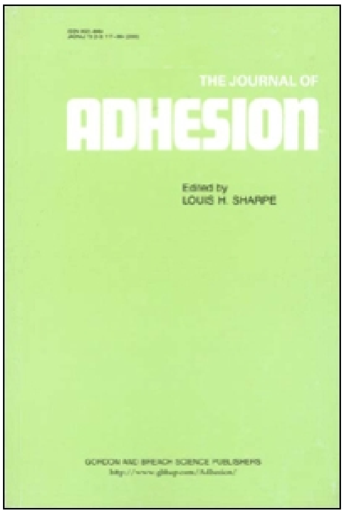

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Nonuniform Pressure Device for Bonding Thin Slabs to Substrates

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Nonuniform Pressure Device for Bonding Thin Slabs to Substrates

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A method employing compliant solid cylinders and spheres as pressure applicators has been developed for use in bonding large-area slabs (e.g., 8″ × ¼″ × 0.010″ thick) to solid substrates or to other slabs backed temporarily by solid substrates. The compliant body body produces a pressure profile causing the viscous bonding agent (e.g., epoxy resin) to flow toward the edges of the slab. The rate of compression of the cylinder is immaterial to the process; sufficient force may be applied instantly to flatten the cylinder against the entire top surface of the slab without impeding the viscous flow. The pressure gradient depends on the Young's modulus and the radius of the compliant solid body, so proper cylinders and spheres can be procured to cause very viscous bonding agents to flow into very thin layers. Several successful bonds have been made with overall thicknesses of 150 Angstroms except around dirt particles.

I INTRODUCTION

The device to be described has been developed for the fabrication of ultrasonic delay lines, but is applicable to other structures. In ultrasonic delay lines utilizing bulk solid delay media, the behavior of the ultrasonic beam depends upon the sizes and shapes of the radiating and receiving transducers. It is necessary to use transducers much larger than one ultrasonic wavelength to shape and steer the beam properly. Sometimes the ratio of dimensions to wavelength is as great as 10,000:1, implying the need for very large transducers (8 in. or greater) even at frequencies around 100 MHz.

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Examples of delay lines requiring exceptionally large transducers are in the various dispersive diffraction grating designs described in the recent literature[1,2]. The transducers must be bonded to the delay medium (substrate) with extremely thin, uniform adhesive layers to optimize the ultrasonic performance of the delay lines[3]. Both the transducers and the substrates must be polished to achieve thin bonds. One or both may be plated to provide electrode areas. To make a thin bond, pressure must be applied to the free surface of the transducer while the bonding agent is between the transducer and the substrate. If the bonding process involves the initial application of an excess amount of the adhesive, the pressure must cause the surplus to flow out and leave a uniform, thin layer under the transducer. Since the pressure is applied normal to the direction of flow, the flow requires a pressure gradient. When the thin layer is achieved it must be maintained during the hardening of the adhesive. It is the purpose of this paper to describe a method and an apparatus employing compliant solid cylinders or spheres for applying the pressure with the proper gradient to cause flow of the adhesive to achieve thin, uniform layers, and to maintain this thickness during hardening. Although the work in this paper deals principally with the use of epoxy resins as bonding agents, the method is not limited to epoxies. It will apply equally well to other polymers, melted solids, softened glasses, visco-elastic materials, and solids which can be fused by thermal-compression bonding.

Epoxy resins seem promising for bonding large slabs to solid bodies. Polymers such as epoxies present problems, however, because during the reaction process the viscosity increases and the elastic moduli develop a real part. Both of these changes impede the flow. Hence, the flow must be complete and the bonding layer thin and uniform early in the polymerization process. Earlier workers have used flat plates[4] and inflatable membranes[5] to apply the pressure. The latter "pressure bag" method is advantageous because it permits the application of the pressure along the centerline of the slab first, forcing the epoxy toward the edges of the slab. Increased inflating widens the area of applied pressure until the entire slab is under pressure and the excess epoxy is squeezed out. The "pressure bag" method has disadvantages, however. An excessive rate of inflation will trap epoxy under the slab by pushing down the edges of the slab before the flow outward is complete. To counteract this tendency, an operator or a timing device must follow a prescribed cycle of temperature and pressure versus time for the inflation of the membrane.

