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DEVELOPMENT OF AN ULTRASONICALLY AUGMENTED DIFFUSION BONDING PROCESS FOR FLUIDIC CONTROL ASSEMBLY FABRICATION

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13. ABSTRACT

For initial investigations into the feasibility of augmenting the diffusion bonding of titanium fluidic control devices, a flexural-beam configuration was designed and fabricated, on the basis of intensive study of the mechanisms of the diffusion bonding process and the candidate modes of ultrasonic activation. Design problems were encountered, however, in achieving efficient ultrasonic power transmission with this activation mode. In order to achieve a workable system within reasonable time, an alternate arrangement comprising a flexural wedge-reed (shear-mode) ultrasonic system of proven design was fabricated. Effective performance of this equipment was confirmed by lightly "bonding" simulated fluidic control devices consisting of thirty 1-inch squares of 0.005-inch-thick aluminum at room temperature, using a clamping pressure of approximately 1000 psi and an ultrasonic pulse time of 0.5 second. A vacuum chamber to contain this equipment and appropriate heating apparatus were also designed and fabricated, to provide a complete functional system.

Extension of the program was recommended in order to permit use of the ultrasonic diffusion bonding equipment in producing comprehensive data on bonding parameters for laminated titanium fluidic control devices.

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AEROPROJECTS INCORPORATED
West Chester, Pennsylvania

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FOREWORD

This summary report on the development of an ultrasonically augmented diffusion bonding process for fluidic control assembly fabrication was prepared by Aeroprojects Incorporated, West Chester, Pennsylvania, under Army Contract No. DAAA21-73-C-0243. The work was carried out under the sponsorship of the Department of the Army, Picatinny Arsenal, Dover, New Jersey, with Mr. Dave Sampar of Picatinny Arsenal serving as Contracting Officer's Representative.

The findings of this report are not to be construed as an official Department of the Army position.

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I. INTRODUCTION AND BACKGROUND

The objective of this investigation has been to analyze methods of applying ultrasonic energy to a representative laminated fluidic control device during solid state diffusion bonding assembly and to examine the effects of the ultrasonic activation on diffusion bonding parameters and bonding behavior.

This investigation has been undertaken as a means of determining the effectiveness of ultrasonics in eliminating problems that have been associated with the manufacture and performance of these control devices. Precise maintenance of channel dimensions and configuration, especially in the nozzle and cusp area, is vital. Fluid-tight bonds between channel layers and between channel layers and covers are essential to prevent false switching or detached flow. There may be over 100 individual channel layers (and perhaps as many as 300 bonds) in a single "monolithic" fluidic assembly; leakage or failure on even one bond plane can be disastrous. Furthermore, not all metals are suitable. Aluminum, with its many advantages, has a tenacious oxide coating which inhibits bonding. Other metals also require long bonding time cycles, high temperatures, and special atmosphere control.

To date, a variety of solid-state diffusion bonding techniques have been evolved. These can be divided into three classes (1)* on the basis of the pressure-time relationships involved.

1. Yield-Stress-Controlled Bonding

Processes such as hot pressure welding and roll bonding utilize very high pressures or temperatures for very short time periods. The yield stress of the material must be exceeded so that gross plastic deformation can occur. There is usually a deformation threshold (which may be as high as 50-60 percent (2)), which must be exceeded to achieve satisfactory bond strength. Such deformation makes this process unsuitable for the dimensional precision required.

2. Diffusion-Controlled Bonding

With isostatic gas pressure bonding or die pressure bonding, the pressure is held below the yield stress, but is kept high enough to produce local plastic deformation of asperities on the contacting surfaces, producing large areas of local contact and permitting diffusion to proceed across the interface. Bonding times may range to a number of hours, depending on the material. Deformation may be in the order of a few mils or a fraction of a percent.

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* Numbers in parentheses designate references cited on page 19.

3. Creep-Controlled Bonding

This process involves low pressures (which may be applied by vacuum or a dead weight), high temperatures, and long times (to more than 24 hours); creep at the interface creates the contact necessary to establish a bond. The major disadvantages of this process are the time and costs involved.

It is believed that the application of ultrasonic energy will offer two avenues to facilitate solid-state diffusion bonding. It has been repeatedly demonstrated that ultrasonics can transiently reduce the yield strength of the material so that the asperities or local contact islands are deformed, surface oxide or other barrier films are broken up or dispersed, and intimate interfacial contact is more readily achieved. It has also been shown that ultrasonics can accelerate the diffusion of atoms across the interface. Both of these effects have been well documented in the research literature (3, 4). Substantial experimental evidence from the related areas of ultrasonic hot pressing and ultrasonic cold welding is available to corroborate both of these phenomena.

