ULTRASONIC MODEL FOR SOLID STATE WELD EVALUATION

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INTRODUCTION

Ultrasonic techniques have classified good and poor solid state welds in several studies [1,2,3]. A number of different types of solid state welds such as pinch welds, inertia welds, and diffusion bonds, have been evaluated with various ultrasonic feature extraction and pattern recognition techniques. The results of these studies have presented trends in the features needed to determine bond quality, but there is no physical explanation as to why certain features of the ultrasonic wave forms are influenced by the bond quality. An appropriate physical model that complements the experimental results would help explain the acoustic interactions measured. One model for the solid state weld is that the acoustic interaction with the bond line is controlled by the effective compliance of the interface. We have designed an experiment to examine this model. In our experiment, two blocks made from a high glass transition temperature (Tg) epoxy are joined together with a thin, lower Tg epoxy interlayer. If the temperature of the specimen is held below the Tg of the low temperature epoxy, then the interlayer compliance ratio across the interface can be changed by varying the temperature. Ultrasonic data are acquired at each temperature and, thus, each compliance ratio. This ultrasonic data can be compared with theoretical predictions from the compliance model. An agreement between experiment and theory will aid in the understanding of the physics involved in the ultrasonic evaluations of solid state welds and the interpretation of feature analysis from advanced waveform processing. The results of this very simple experiment suggest that difficulties remain which impede the understanding.

BACKGROUND

Though much work has been conducted on pinch weld, inertia weld, and diffusion bond evaluation, the simplest bond to model is the diffusion bond. Diffusion bonding generally involves low temperatures and minimal plastic deformation, and thus, does not change the microstructure of the substrates. The variation in microstructure of the parent material caused by certain solid state welding techniques complicates nondestructive evaluation because the microstructure influences the ultrasonic energy propagation. Experimental results from the diffusion bond work have indicated a frequency dependence of the ultrasonic pulse reflected from
the weld. The ultrasonic signal features which exhibit frequency dependence are extracted and selected for analysis. Table I displays the diffusion bond features that have successfully classified welds. Trends in the pertinent features are also shown. Closer examination of the Fourier spectrums, as shown in Figure 1, indicates a subtle but apparent increase in the high frequency content of the ultrasonic pulse reflected by the poor diffusion bond. A computer model explaining this frequency dependence would advance the understanding of the ultrasonic interaction with different levels of bond quality.

<table>
<thead>
<tr>
<th>Table I - Summary of Diffusion Bond Features</th>
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<tr>
<td>Feature</td>
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<tr>
<td>Diffusion Bond</td>
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<td>Diffusion Bond Cu-Ti</td>
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<td>Diffusion Bond JBK75</td>
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<td>Diffusion Bond HP-9420</td>
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NA - Features not available at the time

Ultrasonic Waveform Features

5 Area under video envelope
7 Standard deviation of video envelope
17 Area under R-F spectrum
21 Kurtosis of R-F spectrum
23 Average frequency of analytic spectrum
29 Area under transfer function 15 - 20 MHz.
30 Area under transfer function 20 - 25 MHz.
31 Area under transfer function 25 - 30 MHz.
At present there are two physical models to describe a solid state weld interface: bond/dis-bond, and dispersed compliance. In the bond/dis-bond model, a defective interface consists of discrete regions having metallic bonding and other regions having no bond at all. The quality of the bond and its mechanical performance then depend on the sizes, distribution, and relative percentages of the bonded and dis-bonded regions. In the dispersed compliance model, the interface is treated as a continuum having both area and thickness. The quality of the bond is represented by how closely the interface compliance approaches that of the bulk metal. Clearly these models can merge as one allows the definitions of bonded and dis-bonded to vary continuously. In summary, this quasi-static model [4] can treat both planar arrays of crack like disbands, and near-planar distributions of inclusions (contaminants) in the bond zone. In each case the model predicts bond plane reflectivity to increase with increasing frequency which agrees with our experimental observations.

EXPERIMENT

With the compliance model for solid state bonding in mind, an experiment was designed to produce controlled compliance ratios with corresponding ultrasonic data. This model assumes that the acoustic interaction with the bond line is controlled by the effective compliance of the interlayer. To provide controlled compliance of an interlayer, two blocks made from a high glass transition temperature (Tg) epoxy are joined together with a thin, lower Tg epoxy interlayer. For this study, the temperatures at which ultrasonic data was acquired were held below the lower Tg. Therefore the interlayer compliance could be changed by
varying the temperature. Figure 2 shows the dependence of acoustic velocity, and thus compliance, on temperature for the two resins selected for this study. The sample was a two inch square sandwich configuration consisting of three layers. The top and bottom layers were made of the high Tg resin and were .42 inches thick. The middle layer was made of the low Tg resin and was .004 inches thick. During the data acquisition, a pulse echo immersion technique insonified the specimen with a 5 Mhz broad band, unfocused transducer. The temperature of the water was controlled to change the resins' compliances and the temperature at the interface was measured directly by embedded foil thermocouples. At the appropriate temperatures, ultrasonic reflections were captured and stored for each known compliance.

Figure 2. Acoustic velocity as a function of temperature for two epoxy resins.
RESULTS

Once the ultrasonic reflections from the low Tg interlayer resin were stored in the computer, their frequency spectrums were generated with a Fast Fourier Transform (FFT) algorithm. Figure 3 displays the frequency spectrums at three temperatures. These plots illustrate the dependence of the ultrasonic pulse's frequency content with respect to the compliance ratio. This figure indicates that the high frequency components of the reflected pulse increase as the temperature increases. As the temperature increases the compliance ratio increases causing a larger acoustic impedance mismatch which simulates poorer bonding. Also the spectral plots exhibit a slight increase of the total energy in the reflected signal which agrees with the increase in reflection coefficient for an increase in the acoustic impedance mismatch.

Figure 3. Frequency spectra of reflected ultrasonic pulse off interlayer for 30, 40 and 50°C.
The next step in this study was to test the frequency dependence in the substrate resin as a function of temperature. The same data acquisition technique was performed on a piece of the high Tg resin. The reflected ultrasonic pulse from the back wall, resin to water interface, was captured at the same temperatures as the previous work. These ultrasonic pulses were then Fourier transformed and plotted to display

![Figure 4](image_url)

**Figure 4.** Frequency spectra from backwall reflection of a .25 inch thick, high Tg resin plate for 30, 40, and 50°C.

the frequency spectrums. Figure 4 presents the results and shows a definite increase in attenuation with increasing temperature, but there is no apparent frequency dependence. Figure 5 is a normalized representation of Figure 4 and shows a uniform frequency dependence for the attenuation as a function of temperature. This lack of increasing energy at the high frequencies indicates that the high frequency shift noted in the three layer specimen is due to the differential compliance changes in the layers.
CONCLUSION

The three layer resin samples allow the control of the compliance of an interlayer without affecting the ultrasonic signal's propagation through the top layer. With known compliance ratios and the corresponding reflected ultrasonic waveforms, one may implement computer models to confirm the theory. Also the compliance experiment's results show the frequency dependent nature that agrees with diffusion bond data for bond quality. Therefore a collaborating model would improve our understanding of the physical mechanisms governing the ultrasonic interaction with solid state bonds, and the development of such a model is currently underway.

ACKNOWLEDGMENTS

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REFERENCES