The new method, herein described, has been developed which reduces the need for gradual application of the pressure. This new technique utilizes a compliant solid circular cylinder or a compliant sphere to press upon the slab. Upon the application of a certain force to the sphere, or of a certain

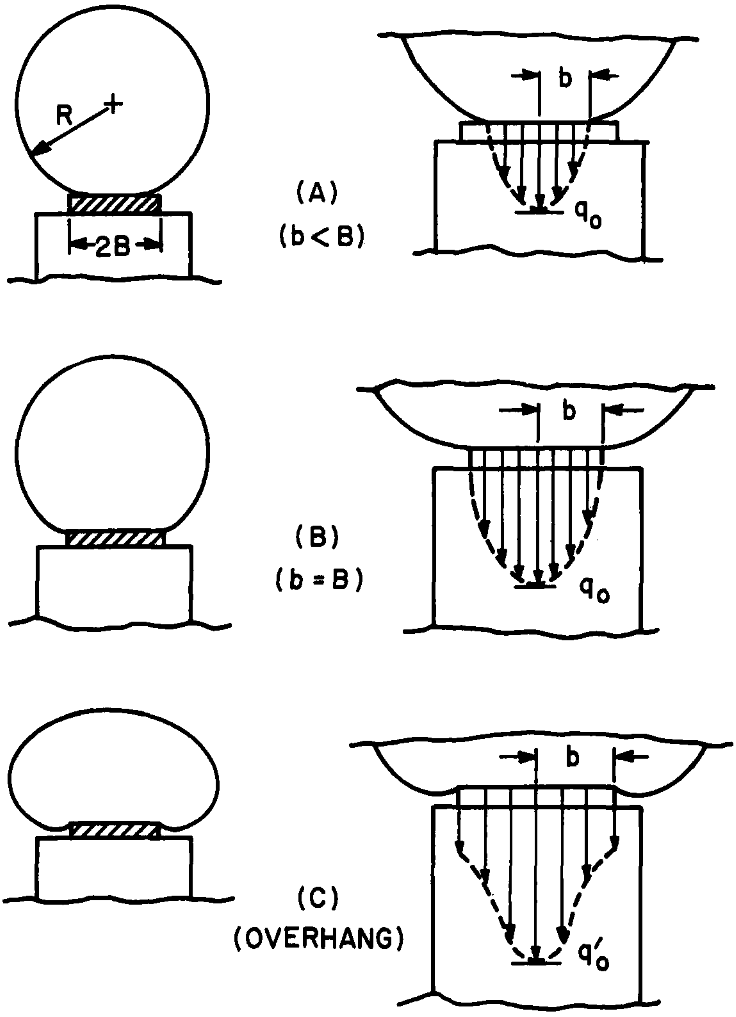

FIG. 1

FIGURE 1 The deformation of a compliant cylinder and the pressure distribution beneath it when pressed upon a rigid plane. (A) Contact half-width b less than transducer half-width B, (B) b just equal to B, (C) overpressure causes overhang. In (A) and (B), the pressure distribution is elliptical.

force per unit length to the cylinder, the surface touching the slab (starting at the center in the spherical case or along the centerline in the cylindrical case) will flatten out until the integral of the pressure applied to the slab over the area of contact supports the applied force. The pressure upon the transducer is maximum at the center (spherical case) or along the centerline (cylindrical case) and is distributed as a semi-ellipse out to the lines along which the compliant body loses contact with the slab. Then the pressure remains maximum at the center and zero at the edges. See Figure 1, view B. Excess force on the compliant body could raise the edge-pressure above the interior pressure, an undesirable consequence. Figure 1, view C, shows the approach to this condition. However, the condition in Figure 1, view B, can be achieved by the instant application of sufficient force per unit length to the cylinder. In view B, there is always a gradient of pressure from the center to the edges of the slab. Hence, outward flow of the excess epoxy will occur as long as the epoxy is fluid. The advantages of the compliant solid bonding press are these:

1) The pressure may be applied to the cylinder rapidly without a complicated cycle,

2) The epoxy need not be heated to lower the viscosity and accelerate the flow, and

3) The epoxy will have a pressure gradient from the center of the slab to the edges and will not be sealed under the slab by the extremities of the contact area on the cylinder unless a large overpressure be applied. Tolerances on the excess can be determined empirically. A moderate deficiency in applied pressure will cause the edges of the slab to have thick bonds while the central area will have a thin bond.

