also by adjusting the distance between the transducer and bond line. An improvement in contrast should also increase the ability to detect differences in compositions and viscosity of the bonded layer. By maximizing the contrast the quality of the visco-elastic bond can be determined, and imperfections detected before adhesive failure.

Nomenclature

R	Reflection Coefficient
T	Transmission Coefficient
Z_1	Acoustic impedance for incidence material (aluminum)
Z_2	Acoustic impedance for second material (air or viscoelastic gel)
ρ	Density
C	Velocity of sound in the medium
CR	Contrast ratio between the air and gel
V_a	Voltage (amplitude) of echo reflected from the aluminum/air interface
V_g	Voltage (amplitude) of echo reflected from the aluminum/gel interface

1. Introduction

Over the past decade, adhesive bonding has found increasing use in a variety of industrial applications. The automotive industry relies heavily on such technology, due to the possibility of bonding dissimilar metals along with benefits of joint durability and flexibility. As these joining techniques have become more widespread, the need for non-destructive evaluation of different joints and quality control has become increasingly important [1]. This paper explores ways to optimize the image of an adhesive bond using ultrasonic methods.

There are three types of defects of interest to those studying adhesive bonds. These defects include the absence of adhesive (also known as porosity or disbonds), poor adhesion between the adherend and the adhesive layer (analyzed at the point called the *interlayer*), and poor cohesive strength of the adhesive itself (failure within the adhesive rather than at the interlayer) [2].

Several different types of ultrasonic transducer configurations have historically been applied to different inspection levels for adhesive bonds. In general, normal incidence has been used to find areas lacking adhesive, while oblique transducer incidence has lent itself to analyzing adhesive strength between bonded materials. A dual beam scanning technique that embodies both these transducer elements at once has recently been developed, and is called Angle Beam Ultrasonic Spectroscopy (ABUS) [3]. It has been argued that without the transverse waves generated in the interlayer by the oblique angled transducer, bond adhesion quality cannot be determined [4]. However, normal transducer incidence has been used for bond adhesion quality inspection with some success by analyzing changes in reflection coefficient at the interlayer [5]. Reflection coefficient changes have also been used to find voids in the adhesive layer, both with normal and oblique transducer incidence [6]. The scans performed for this experiment will use normal transducer incidence to find areas with little or no adhesive layer and parameters will be changed to maximize the contrast of the scanning system.

Most ultrasonic inspection research to date has been performed on bonds where the adhesive is either an epoxy or urethane. Both of these materials are firm, providing good ultrasonic wave transmission and relative ease of detection. The tests to be conducted in this study differ from past endeavors in that they are performed on a two-part viscoelastic gel compound (Nusil 8100, 8150) [2]. This viscoelastic gel is finding use among the aerospace industry and others for vibration damping and electronic component potting. The advantages of this material over a stiffer epoxy are that it self heals and rebonds in addition to being hydrophobic. Difficulties arise in scanning of such a material because its low impedance causes the contrast ratio to be low. Other factors that impede the detection of the material are low signal levels reverberant oscillations and general electromagnetic noise [1]. By varying transducer type, size, signal wave frequency and excitation type, and transducer focal zone position, the signal-to-noise ratios can be optimized to provide maximum contrast between adhesive and voids as well as other damage and in-service adhesive degradation.

2. Background

Three types of scans are used for analyzing adhesively bonded joints. The first is the A-scan, a scan conducted over a single point that displays wave amplitude versus time. By looking at the time of arrival between subsequent wavefronts and the sound wave speed in each medium the depth of the various layers can be determined. B-scans develop vertical cross-sections of the medium by measuring time-of-flights along a scan line to find flaw depths. Finally, C-scans are images of the medium made by scanning in two directions and plotting wave amplitude versus position [6]. These C-scans produce very useful ultrasonic images of the adhesive interface, and are valuable in detecting adhesive absence. The images formed in the tests reported here are C-scans of the adhesive interface as derived from the peak to peak variation in the first received echo from the interface between the aluminum-gel interface.