Hot pressing and sintering of silver powder, calcium fluoride, and alumina under ultrasonic influence (5) has demonstrated the effectiveness of ultrasonic systems in transmitting vibratory energy into elevated-temperature, elevated-pressure fields. The mechanism of action is believed to be the phenomena delineated above plus the improving of particle-to-particle contact.

In ultrasonic cold welding (6), the materials to be joined are clamped together under moderate clamping forces, and vibratory energy is transmitted through them for a brief interval, generally less than 1 second. The rapid stress reversals and microdisplacements at the interface disrupt and disperse surface films such as oxides and adsorbed layers. Both increased plasticity and diffusion have been repeatedly observed in connection with ultrasonic welding at ambient temperatures.

The plasticity observed during ultrasonic welding can not ordinarily be induced at the measured weld-zone temperatures. Rhines (7) maintains that two factors are involved in this enhanced plastic flow: (a) an overall reduction in the yield strength of the entire volume of metal subjected to vibration, and (b) a localized softening of the metal within the weld nugget. This transient fluidity of the metal also accounts for the virtual elimination of the weld interface that has been observed in many ultrasonic welds. Rhines contends that induced vibration lowers the force required to move the dislocations within a metal crystal and that new dislocations are generated within the crystals so that the dislocation density is increased. Diffusional phenomena are sometimes present in normal ultrasonic welds and have been observed and identified by microstructural changes such as intermediate phases at the interface, depletion and/or enrichment of solute concentrations in localized areas, recrystallization and grain growth, sub-grain formation, etc.

Although ultrasonic welding is a self-sufficient joining process, ultrasonic energy delivered to materials as in welding may be used to assist conventional diffusion bonding techniques. In work conducted at Bell Laboratories (8), a standard ultrasonic spot-type welder with an input power of 300 watts to the magnetostrictive transducer has been used to assist diffusion bonding of gold-plated Kovar parts. The reported effect was to reduce temperatures to below those normally required to produce sound bonds without ultrasonics. Earlier work at Aeroprojects (9) demonstrated that external heating during ultrasonic welding of some structural aluminum alloys improved bond quality, although the result was not then interpreted on the basis of diffusion.

A cursory investigation was conducted in ultrasonically assisted diffusion bonding (butt-joining) of Type 304 stainless steel tubes of approximately 1/2-inch diameter, 0.040-inch wall thickness, and 2.5 inches long. The parts were installed between the tip and anvil of a standard ultrasonic welder (in a vacuum) and the ends to be joined were induction heated. Despite certain experimental difficulties, tensile tests of bonded samples showed corresponding strength was achieved in approximately one-third the usual bonding time with the introduction of relatively low ultrasonic power levels.

In another study (10), the diffusion bonding of small sheet coupons of 0.010-inch-thick beryllium was markedly enhanced by the application of ultrasonic energy in a shear (torsional) mode. Metallographic examination of diffusion bonded samples indicated that the ultrasonic process permitted reductions in bonding temperature at least from 770°-825°C to 675°C (12-18 percent) and reductions in bonding time from 2-3 hours to 15 minutes (87-92 percent). In the course of this study, it was discovered that the time and temperature reduction benefits could be derived with only a brief interval (25 seconds) of ultrasonic power applied at the beginning of the bonding cycle.

The present work was undertaken to establish the feasibility of applying ultrasonic power to the bonding of a fluidic control package of stacked titanium laminations. Vibratory modes that should enhance diffusion bonding were examined and methods of introducing the vibratory energy to the stack were evaluated in an effort to evolve a practicable ultrasonically assisted diffusion bonding concept. A diffusion bonding array incorporating the selected vibratory mode concept was designed and fabricated for evaluation to establish tentative diffusion bonding/ultrasonic parameters for the titanium assembly. An exploratory examination of the bonding response of a stack of aluminum laminations was undertaken.

II. CHOICE OF DESIGN CONCEPT

During the initial phases of the program, a literature review of titanium and aluminum diffusion bonding was undertaken, and methods and systems design for introducing ultrasonic energy to the stacked laminations were studied.

Three equipment configurations were initially considered: (1) axial vibration of the ultrasonic coupling member oriented perpendicular to the plane of the laminations (impingement mode), (2) orientation of the ultrasonic wave guide to produce displacement in the plane of the interfaces (shear mode), and (3) unidirectional flexure of the stacked laminations producing shearing displacements at the interfaces (flexural mode).

