ULTRASONIC MEASUREMENT OF INTERFACIAL PROPERTIES IN COMPLETED ADHESIVE BONDS

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ABSTRACT

The problem of detecting weak adhesion in completed adhesive bonds can be considered a problem in measuring the effective acoustic impedance of a thin layer at the adherend to adhesive interface. By calculating the ultrasonic reflection coefficient of the entire sandwich structure as a function of frequency including an interfacial layer, it can be shown that quite obvious changes in the reflection spectrum can be produced by minor changes in the properties of the thin layer. The inverse problem of deducing the properties of the thin layer from experimental measurements is more difficult because of the sensitivity of the results to small experimental errors in the data. However, special procedures based on estimation theory are being developed for use on actual ultrasonic data obtained from specimens with both optimum and degraded adhesive bonds. Once the elastic properties of the interfacial layer have been deduced from ultrasonic or other nondestructive measurements, they can be used to infer the physical state of the material at the interface. Models that relate the physical state of polymers to their failure probability such as that being developed by D. H. Kaelble can then be used to predict the strength and reliability of the adhesive bond.

APPRAOCH

Posters 1 and 2 describe the general strategy and the specific approach being used here to obtain a nondestructive method for predicting the strength of a completed adhesive bond. Although the optimum method of developing a quantitative NDE tool depends upon a knowledge of the mechanism of failure and utilization of an NDE tool appropriate to that mechanism, the present approach combines two new developments in an attempt to produce a semi-empirical technique for making a prediction of bond strength. These two developments are the use of an on-line computer to perform a detailed analysis of the ultrasonic waveforms and a newly developed molecular theory of polymer reliability to relate the computer output to a general mathematical model that describes mechanical failure in polymers. The experimental data is in the form of broad band (short time duration) ultrasonic pulses reflected from the various planar interfaces within the adhesive bond as shown in the Theoretical Time Domain Response graph. When this entire train of echoes is Fourier transformed, the Frequency Domain graph is obtained which shows many sharp minima in the reflectivity at frequencies corresponding to standing wave modes of vibration in each of the individual layers of the bond.

Mathematical Basis

Since a rigorous mathematical description of the reflection of ultrasonic waves by a layered medium exists, it is easy to model a weak adhesive-to-metal joint by a thin layer of unknown material at the interface. In the parametric approach shown on Poster 3, the acoustic impedance of the layer was varied and the changes in the frequency domain presentation were noted to determine empirically what features in the spectrum were most likely to be good candidates for correlating with bond strength. In the inversion approach, shown on Poster 4, the techniques of estimation theory were used to deduce the properties of the adhesive layer as well as the unknown interfacial layer from the time domain echo train reflected by the adhesive layer alone. It has been found very valuable to use two transducers in order to provide the inversion process with two waveforms taken from each side of the bond at the same location. The results of an inversion of some theoretical wave form data in which the interface layer had an average impedance equal to one quarter of the adhesive layer is shown in the table.

Comparison with Experiment

In order to determine how well the ultrasonic measurements can predict adhesive bond strength, it was necessary to construct a series of specimens with weak adhesion between one aluminum plate and the adhesive. Poster 5 shows Probability of Failure type graphs for the two modes of failure available to adhesive bonds (peel failure and shear failure) for five different surface preparations. Those specimens which showed the largest variation in bond line thickness and the greatest strength difference were the compression shear specimens prepared with an FPL etch and with no surface preparation. Poster 6 (upper right) shows how measurements of the resonances at and near the bond line resonance were used to define the bond line thickness and how this thickness was used to define a predicted location of the Dumbbell resonance. The deviation between the predicted resonance, F_M, and the measured resonance, F_M, provides a parameter that should correlate with the condition of the interfacial layer and hence the strength of the bond. In the lower left hand part of Poster 6, a cumulative distribution graph displaying the percentage of specimens which exhibited a value for the (F_M - F_D) parameter that was less than the value plotted on the abscissa is shown for the two types of surface preparations. Obviously, the (F_M - F_D) parameter (after correction for the bond line thickness) appears to correlate with bond strength but the distribution in values of strength and (F_M - F_D)
parameters for the specimens tested overlap one another.