Transducers were used in pulse-echo mode, in which one transducer both transmits a pulse and measures the reflected signal. When the transmitted pulse meets the interface between the aluminum and gel or air, part of the signal is transmitted and part of it is reflected. The amount that is reflected or transmitted depends on the material properties. If the materials are similar, then most of the signal gets transmitted. However, if they are different, most of the signal is reflected. These relations are governed by the following equations [7]:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$ Reflection Coefficient (Eq. 1)

$$T = \frac{2Z_2}{Z_2 + Z_1}$$ Transmission Coefficient (Eq. 2)

$$Z = \rho C$$ Acoustic Impedance (Eq. 3)

where ρ is density and *C* is the velocity of the wave in the material. Z_1 and Z_2 are the acoustic impedances of the incident and subsequent material, respectively. The aluminum/gel and aluminum/air interfaces reflect most of the signal since aluminum ($Z = 1.70 \times 10^6$ g/cm^{2}s) has a different acoustic impedance than both air ($Z = 42.6$ g/cm^{2}s) and the viscoelastic gel ($Z = 9.80\times10^4$ g/cm^{2}s).

3. Experimental Setup

To study the adhesive bond between two plates, drops of Nusil 8100 and 8150 high purity dielectric silicone gels were placed between clear Lucite bases 14.6 cm x 14.6 cm (5.75 in) by 2.54cm (1in) thick and aluminum top plates 15.2 cm x 15.2cm (6 in) by 0.647cm thick (~ 0.25 in) and allowed to cure as shown in Figure 1. The resulting sets of circular adhesive layers were 0.020 in. (0.508 mm) thick and approximately 2 in. (50.8mm) in diameter. The gaps between the Lucite and aluminum layers around the plate edges were then sealed with clear room temperature vulcanized (RTV) silicone to form a watertight barrier leaving the adhesive surrounded by air. Using clear Lucite bases enabled us to determine the integrity of the watertight boundaries and verify accurate scan images as well as furnishing a rigid base.

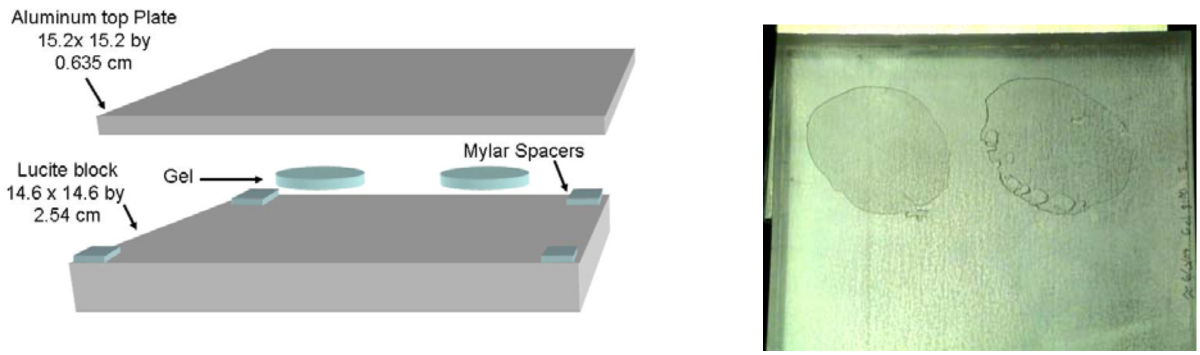

Figure 1. Left; exploded view of plate assembly and right; showing drops of Nusil 8100 silicone bonded to the aluminum and Lucite as seen through the Lucite.

Two-dimensional ultrasonic immersion scans (as shown in Figure 2) were used to examine the adhesive layer within the plates. After immersing the plates in a de-ionized water bath with the aluminum side up, the top surfaces were scanned using piezoelectric transducers that were interchanged as needed for the study and set to various heights above the plate. The first transducer was a 10 MHz Panametrics V312 focused transducer with a 0.25 in. (6.4 mm) diameter and a 1.50 in. (38.1 mm) focal length. The second transducer was a 10 MHz Panametrics V312 unfocused transducer with a diameter of 0.25 in. (6.4 mm). The third transducer was a 5 MHz NDT Systems AE04711 focused transducer with a 0.25 in. (6.4 mm) diameter and a 1.25 in (32.8 mm) focal length. Precision motion of the transducers was obtained through a three axis scanning platform powered by stepper motors and low noise stepper amplifiers (Precision Motion Controls LNII) driven by a Galil 1030 motion indexer controlled by Winspect software.