In short, the thickness of the bond is fairly insensitive to the rate of application of the pressure and to the magnitude of the pressure above the minimum needed to flatten the compliant solid across the entire width of the slab.

II THEORY

A. Cylinder

Timoshenko and Goodier[6] give the solution to the force and displacement at the contact surface of two parallel cylinders pressed against each other. The solution is valid when St. Venant's principle holds; that is, when the points of application of the forces pushing the cylinders together are far from the contact surface in comparison to the width of the contact area. The cylinders and associated parameters are defined by subscripts 1 and 2. See Figure 2 for a diagram of the structure and a definition of the terms. The cylinders are of radii R, Young's moduli E, and Poisson's ratios ν. When a force P' per unit length presses the cylinders together contact is made over an area of half width b. The pressure along the centerline of the contact area is q_0; the pressure profile across the contact area is a semi-

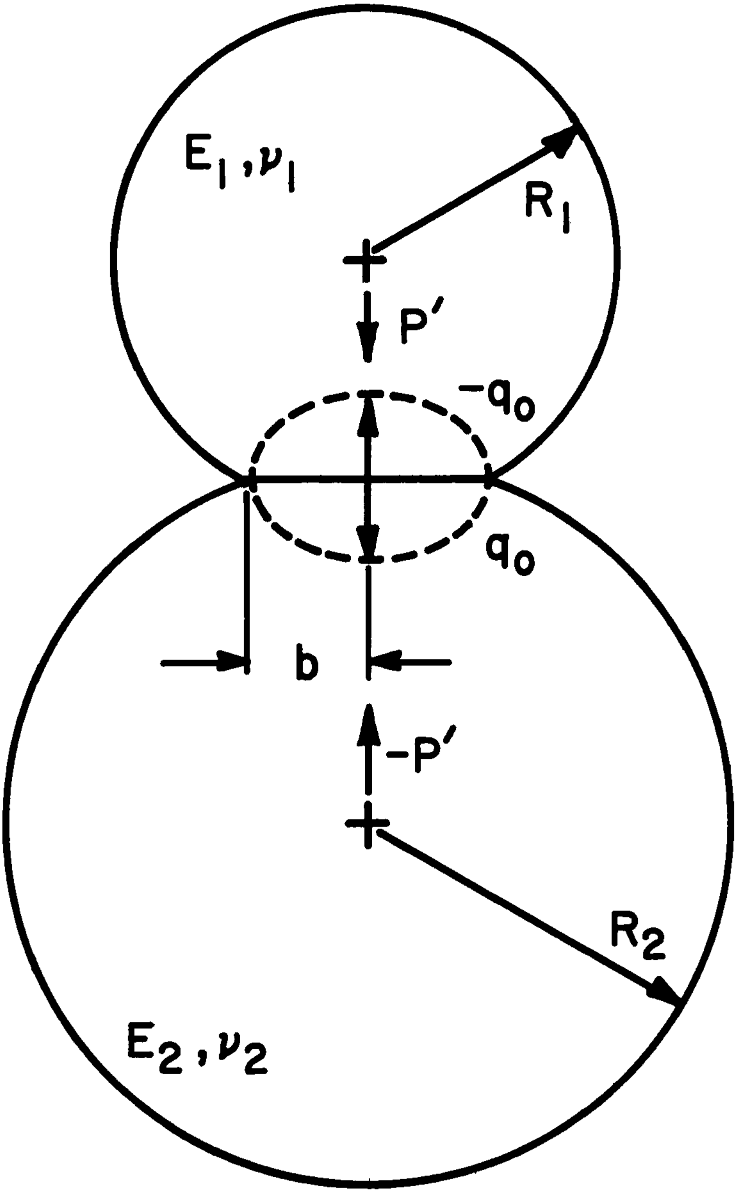

FIGURE 2 Two cylinders of different radii and moduli pressed together by a force density P′ per unit length. By choosing $R_1/R_2 \ll 1$, $E_1/E_2 \ll 1$, $0 < \nu_2 - 0.5$, and $v_1 = 0.5$, one arrives at condition (A) or (B) of Fig. 1 for a rubber cylinder pressing on a glass block.

ellipse, is maximum along the centerline, and falls to zero with an infinite slope at ± b.

