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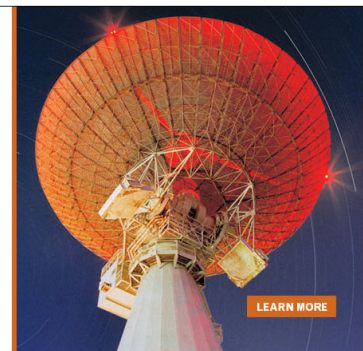
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Adhesive bondline interrogation using Stoneley wave methods

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In this work, a new technique for analyzing interfacial conditions in completed adhesive bonds is discussed. This method is based on the sensitivity of Stoneley waves, which propagate along the boundary between dissimilar solid media, to changes in the material properties of the interface region. Stoneley wave attenuation measured after processing was found to increase as a function of increasing surface roughness in specimens of borosilicate crown glass bonded with an aerobic cement to a substrate of 7740 Pyrex mirror glass. Possible extensions of these results to high-strength structural adhesively bonded composites are discussed.

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INTRODUCTION

The development of a nondestructive technique for post process assessment of bond strength in adhesively bonded materials has long been recognized as critical to the acceptance of adhesive bonding as a substitute for conventional fastening techniques in high-strength applications. While adhesive joining techniques offer numerous design advantages over conventional methods, there is a great reluctance to use a method which is quite sensitive to processing variables (surface treatment, cure cycle, etc.) and impossible to reliably inspect once the bonding process is completed. While large-scale defects such as voids or delamination can be detected with standard nondestructive testing procedures (ultrasonic, radiography, acoustic resonance), there is no known way to treat the problem of the "weak bond" where adhesive and adherend are in intimate contact but there is little interfacial strength. It has been proposed that in the absence of such a method, adhesive bonding could be used if the bonds were made in an environment where each step could be tightly controlled. This approach is clearly less desirable than post process inspection, as the human error factor has been neglected as well as the fact that once such parts were fabricated and in service, there would still be no way to ensure their continuing reliability.

This research is directed toward the application of experimental interfacial wave techniques to the development of a nondestructive test method for bond strength analysis in completed adhesive bonds. Many investigators have attempted to apply conventional sonic techniques to study weakly bonded adhesive systems without dramatic success. This is primarily due to the incompatibility of the wavelength ($0-100 \mu\text{m}$) of normally incident bulk waves at experimentally feasible frequencies with the dimensions of the adhesive-adherend interface region ($0-100 \text{ \AA}$). Stoneley waves, on the other hand, propagate along the boundary and are not subject to this restriction. Changes in the properties of the boundary region should result in altering the characteristics of propagating Stoneley waves via attenuation, dispersion, etc. This investigation studies the effect of surface roughness on the propagation of Stoneley waves in adhesively bonded materials. An optical detection system is used for

absolute measurement of the wave amplitudes of SAW impinging on and emerging from an adhesive bondline. Since this is a noncontact method, it avoids the difficulties in attenuation measurement introduced by variations in coupling efficiency when contact sensors are used.

THEORY

The first-order Stoneley theory assumes two semi-infinite isotropic elastic solids in perfect contact along the x - y plane as shown in Fig. 1.¹ The material constants of the media defined by $z > 0$ and $z < 0$ are the Lamé constants μ_1 and μ_2 , and λ_1 and λ_2 , and the densities ρ_1 and ρ_2 , respectively. Induced particle displacements in the upper medium are denoted by x_1 , y_1 , and z_1 parallel to the x , y , and z coordinate axes, and by x_2 , y_2 , and z_2 , in the lower medium. Stoneley and others have shown that if a wave propagates in the positive x direction along the boundary, particle motion is confined to the x - z plane and has components x_1 , z_1 , and x_2 , z_2 on either side of the boundary.^{2,3}