Two pulser-receivers generated and collected the acoustic signals. To send a one shot pulse to the transducer, a Panametrics Model 5800 computer controlled pulser-receiver was used. The pulser-receiver was connected to an eight-bit Sonics 81G A/D converter with a maximum real-time sampling rate of 1GHz. To send a tone-burst pulse, a MATEC Instruments Explorer II NDT Workstation with an internal eight-bit A/D converter and a sampling rate of 100 MHz that can be expanded up to 3.2 GHz using an equivalent time sampling function on periodic signals.

Data collection and initial analysis was completed using Winspect ultrasonic software, program version 6.0. Further data reduction and statistical image analysis was conduced in MATLAB version 7.0.

The Nusil gel is a two component gel and was mixed 50% each part by weight. After curing the 8100 gel is a soft material with a “tacky” surface while the 8150 is similar to a very viscous fluid with a tendency to adhere to any solid material it contacts. The measured density and longitudinal velocity of the cured 8100 and 8150 gel was 0.970 g/cm^3 and 1.017 x10^5 cm/s and 1.011± 007 x10^5 cm/s. The measured longitudinal velocity in the rolled aluminum 6061 plate was 6.30±01 x 10^5 cm/s with a density of 2.70±.01 g/cm^3

4. Scanning Procedure and Results

To determine the optimum setup for maximizing the contrast ratio between the silicone gels and the air gap, a series of C-scans were run with various scan parameters. After each scan, the contrast ratio was calculated by performing a statistical analysis on portions of the C-scan that represented both the air gap and the gel adhesive layer as below

$$CR = \frac{V_a - V_g}{V_a} \qquad CR_n = 1 - \left[\frac{\rho_{al} C_{al} - \rho_g C_g}{\rho_g C_g + \rho_{al} C_{al}} \right]^n \qquad \text{Contrast Ratio} \qquad \text{(Eq. 4)}$$

where V_a is the mean voltage returned from the area over the air gap and V_g is the mean voltage returned from the area over the gel using the first returned echo. This experimental value could be compared to the expected plane wave value where ⑧$_{g,}$ C_g , ⑧$_{al,}$ C_{al} are the density and longitudinal sound velocity of the gel and aluminum. The CR ratio (for the first returned echo, n=1) between the gel and air is 0.109 (0.207 for n=2). To improve the contrast ratio it appears if one chooses a later echo then the CR can be made larger, however intrinsic material noise and the digitization noise as well as the dynamic range of the digitizer limits what can be achieved for any given material.

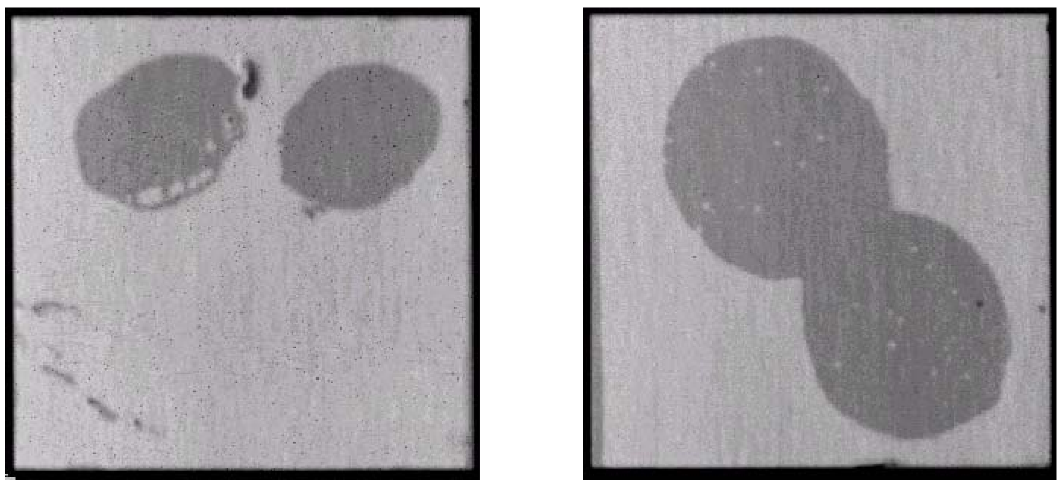

Figure 2. Ultrasonic C scan image of the 8100 gel (left) through the top aluminum plate as recorded by the first returned echo at 10 MHz, a series of small voids in the gel are resolved in this image. The 8150 gel was more fluid and the two drops ran together as shown (right).