Expressions for b and q_0 are

$$b = [4P'R_1R_2(k_1 + k_2)/(R_1 + R_2)]^{1/2} \tag{1}$$

and

$$q = [P'(R_1 + R_2)/\pi^2(k_1 + k_2)R_1R_2]^{1/2} \tag{2}$$

The parameter k is the ratio

$$k = (1 - v^2)/\pi E. \tag{3}$$

This formulation may be specialized to the case of a compliant cylinder pressed against a stiff plane by letting R_2 approach infinity and the ratio E_1/E_2 become very small. Inserting the expression for k into the expressions for b and q_0, and making the assumptions

$$R_2 \to \infty, \tag{4}$$

and

$$E_1/E_2 \ll 1, \tag{5}$$

one finds

$$b \cong [4P'R_1(1 + v_1^2)/E_1]^{1/2}, \tag{6}$$

and

$$q_0 \cong [P'E_1/\pi^2(1 + v_1^2)R_1]^{1/2}. \tag{7}$$

The configurations of Figure 1(A) and (B) result as P' in increased on a given cylinder. As an example, consider the case of a rubber cylinder pressing on a glass plane. The magnitudes of the moduli are $E_1 \leqq 2{,}000$ psi and $E_2 \sim 10{,}000{,}000$ psi, so $E_1/E_2 \leqq 1/5{,}000 \ll 1$. For rubber, $v_1 = 0.5$. To bond a ¼-inch wide slab, for instance, $b = 0.125$ in. Then for various values of R_1 and E_1, the required force density P' and the resulting maximum pressure q_0 may be calculated. Some representative values are given in Table I.

TABLE I
Values of P′ and q_0 for Rubber Cylinders
$\nu_1 = 0.5$ and $b = 0.125$ in.

E_1, psi	R_1, in.	P′, lb/in.	q_0, psi
500	0.25	20	57
	0.50	10	28
	1.00	5	14
1000	0.25	39	113
	0.50	20	57
	1.00	10	28
2000	0.25	78	225
	0.50	39	113
	1.00	20	57

The pressures are directly proportional to the modulus and inversely proportional to the cylinder radius for a constant contact width *b*. The interposition of the thin, stiff slab will change the pressure distribution only in Case (A) in Figure 1. There, the substrate will feel a small pressure outside the contact area of the cylinder because of the flexural stiffness of the slab. Small cylinders may be advantageous because the deflection of the cylinder surface to provide a constant contact width is roughly inversely proportional to the square of the radius. The surface deflection is 0.004 in. for a cylinder of 2-in. diameter, 0.015 in. for a 1-in. cylinder, and about 0.050 in. for a ½-in. cylinder. The effects of imperfections in the cylinders might be minimized with fairly small cylinders. On the other hand, the analysis would no longer hold quantitatively and experimental troubles might develop if the cylinders were small enough so that the deflection was not small compared to the cylinder radius. Probably an optimum combination of R_1 and q_0 can be found for a slab of a given thickness and an epoxy of a certain viscosity. The stiffness of the slab itself will tend to negate the effects of imperfections in the cylinder.

Both b and q_0 in Eqs. (6) and (7) are proportional to $(P')^{1/2}$; so as a cylinder is pressed down on a plane, the pressure profile is an ellipse of increasing size but constant eccentricity,

$$\frac{x^2}{b^2} + \frac{y^2}{{q_0}^2} = 1. \tag{8}$$

The pressure gradient $-dy/dx$ causing outward flow is

$$-\frac{dy}{dx} = \frac{q_0}{b}\frac{x}{b}\frac{1}{(1 - x^2/b^2)^{1/2}}. \tag{9}$$

Since q_0/b is constant, the gradient near the centerline of the transducer is proportional to x and inversely proportional to b. An outward gradient exists right up to the centerline of the transducer at all times as long as the cylinder does not overlap the edges of the transducer severely. See Figure 1(C). Slab stiffness will modify Eq. (9) somewhat.

B. Sphere

Timoshenko and Goodier[6] also give the solution to the problem for spheres. The force distribution under the compressed sphere is spheroidal,

$$\frac{x^2}{B^2} + \frac{y^2}{B^2} + \frac{z^2}{Q_0^2} = 1, \tag{10}$$

where the area of contact is in the xy-plane and the force is exerted in the z-direction. In this case there is a pressure gradient along $r = (x^2 + y^2)^{1/2}$ causing outward flow of the bonding agent. The expressions for B, the radius of the contact area, and Q_0, the maximum pressure at the center of the contact area, are

$$B = [3PR(1 - \nu_1^2)/4E_1]^{1/3} \tag{11}$$

and

$$Q_0 = 3P/2\pi B^2 \tag{12}$$

where the radius R_2 of the lower sphere has been expanded approaching infinity and the ratio of Young's Moduli E_1/E_2 has been made much smaller than unity to correspond to the rubber sphere pressing on a plane metal, glass or ceramic substrate. In Eqs. (11) and (12), P is the total force in the z-direction upon the upper sphere having a radius R_1, Young's modulus E_1 and a Poisson's ratio ν_1, respectively.