The selection of the third approach for initial studies was based on the following rationale:

In terms of conventional diffusion bonds between similar metals, Gerken and Owczarski (11) have suggested a bonding mechanism involving three stages. The first stage, the initial contact of the surfaces, includes sufficient instantaneous deformation of the surfaces to establish mechanical contact. A second stage involves time-dependent deformation (creep) of the interfaces. In the final stage, there is a diffusion-controlled elimination of the original interface. In situations where the contact pressure is below the yield strength of the materials at the bonding temperature, the surface deformation is not instantaneous, and the time-dependent mechanism must operate if bonding is to occur. This was the condition that had to be met in the case under consideration, where essentially no gross deformation of the stack could be tolerated. The role of the ultrasonic energy under these conditions would involve fragmentation of the surface barrier films, mutual accommodation of the faying surfaces, and nascent metal contact, leading to the diffusion-controlled bond formation (which may also be accelerated by the application of ultrasonic energy).

This proposed role for ultrasonic energy is identical to its role in ultrasonic welding at room temperature, where the local upsetting and weld formation are effected by the breakup and dispersion of the oxide and other barrier films by the high-frequency, low-amplitude stress reversals at the interface. In order to obtain this barrier film breakup, the necessary shearing displacements at the interface are achieved by clamping the workpieces with a resonating ultrasonic system that "drives" the workpieces relative to each other at the area of contact. The normal interfacial force on the workpieces must be sufficient to mechanically couple the vibratory energy into the weld coupon effectively. This results in thickness deformations of the weld area of 5 to 20 percent, unsuitably high for the diffusion bonding application under consideration. If the ultrasonic sonotrode could be coupled to the workpiece by other than frictional means (i.e., by positive mechanical drive), then the clamping force could be reduced, and the amount of thickness deformation would be decreased.

With regard to the three configurations being considered, the first two--direct impingement and direct shear (the ultrasonic welding mode)--involve pressure coupling to the ultrasonic system such that the clamping force and amount of ultrasonic power delivered are interdependent. This means that a certain level of clamping force is required to achieve the level of ultrasonic power needed to effect the desired bond. A higher or lower clamping force level results in an impedance mismatch and therefore a less-than-satisfactory bond. This interdependence of clamping force and ultrasonic power level implies the necessity of deforming the fluidic stack workpiece in order to deliver sufficient ultrasonic energy to effect the bond. As precluding workpiece deformation was an important objective of the program, these two configurations were rejected for initial studies. In addition, the direct impingement approach would provide shear displacement of the interface only during yielding of the faying surfaces, since the vibratory displacements are normal to the interface.

The third configuration, the flexural vibration of the fluidic stack, however, could probably be effected without pressure coupling of the ultrasonic system, thus allowing the pressure to be independently adjustable. Additionally, it appeared more straightforward to obtain a uniform distribution of normal force and vibratory energy over the fluidic-device-size pieces using this approach than using the others.

This was a novel approach, and little background information existed on equivalent designs and performance. Nontheless, the apparent advantages of this approach in developing a "deformationless" diffusion bonding method outweighed the possible advantages of the alternate approaches for the reasons delineated above, and this approach was chosen for initial experimentation.

III. FLEXURAL-BEAM EQUIPMENT TESTING AND EVALUATION

A flexural-beam test system was designed and fabricated. The apparatus consisted of a flexurally resonant (at 15 kHz) beam, attached at each end to 15-kHz transducers through appropriate wave guides. Precautions were taken to ensure that a progressive-wave pattern, rather than a standing-wave pattern, was developed in the workpiece: one of the two transducers was ultrasonically driven, and the other functioned as a receiver by being attached through a transformer to a resistive load.

In a progressive-wave system, the incident wave passes through the workpiece and into the dissipative load with no reflected component. The peak vibratory dynamic stress is thus achieved along the entire length of the workpiece as the wave progresses, effecting uniform vibratory strain. In a standing-wave system, the strain distribution in the workpiece is the resultant of an incident and a reflected wave and is not uniform over the entire length.

Pressure on the stack was adjustable using compression springs between the cover and through-bolts.

During preliminary performance tests, this system was observed to overheat rapidly in the region of the through-bolts, indicating that the system was limited in its ability to transmit power.

In an attempt to minimize the heating, the over-beam length was modified, and an improved method of clamping the workpiece (laminations) between the beams was devised: the through-bolts were discarded in favor of cradle assemblies which supported each beam at nodal points. Each beam support consisted of a channel-shaped member with four hardened set-screws as shown in Figure 1. The set-screws were pointed, and engaged the neutral axis of the beam, which contained corresponding countersunk depressions. The spacing of the screws corresponded to the nodal positions of the beam at 15-kHz flexural mode. The two beams could thus be clamped together by applying force through the cradle supports without changing the resonance characteristics of the beams. The experimental apparatus shown in Figures 1 and 2 includes the two transducer-coupling systems.

Evaluation of the apparatus was performed using four 1 x 1 x 0.005-inch sheets of aluminum stacked together and clamped between the beams. It was anticipated that inspection of the faying surfaces of the laminations would provide indications of the effects of the vibratory displacements.