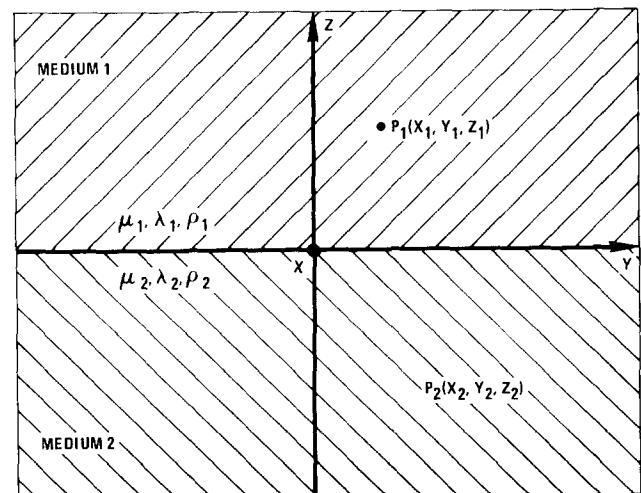


FIG. 1. Ideal Stoneley wave geometry. Infinite half-spaces $z > 0$ and $z < 0$ are in perfect contact at $z = 0$. No relative particle motion or stress discontinuities occur at the boundary.

Stoneley wave existence requires that both particle motion and stress components in each material be continuous across the boundary. These six individual conditions at $z = 0$ may be expressed as

$$x_1 = x_2, \quad (1)$$

$$y_1 = y_2, \quad (2)$$

$$z_1 = z_2, \quad (3)$$

$$\mu_1 \left(\frac{\partial x_1}{\partial z} + \frac{\partial z_1}{\partial x} \right) = \mu_2 \left(\frac{\partial x_2}{\partial z} + \frac{\partial z_2}{\partial x} \right), \quad (4)$$

$$\mu_1 \left(\frac{\partial y_1}{\partial z} + \frac{\partial z_1}{\partial y} \right) = \mu_2 \left(\frac{\partial y_2}{\partial z} + \frac{\partial z_2}{\partial y} \right), \quad (5)$$

$$\lambda_1 \Delta_1 + 2\mu_1 \frac{\partial z_1}{\partial z} = \lambda_2 \Delta_2 + 2\mu_2 \frac{\partial z_2}{\partial z}, \quad (6)$$

where the dilatation Δ_i is defined by

$$\Delta_i = \frac{\partial x_i}{\partial x} + \frac{\partial y_i}{\partial y} + \frac{\partial z_i}{\partial z}. \quad (7)$$

An elastic wave at the interface satisfying the desired stress and motion boundary conditions has the speed C where

$$C^4 [(\rho_1 - \rho_2)^2 - (\rho_1 M_2 + \rho_2 M_1)(\rho_1 N_2 + \rho_2 N_1)] + 2PC^2(\rho_1 M_2 N_2 - \rho_2 M_1 N_1 - \rho_1 + \rho_2) + P^2(M_1 N_1 - 1)(M_2 N_2 - 1) = 0. \quad (8)$$

In Eq. (8), $M_1 \equiv (1 - C^2/\alpha_1^2)^{1/2}$, $M_2 \equiv (1 - C^2/\alpha_2^2)^{1/2}$, $N_1 \equiv (1 - C^2/\beta_1^2)^{1/2}$, $N_2 \equiv (1 - C^2/\beta_2^2)^{1/2}$, and $P \equiv 2(\rho_1 \beta_1^2 - \rho_2 \beta_2^2)$, where α_1 and α_2 are the dilatational wave speeds in the two media, and β_1 and β_2 are the shear wave speeds. Equation (8) has real solutions for C only if the material constants of the two bonded media are suitably related.⁴⁻⁷

ATTENUATION MEASUREMENTS

Experimentally, boundary conditions (1)–(6) require that no relative displacement occurs between the two media surfaces and that no voids exist at the boundary. Stress discontinuities at the interface could originate at inclusions, voids, porosity, or regions of poor adhesion. All of these factors can affect the propagation of Stoneley waves along the boundary.

Stoneley waves were generated at 8 and 9 MHz on several bonded sample interfaces and directly detected using a differential optical probe. As shown in Fig. 2, SAW were

TABLE I. Abrasives used to generate interface surface defects prior to bonding.