III EXPERIMENTS

A. Equipment

1. *Cylindrical Case* Molded neoprene cylinders[7] were mounted in V-grooved steel bars slotted to slide vertically on the pillars of a bonding fixture. The force density P' was applied to the top of the V-grooved bars by a row of spring-loaded screws tightened by torque wrenches. Figure 3 is a simplified drawing of the equipment. The force density P' could be applied equally well by a row of hydraulic or pneumatic cylinders.

For calibration of the torque necessary to flatten out a cylinder over the entire area of a transducer, a test bar polished flat and half-silvered with

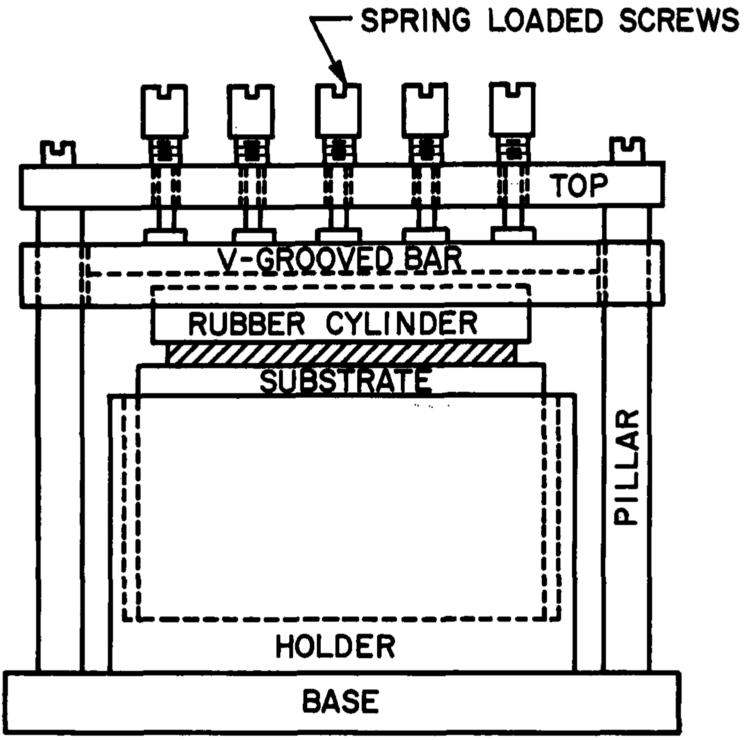

FIGURE 3 The Solid Cylinder Bonding Press. Force from the spring-loaded screws is applied to the V-grooved bar in which the rubber cylinder is mounted. The cylinder presses upon the transducer which is laid upon the epoxy-coated substrate. In practice, there is a thing Teflon sheet between the cylinder and the transducer to prohibit adhesion of the epoxy to the cylinder.

chromium was used as the substrate in a bonding fixture with slotted bottom[8]. A polished, Y-cut quartz transducer plated with 500 Å of chromium and 2000 Å of gold was laid on the flat, and pressure was applied through the rubber cylinder. Interference fringes analogous to Newton's rings were observed along the boundaries of the contact area. As the pressure was increased, the boundaries moved outward, finally reaching the edges of the transducer. The torque wrench was then set to slip at the value of torque needed to turn the screws to achieve the needed deflection of the cylinder one inch in diameter.