Inspection of the surfaces at low power input levels (to 50 watts) failed to reveal interface effects. At higher power levels (to 300 watts), some evidence of surface abrasion was noted. Figure 3 shows surfaces typical of these later runs. The black residue is apparently Al_2O_3 generated by the scuffing of the surfaces, and the disregistry of the coupons due to some slippage is apparent. The clamping pressure was increased but the support points showed signs of deformation at the higher clamp loads.

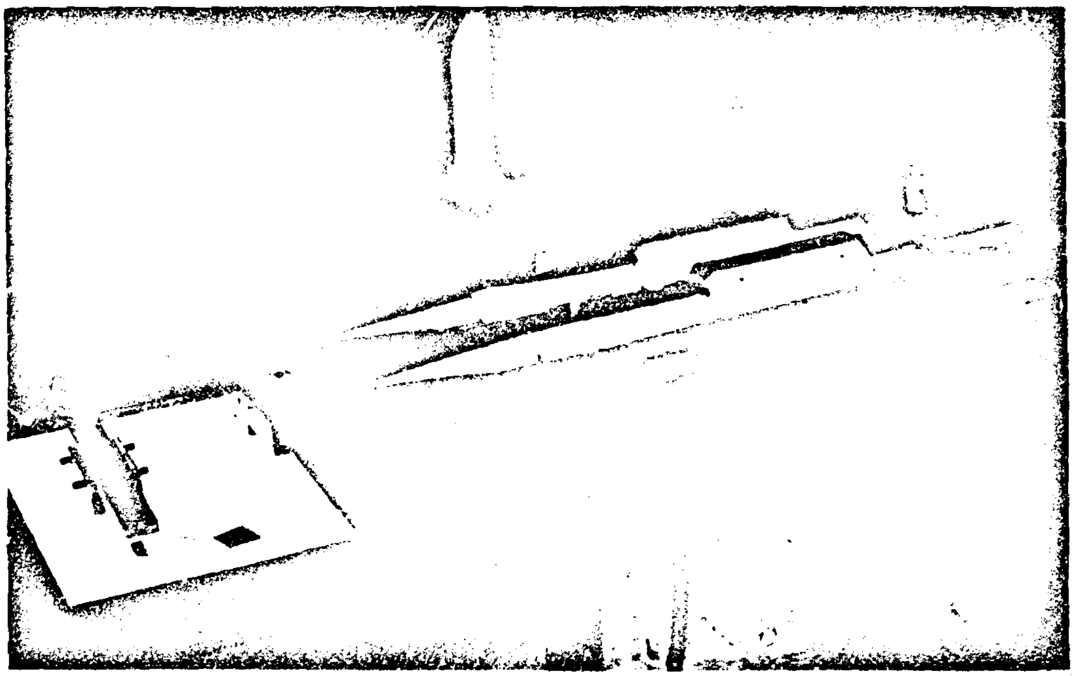

Figure 1

MODIFIED ULTRASONIC FLEXURAL-BEAM AND
CHANNEL ASSEMBLY WITH TWO 15-KILOHERTZ
TRANSDUCERS AND COUPLING ASSEMBLIES ATTACHED