Abrasive material	Nominal particle diameter (mm)	Average measured pit size (mm)
#220 carborundum	0.025	0.027
#400 carborundum	0.064	0.062
#305 emery	0.115	0.108

initially generated on the plane surface of an optically reflective 7740 Pyrex mirror glass substrate by an x -cut piezoelectric crystal transducer mounted on a conventional Rayleigh angle water wedge. SAW with 42-Å peak-to-peak maximum surface particle displacement amplitudes were optically measured 1 mm from the top of the water wedge. At the near edge of the borosilicate crown block shown bonded to the substrate in Fig. 2, more than 95% of the energy in the incident SAW was reflected and a large SAW SWR was observed on the substrate surface between the transducer wedge and the block.

Incident SAW were mode converted at the front corner of the block into Stoneley waves on the interface between the substrate and the block as well as into dilatational and shear waves in both media. Stoneley wave attenuation from the front edge to the back edge of the block was caused in part by artificially generated interface defects. These defects were introduced on the surface of the borosilicate crown glass specimens prior to bonding by polishing the block surfaces with different grades of carborundum optical abrasive. To prevent excess wear on the edges of the $1 \times 1 \times 2$ cm blocks, each was mounted flush with similar blocks in a 4-cm-square array and the entire array was ground on a circular 15.24-cm-diam flat mirror polishing tool. Several sets of sample blocks were uniformly ground, each set with an abrasive grit having a different diameter. Grinding produced a relatively uniform distribution of pits in the glass surface and the average diameter of these pits increased with the size of the abrasive particles. Measured average defect and abrasive sizes for the grades of abrasive used are listed in Table I.⁸

After the sample blocks were polished, they were cleaned in dilute acid and distilled water baths, dried, and bonded to the 5.08×7.62 -cm mirror glass substrates with

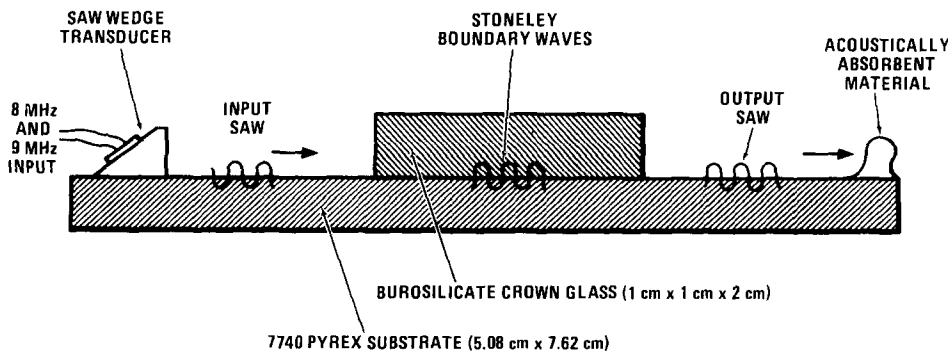


FIG. 2. SAW-to-Stoneley wave mode conversion on bonded borosilicate crown glass and Pyrex specimens.

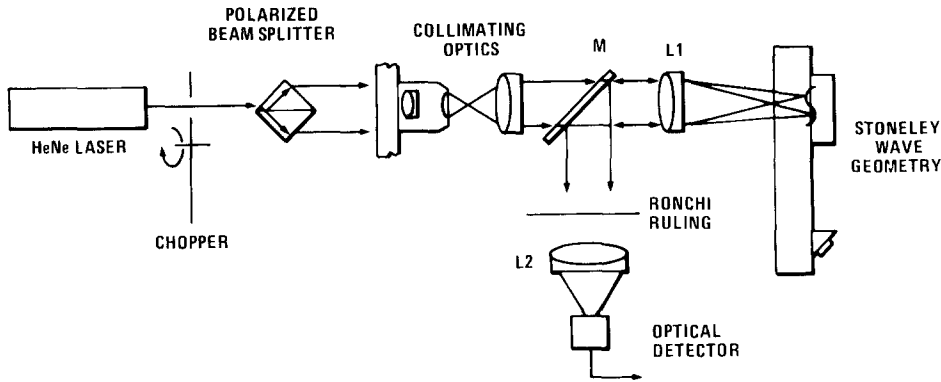


FIG. 3. Differential interferometric optics. Calibrated measurements of 3×10^{-3} Å SAW on Corning 7070 Pyrex have been obtained using this system. Light reflected from the Stoneley interface is recollimated by lens L1, reflected by mirror M positioned below the input beams, and imaged on the Ronchi ruling. Modulation of the transmitted light is synchronously detected.

anaerobic cement. The cemented pairs were clamped and cured for 24 h at room temperature. Optical inspection after curing indicated that the thickness of the bond layers had been reduced to less than 0.03 mm, approximately 10% of the 8-MHz Stoneley wavelength, and that no voids or gaps in the adhesive had formed.