2. *Spherical Case* Solid rubber spheres[9] were mounted in conically incised aluminium blocks arranged to slide vertically on the pillars of a

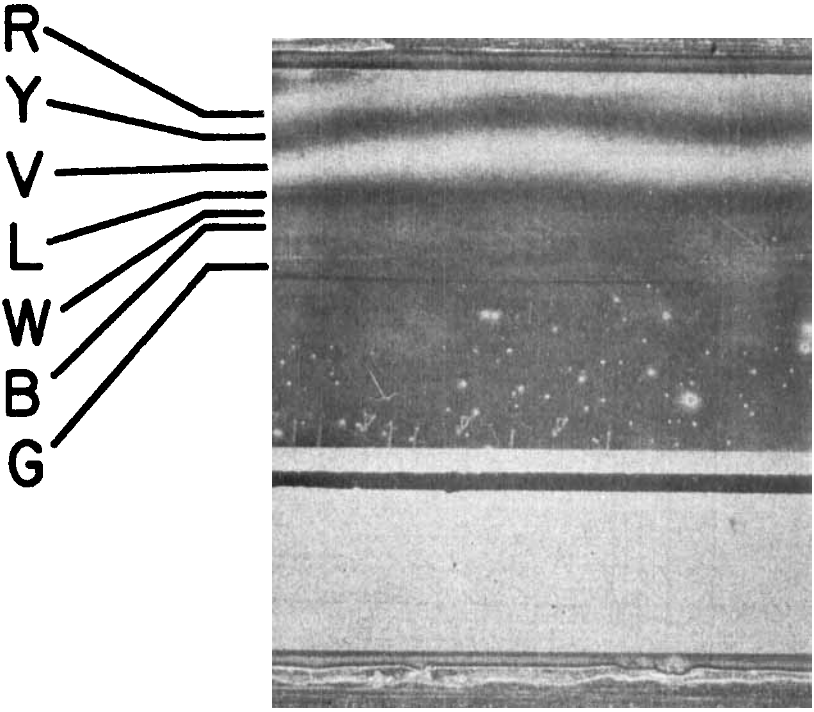

FIGURE 4 Interferogram of a good epoxy bond made with the Solid Cylinder Bonding Press with enough pressure to give the configuration in View (A) of Fig. 1. The fringes (Newton's "Rings" from a cylinder instead of a sphere) indicate that the cylinder did not make contact over the entire width of the transducer. Fringe colors are indicated as follows: G: golden, B: black (grey), W: white, L: lemon-yellow, V: orange, red, violet, blue, green in that order, Y: pale yellow, R: orange and red. About 1/3 of the transducer (from the dark stripe to the edge) was unplated, so no fringes appear there although the thickness of the bond is symmetric about the centerline of the transducer. The stripe is an unplated band on the substrate.

bonding fixture analogous to the one shown in Figure 3 for cylinders. Operation and calibration were similar, also.

B. Test Bonds

Several test "bonds" were attempted using no bonding agent. (Such are commonly termed "air bonds".) Cylinders of various diameters and moduli were tested. It was found that the transducers flattened down upon the substrate as expected, the contact between transducer and substrate being made first along the line of tangency of the cylinder and the transducer, then spreading out toward the edges of the transducer as more pressure was applied. Except for dirt particles, the bonds were black with shaded streaks of white and gold when viewed under white light. Interferograms such as this represent thicknesses of 150 to 650 Å[10] with some thinner (gold) areas. The errors in these measurements are probably about 80 Å, approximately double the electromagnetic skin depth in the plating materials which is about 40 Å at optical frequencies.

Several more test bonds were made with non-hardening epoxy resin (no catalyst added) as a fluid bonding agent. These tests were undertaken to determine the flow rate of viscous bonding agents in a solid-cylinder press. It was determined that at room temperature the bond became as thin and as uniform as an "air bond" in the time it took to turn down the screws. More flow took place over a matter of hours so that an interferogram of an "old" non-polymerizing bond was uniformly golden. This coloration indicates a thickness under 150 Å.

C. Permanent Bonds

1. *Cylindrical Case* Several permanent bonds of epoxy resin have been made on polished and plated fused quartz substrates $\frac{1}{2}$-in. wide and 5 to 15 in. long. Transducers 15-mil thick by $\frac{1}{4}$-in. wide and up to 8-in. long were applied. During bonding, the substrates were held at 60°C for 1 hour after the pressure application, then allowed to cool and cure with the pressure still on. Bonds made in this manner are tenacious; the attempted removal of the transducer with solvents resulted in the breakaway of a long section of the face of the substrate under the transducer instead of the unbonding of the transducer in one case. In general, bonds have resulted in epoxy layers under 150 Å thick which were grey with golden tones throughout in a white-light interferogram. An enlarged photograph of one section of a typical bond is reproduced in Figure 4. Because the applied pressure was a little low in this case, one "Newton's fringe" appears along one edge and three or four appear along the other edge of the transducer. However, about $\frac{7}{8}$ of the bond width is flat and ultra-thin. When the applied force density P' was raised the next time to eliminate all fringes from the edges of the transducer, the interferogram of the resulting bond was a uniform golden grey. Along one edge there was a dark grey band with a white band at the very edge for part of the length. It is probable that the golden-grey area was uniformly less than 150 Å thick. The bond stood up under the usual grinding and plating operations necessary to produce high frequency transducers. Based upon optical observations, it can be stated that the bonds made by the solid-cylinder bonding method appear to be as good as bonds made by other methods and, indeed, better than many bonds on operable delay lines made to date.