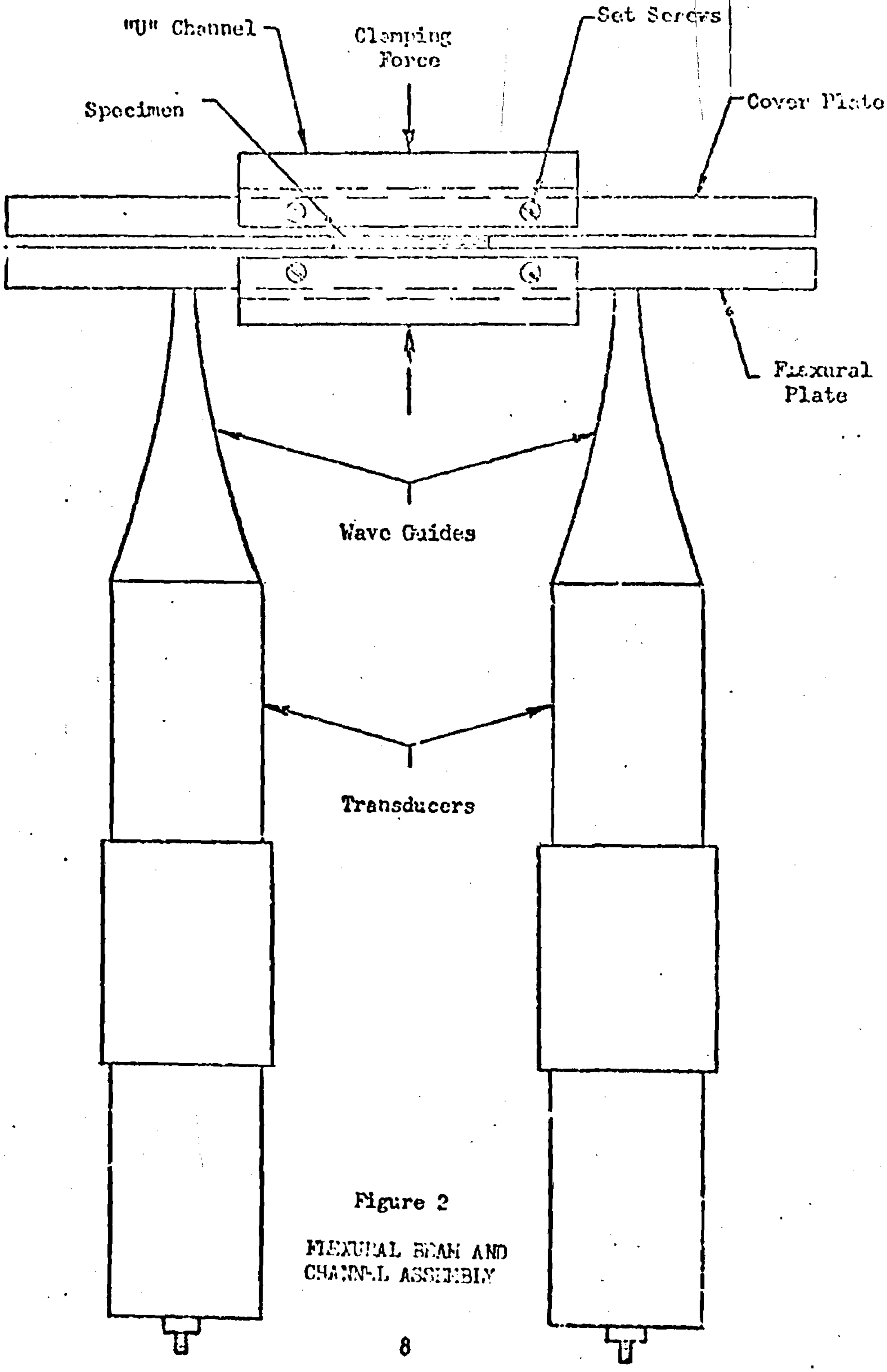

Figure 2

FLEXURAL BEAM AND
CHANNEL ASSEMBLY

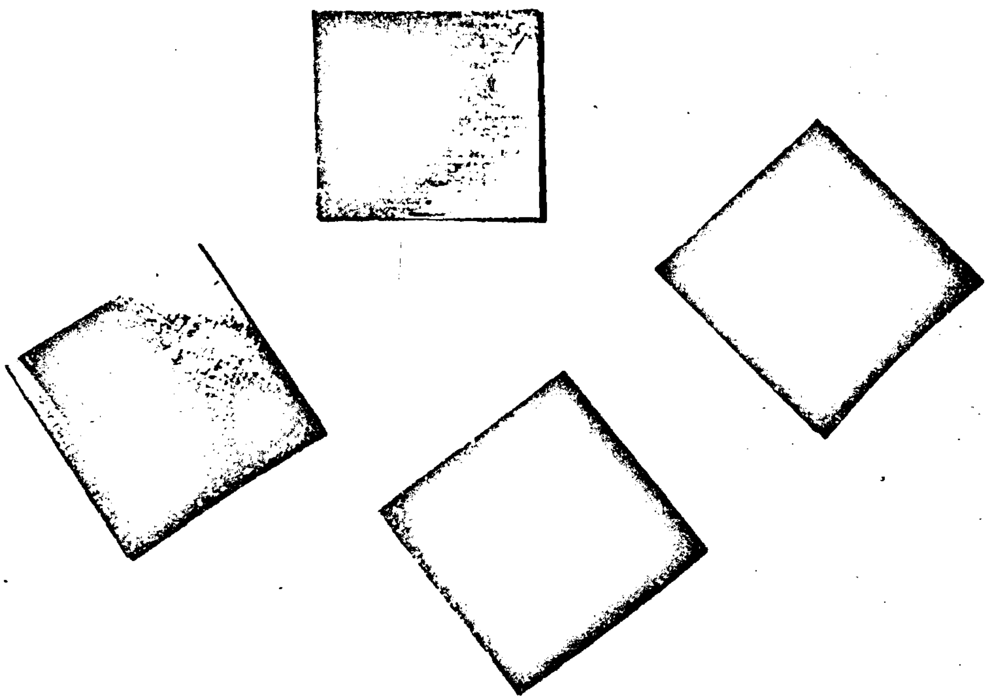

Figure 3

TYPICAL SURFACES OF TEST SHEETS OF
1 x 1 x 0.005-INCH ALUMINUM SHOWING SURFACE ABRASION
AFTER EXPOSURE IN MODIFIED FLEXURAL-BEAM DIFFUSION BONDING SYSTEM

It therefore appeared that adequate vibratory displacements could be obtained within the stack of laminations, but that substantially higher clamping forces (pressures) were required. A more rugged flexural-beam apparatus was fabricated, involving a beam of larger cross section and heavier support channels to enable testing at higher clamping pressures (up to approximately 3000 psi).