Attenuation for each specimen pair was determined by measuring input and output SAW amplitudes as well as Stoneley-wave-induced interface particle displacements directly on the boundary. These measurements were obtained using the modified differential interferometric system shown in Fig. 3.⁹ On the left, the input 2.0-mW HeNe laser beam is mechanically chopped to provide a synchronous detection reference signal, divided by a polarized cube beam splitter, and expanded using a microscope objective and lens combination. The two beams are then focused as shown through the transparent glass substrate to points on the interface separated by half a Stoneley wavelength. Wave-induced particle displacements produce differential changes in the optical path lengths of the two beams. Upon reflection, the optical beams interfere producing a straight-line interference pattern that is superimposed on a straight-line Ronchi transmission grid having the same spatial period. Interface particle displacements modulate the amount of light transmitted by the grid and this light is focused on a low-noise photodetector. Detected optical signal power is approximately propor-

tional to Stoneley wave amplitude if that amplitude is 10 Å or less. Absolute calibration may be obtained by comparing the theoretical and measured optical system transfer functions and by calculating the electronic system response. Calibrated measurements of 9-MHz standing surface waves on Pyrex with peak-to-peak particle displacement of 3×10^{-3} Å have been obtained using this system.¹⁰

RESULTS

Measured Stoneley wave attenuation is plotted in Fig. 4 versus boundary pit size. Attenuation was determined by measuring SAW amplitudes at the front and back edges of the crown glass blocks. Sets of four blocks were prepared using each of three grades of abrasive. The polished blocks as well as unpolished 1/10 wave optically flat samples were bonded and the composites tested at both 8 and 9 MHz. No significant difference between 8- and 9-MHz attenuation was detected.

Probable causes of data scatter are variations in geometrical alignment between samples and nonuniform surface polishing between the individual samples in each set.¹¹

CONCLUSIONS

The research demonstrates the potential of using Stoneley wave techniques for the evaluation of adhesively bonded materials. It is recognized that surface conditions and the properties of the interface region are the most critical factors in determining the mechanical behavior of bonded structures. Measurements of Stoneley wave attenuation as a function of boundary surface roughness indicate that the technique is sensitive to changes in interfacial conditions. These results should be extended to a more detailed study of interfacial phenomena in order to assess the applicability of this experimental method to bond strength determination in high-strength adhesive systems. Attention should be directed toward assessing the effects of chemical surface contamination on Stoneley wave propagation. It is hoped that this method will be the basis for an industrial (particularly for high-performance aircraft) evaluation system for completed adhesive bonds.

ACKNOWLEDGMENT

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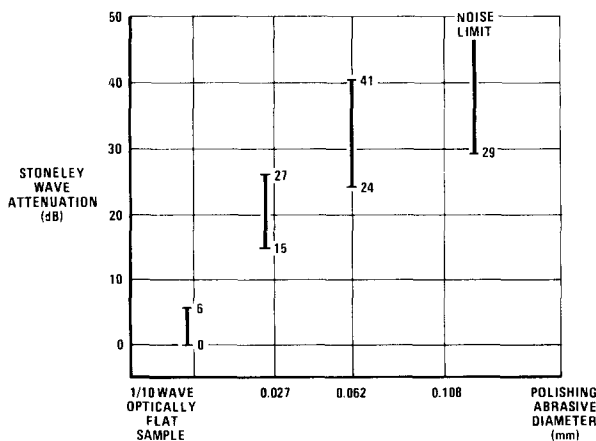


FIG. 4. Stoneley wave attenuation versus polishing abrasive diameter. Attenuation is normalized to the least attenuation measured for unpolished flat optical substrates.

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