The images shown in Figure 2 are proportional to the reflected peak to peak amplitude of the bond line. Lighter areas are indicative of higher amplitudes and as shown in Figure 2 the difference between the bonded levels and air is ~11%. Some mottling is seen in the two areas of the image, this is due to noise in the system and limitations on the digitization rate and material homogeneity. To adequately detect and separate the gel area from the air area one has to know the distribution of amplitudes of the two areas. Detection of the gel or air areas is therefore dependent on increasing the CR and reducing the variance in the distribution of the signals. Reduction in the variance of the received signals can be achieved by using low jitter electronics, high sampling rate digitizers, signal averaging and/or software interpolation of the data. Once these measures are implemented then the remaining signal fluctuations will be due to material grain noise, inhomogeneities in the material and bonding uniformity.

The initial set of scans were conducted using the Panametrics spike pulser and the 10 MHz focused transducer, in an immersion tank, while the height above the bonded plate was varied by 0.25 in. (6.35 mm) from 0.25-1.5 in. (6.35-38.1 mm). Similar scans were then made using the 5 MHz focused transducer and the 10 MHz flat transducer. Figure 3 shows the variation of the contrast ratio with the height above the plate for the first returned echo.

As expected, the focused transducers gave a sharper image and surprisingly gave much higher CR values than the flat transducer. In addition, as shown in Figure 3 the CR for the 5 MHz transducer was significantly higher than that of the 10MHz transducer despite the fact that the calculated CR's are independent of frequency. The CR for the 10 MHz transducer shows a dramatic and unexpected drop at large distances beyond the focal length. The flat transducer also shows a very pronounced decrease in CR at very close distances that was not expected. These effects illustrate the need to test various transducers and configurations for a given application.

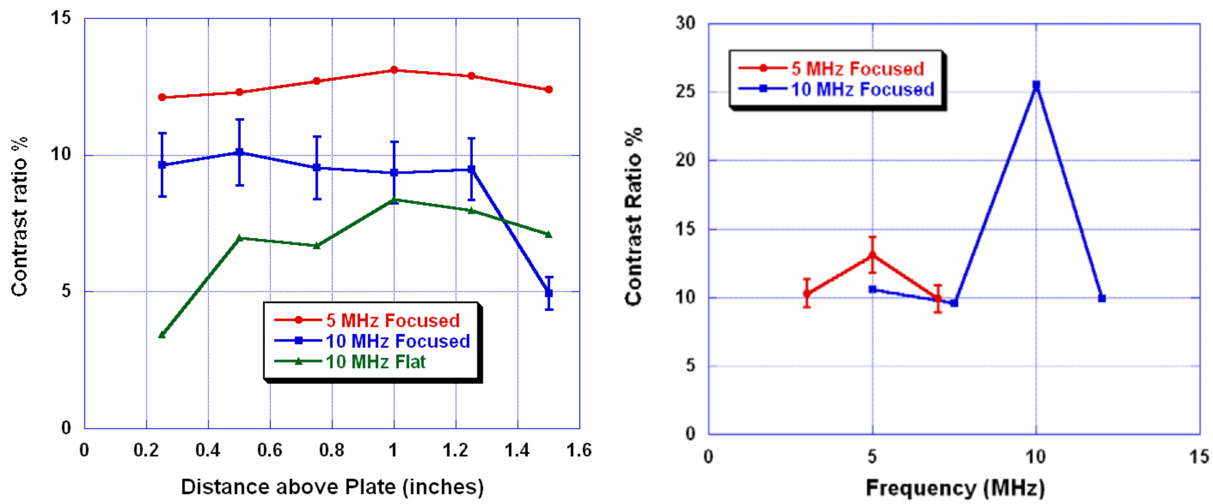

Figure 3. Contrast ratio as measured by three different transducers at various heights above the test plate (left).The contrast ratio as measured by using the Matec sine wave pulser as a function of frequency for the two focused transducers (right).

Next the frequency was varied using the MATEC tone-burst pulser. The frequency of the 10 MHz focused transducer was varied from 5-12 MHz and the 5 MHz focused transducer was varied from 3-7 MHz. Peaks in each data set are seen at the resonant frequency of the transducer. The small peak at 5MHz is close to the expected maximum signal level (10.9%) but the 10 MHz shows a remarkable and unexpected increase in the contrast ratio.