Subsequent observations of the modified equipment indicated that skidding was reduced as expected by the application of higher clamping forces without measurable deformation of the stack. The flexural response of the beam, however, had changed, and indications of vibratory effects on the lamination surfaces were observed only in the region of the beam supports.

IV. FLEXURAL-REED EQUIPMENT TESTING AND EVALUATION

A review was made of the problems encountered in the development of the flexural-beam diffusion bonding system and the clamping force sensitivity problems observed in the operational model, as described above. As it appeared doubtful that the development problems could be solved in the contractual time remaining, one of the alternate approaches previously considered involving a flexural wedge-reed/coupler (shear mode) ultrasonic system was chosen for development. Flexural wedge-reed/coupler ultrasonic systems are standard components used in ultrasonic spot-type welders, and the adaptation of such a system for diffusion bonding work was straightforward, and is described in section V of this report.

Confirmation of the efficacy of this approach was obtained by conducting room temperature bench tests with 0.005-inch-thick aluminum laminations using a standard wedge-reed type ultrasonic welding system. These tests were similar to those used to evaluate the flexural-beam apparatus. Where the flexural-beam experiments demonstrated non-uniform interfacial (scuffing) effects, the flexural wedge-reed system produced improved interfacial uniformity and adhesion. Thirty plies of 0.005-inch-thick aluminum were lightly "bonded" at room temperature at a clamping pressure of approximately 1000 psi with an ultrasonic pulse duration of 0.6 second. Typical stack samples (1-inch square coupons) are shown in Figure 4. Actual test samples have been forwarded to the Project Officer for examination.

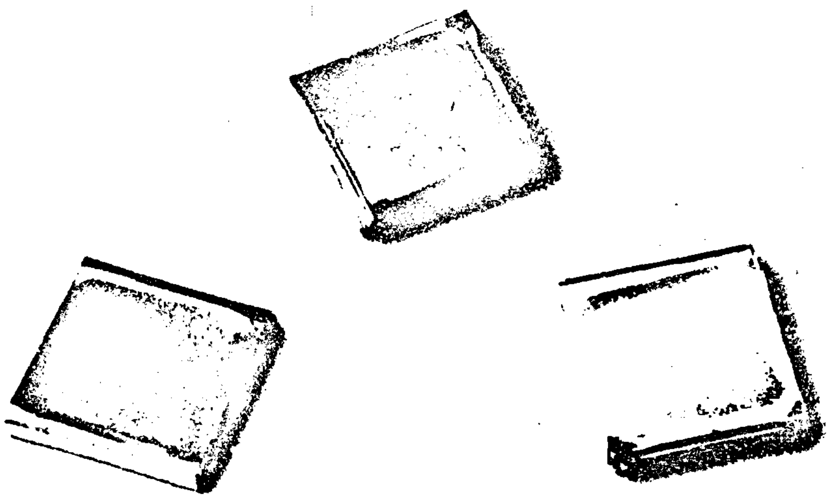

Figure 4

STACKS (30 PLIES, 1 INCH SQUARE) OF 0.005-INCH ALUMINUM LAMINATIONS SHOWING ADHESION OBTAINED WITH FLEXURAL WEDGE-REED ULTRASONIC SYSTEM

V. FLEXURAL WEDGE-REED AND DIFFUSION BONDING CHAMBER DESIGN

A diffusion bonding chamber designed and constructed for a previous ultrasonic diffusion bonding investigation (10) was available for use when the present program was undertaken. It was anticipated that this chamber, with only minor modifications, could be used in this investigation. Initial designs of the ultrasonic flexural-beam system were scaled to ensure that the ultrasonic apparatus could be accommodated within this chamber. The performance difficulties experienced with the first prototype as described in Section III of this report necessitated modifications which enlarged system components and made accommodation within the existing chamber marginal.

When continued testing of the flexural-beam apparatus led to the conclusion to adopt the wedge-reed (shear) ultrasonic system geometry, a larger diffusion bonding chamber was mandatory. A new chamber design was undertaken, and the wedge-reed system and chamber were fabricated and assembled.