CONCLUSIONS

1. Parametric studies of the effect of a thin interface layer at the metal to adhesive joint show that certain resonant frequencies and relative depths of minima in the reflectivity can be used to infer the interface properties.
2. The inverse problem of deducing the impedance of an interfacial layer from the time domain reflectivity of the total adhesive layer can be used for characterizing the interface in weak bonds.
3. Special procedures must be employed to correct the ultrasonic measurements for the local thickness of the bond line.
4. An experimental correlation between measurements of bond strength and the resonant frequency of the Dumbbell mode was observed on a set of specimens for which a bond line thickness correction could be made.

ACKNOWLEDGMENT

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REFERENCES


Poster 1: Block diagram comparing the approach used for general problems in quantitative NDE with the specific approach used here on adhesive bonds where new computer methods and molecular theories of polymer reliability have recently become available.
Poster 2 The general experimental arrangement and origin of the ultrasonic echos is shown on the left while the diagrams on the right show the time and frequency domain representations of these signals.
HOW DOES A THIN LAYER AT THE METAL-TO-ADHESIVE INTERFACE MODIFY THE FREQUENCY DEPENDENCE OF THE ULTRASONIC REFLECTIVITY?

EFFECT OF CHANGES IN METAL-ADHESIVE INTERFACE ON FREQUENCY DEPENDENCE OF ULTRASONIC REFLECTIVITY.

THE PRESENCE OF AN INTERFACIAL LAYER WHOSE IMPEDANCE IS EQUIVALENT TO A LAYER OF THICKNESS 10% OF THE ADHESIVE THICKNESS WITH AN IMPEDANCE 60% LOWER THAN THE ADHESIVE IMPEDANCE MAKES A CLEAR QUALITATIVE DIFFERENCE IN THE REFLECTIVITY SPECTRUM.

Poster 3 Diagram of a model adhesive bond between two aluminum plates in which one interface is weak and described by a thin layer with an impedance lower than that of the bulk adhesive.
ESTIMATION THEORY CAN BE USED TO DEDUCE THE ACOUSTIC IMPEDANCE OF AN INTERFACIAL LAYER

Poster 4  Synthetic time domain echos from the adhesive layer as detected by two transducers on each side of the bonded structure were used to estimate the values of the transit time and acoustic impedance of both the adhesive layer and the interface layer.

• THE STRENGTH OF AN ADHESIVE BOND IS MEASURED BY TWO SEPARATE AND DISTINCT MODES: PEEL STRENGTH AND SHEAR STRENGTH

• EACH MODE RESPONDS DIFFERENTLY TO CHANGES IN THE METAL TO ADHESIVE INTERFACE CONDITION

MODIFICATIONS OF THE METAL INTERFACE USED TO PRODUCE SPECIMENS WITH DIFFERENT ADHESIVE BOND STRENGTHS:

A. PHOSPHORIC ACID ANODIZE
B. FPL ETCH
C. NO SURFACE PREPARATION

Poster 5  Cumulative distribution functions for both peel and shear strengths that were observed on specimens with one aluminum plate surface prepared in a manner indicated by the letter designations. (The opposite aluminum plate surface was prepared by an optimum FPL etch.)
ULTRASONIC MEASUREMENTS CAN DISTINGUISH BETWEEN SPECIMENS WITH DIFFERENT INTERFACIAL STRENGTHS

Poster 6 Detailed analysis of specimens showing the maximum degradation of shear strength due to the aluminum surface preparation. The method of using the bond line resonance to define the bond line thickness and then using that thickness to define the expected dumbbell resonance frequency is outlined in the upper right. The ability of the parameter \( (F_m - F_0) \) to segregate the specimens into the weak and strong groups is shown in the lower right.