Attempts were made to model the CR with two software packages, Wave 2000pro and Imagine 3D. A simulated received waveform from a gel layer and an air layer at a frequency of 4 MHz are shown in Figure 4 as calculated by Wave 2000 pro. In order to generate this plot, the transducer was modeled with a Gaussian aperture and 20 points per waveform were selected. The material damping was disabled since, at these frequencies, the model ran very slowly if the damping was included in the model. The first peak (3 microseconds) is the reflection off of the aluminum top surface and subsequent peaks (5 microseconds and 7.5 microseconds) are due to reflections off of the aluminum and air or gel interface. One can see that the initial reflection is not symmetrical (the input drive was symmetrical) and that neither are the reflections. A peak to peak comparison of the CR for the first and second echoes yields values of 10.6% and 19.6% respectively.

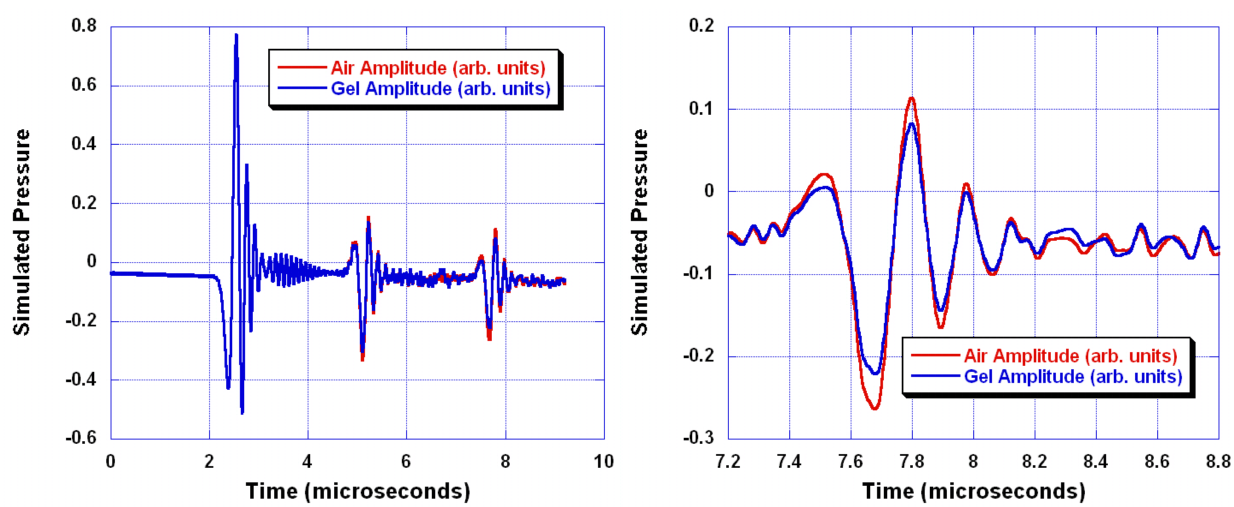

Figure 4. Wave2000pro simulation (4MHz) of air vs. gel reflection amplitudes, an expanded view of the 2^{nd} echo clearly showing the difference between the waves reflected from the air or gel interface (right).

This is in good agreement with the plane wave values of 10.9% and 20.7% as calculated from Equation 4. Imagine 3D was very useful in modeling the focusing from the transducers as modified by the aluminum top layer.

As Imagine 3D is a ray tracing program, its primary use is to follow rays to determine the depth of focus in materials and to determine where the beam is propagated in complicated structures.

5. Conclusions

We have shown that the contrast ratio can be modeled adequately with Wave 2000 pro software and that the contrast ratio may not be correctly measured if it is measured on the asymmetric peak of a waveform as is often done in practice. In addition, the contrast ratio as experimentally measured as a function of height using three different transducers from the sample was not constant. This study has shown that to optimize the CR ratio it is necessary to carefully select the transducer, frequency and configuration for a given application.

6. Acknowledgments

Funding for the Los Alamos Dynamics Summer School was provided by the Engineering Science and Applications Division at the Los Alamos National Laboratory and the Department of Energy's Critical Skills Programs Office. The following companies generously provided various software packages that were necessary to complete the student projects: Vibrant Technologies (experimental modal analysis software), The Mathworks, Inc. (numerical analysis software), Hibbitt, Karlsson and Sorensen, Inc. (ABAQUS finite element software), Winspect, and Wave2000 Pro.

7. References

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