Details of the final array are shown in Figures 5 and 6. The wedge-reed system consists of a bar of circular cross section (reed), which contains a nodal flange to which a solid ultrasonic wave guide (wedge) is attached. The ultrasonic transducer drives the wedge in longitudinal vibration. These vibrations are induced into the reed as flexural vibrations. One end of the reed is rigidly supported by a mass. The free end of the reed thus undergoes essentially lateral vibrations in a plane parallel to the stacked laminations. Pressure is applied to the workpieces by a spring-loaded contra-resonant anvil mass on a movable wayslide. Details of the anvil system are shown in Figure 5.

Modifications to the standard wedge-reed ultrasonic welding system were required in order to use the system in elevated temperature and vacuum conditions. The transducer, mounted to the wedge by a force-insensitive mounting sleeve, is sealed with O-rings to a heavy baseplate. The reed is rifle-drilled to allow for the passage of cooling water to provide a controlled ambient temperature for the ultrasonic system. This was done in order to ensure the integrity of the silver-brazed wedge-reed joint and to prevent changing of the acoustic properties of the reed due to temperature changes. The size of the diffusion bonding chamber, which was dictated by the dimensions of available bell jars, necessitated shortening of the ultrasonic reed. After being shortened, the reed was acoustically trimmed. A thermocouple is attached to the surface of the reed in the vicinity of the wedge-reed joint to monitor reed temperature during operation.

The tips of the reed and anvil stem are screw-attached and are replaceable. An induction heating coil surrounds the workpiece and tips to provide the requisite heating for the bonding studies.

The entire apparatus is enclosed in a glass bell jar as shown in Figure 6. The overall equipment array is shown in Figure 7.