2. *Spherical Case* An optically flat transducer 1″ x 0.30″ x 0.015″ in size plated with chromium was bonded with phenyl salicylate to an optically flat block of fused quartz which was plated to half-transparency with chromium. Pressure was applied to the center portion of the rectangular slab with a sphere 2.0″ in diameter. About ⅔ of the length of the slab was in contact with the compressed sphere. Over this area the bond was uniform as shown in Figure 5, and the color indicated a thickness of less than 150 Å. Several other bonds have been made on transducers having less uniform plating. These also show up as flat and thin bonds except at areas on nonuniformity in the plating.

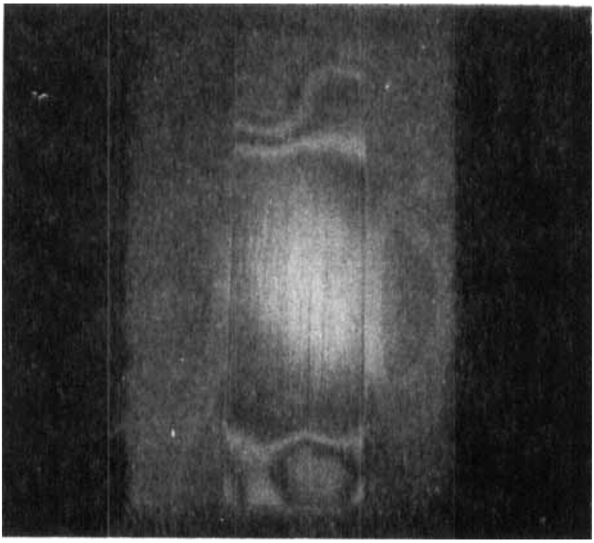

FIGURE 5 Interferogram of a good Salol bond made between a rectangular slab and a flat block when a compliant sphere was pressed down over part of the area of the rectangle. The center area of the bond is less than 150 Angstroms thick.

IV CONCLUSIONS

A novel bonding technique called the Compliant Solid Bonding Method has been invented, explored, and developed. This development has proceeded to a point where polished slabs a few mils thick, ¼-in. wide, and 8 inches long can be bonded with epoxy layers less than 150 Å thick to optically flat substrates. Pressure fixtures have been built to accomplish the bonding. Several bonds have been made to demonstrate thinness and uniformity.

Optical observations indicate that these bonds are as good as the best bonds made by other methods. The other two principal methods for bonding use different pressure applicators, and have certain disadvantages relative to the Compliant Solid Bonding Method.

1) Bonding with a rigid, flat pressure applicator has the disadvantage that the whole bond must become thin simultaneously by viscous flow between parallel plates of decreasing separation. Bernoulli forces may pull the edges together, trapping fluid. Very large forces are necessary, and may not be sufficient to achieve an adequate flow rate if the bonding material is in the process of polymerizing and developing a real shear modulus. The Compliant Solid Bonding Method eliminates the excess bonding material from the center of the bonding area first, and pushes it out between areas of the slabs which are relatively far apart due to elastic flexure. Pressure may be applied very rapidly. A pressure gradient from center toward the edges always exists.

2) Bonding with an inflatable bag does tend to eliminate the excess bonding material from the center of the bonding area first, but may actually trap bonding material in a thicker layer than the flat plate would leave if inflation occurs too fast. In the final inflated configuration, there is no pressure gradient toward the edges, so trapped fluid is permanently trapped. The rate of inflation of a pressure bag must be accurately controlled, and the necessary speed may be incompatible with the rate of polymerization of the bonding agent. The presently described Compliant Solid Bonding Method can be brought to its final position rapidly without trapping any fluid, and has an outward pressure gradient at all times.

Acknowledgments

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