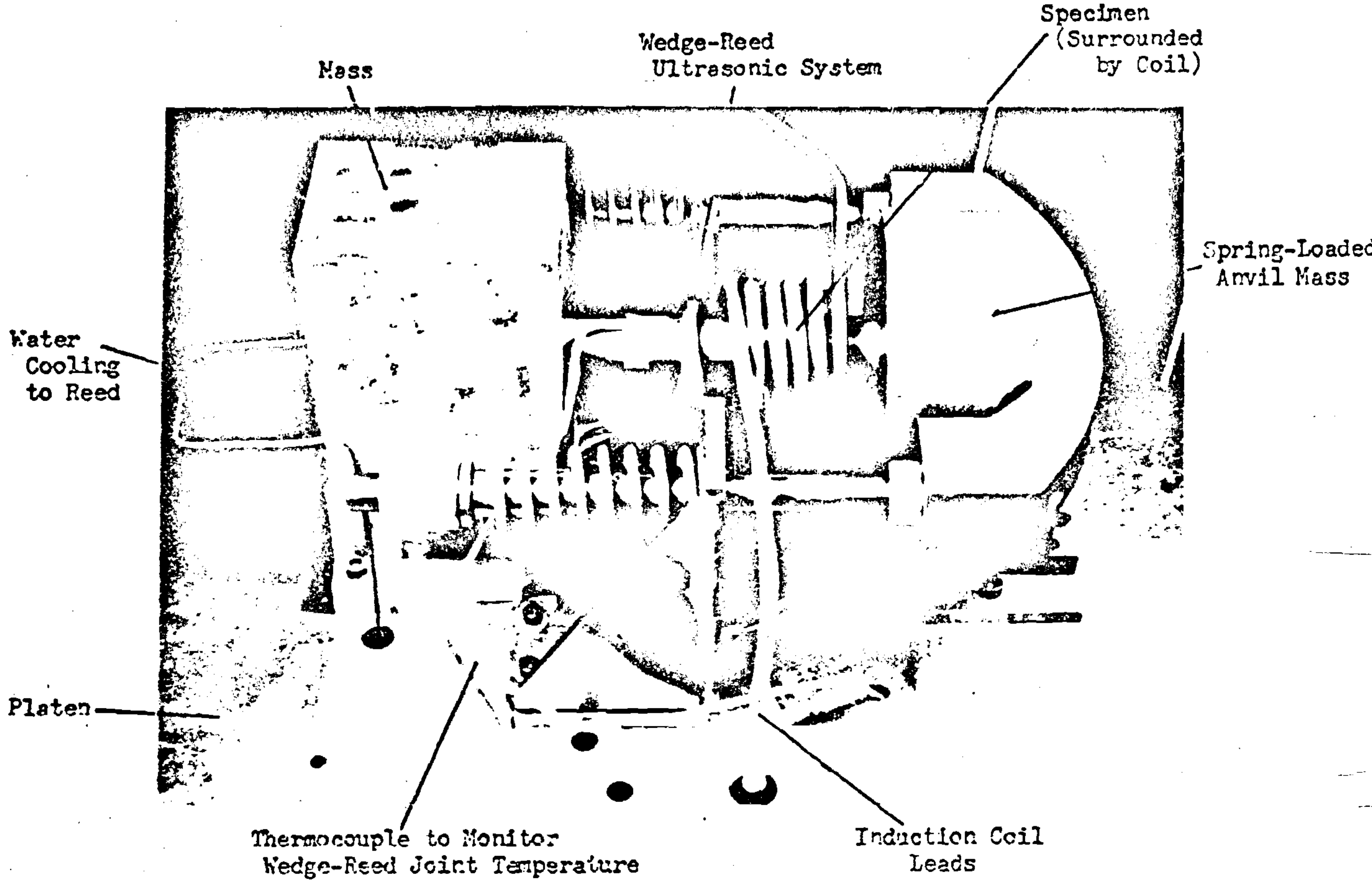

Figure 5

EXPERIMENTAL FLEXURAL WEDGE-REED
ULTRASONIC DIFFUSION BONDING APPARATUS

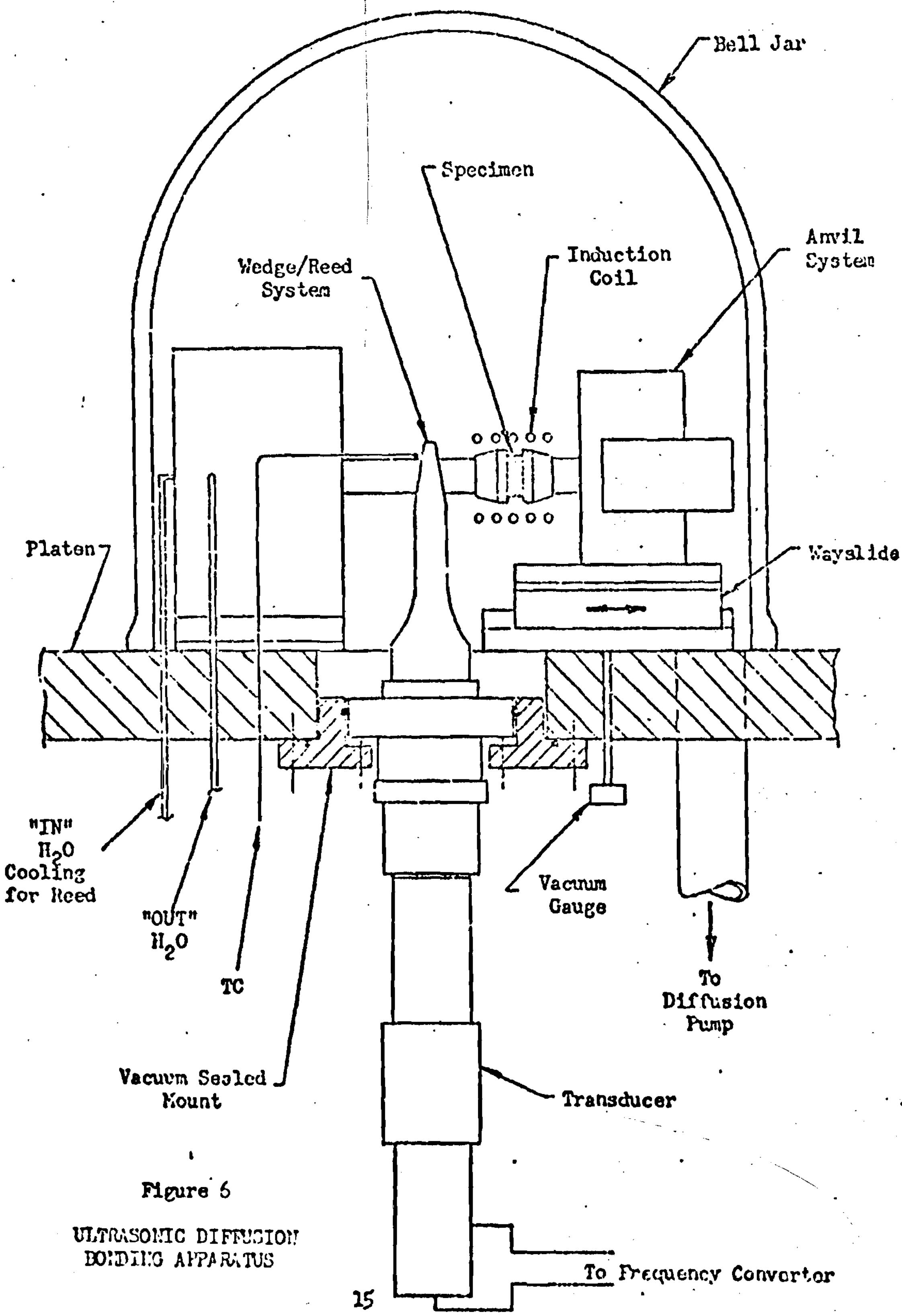

Figure 6

ULTRASONIC DIFFUSION BONDING APPARATUS

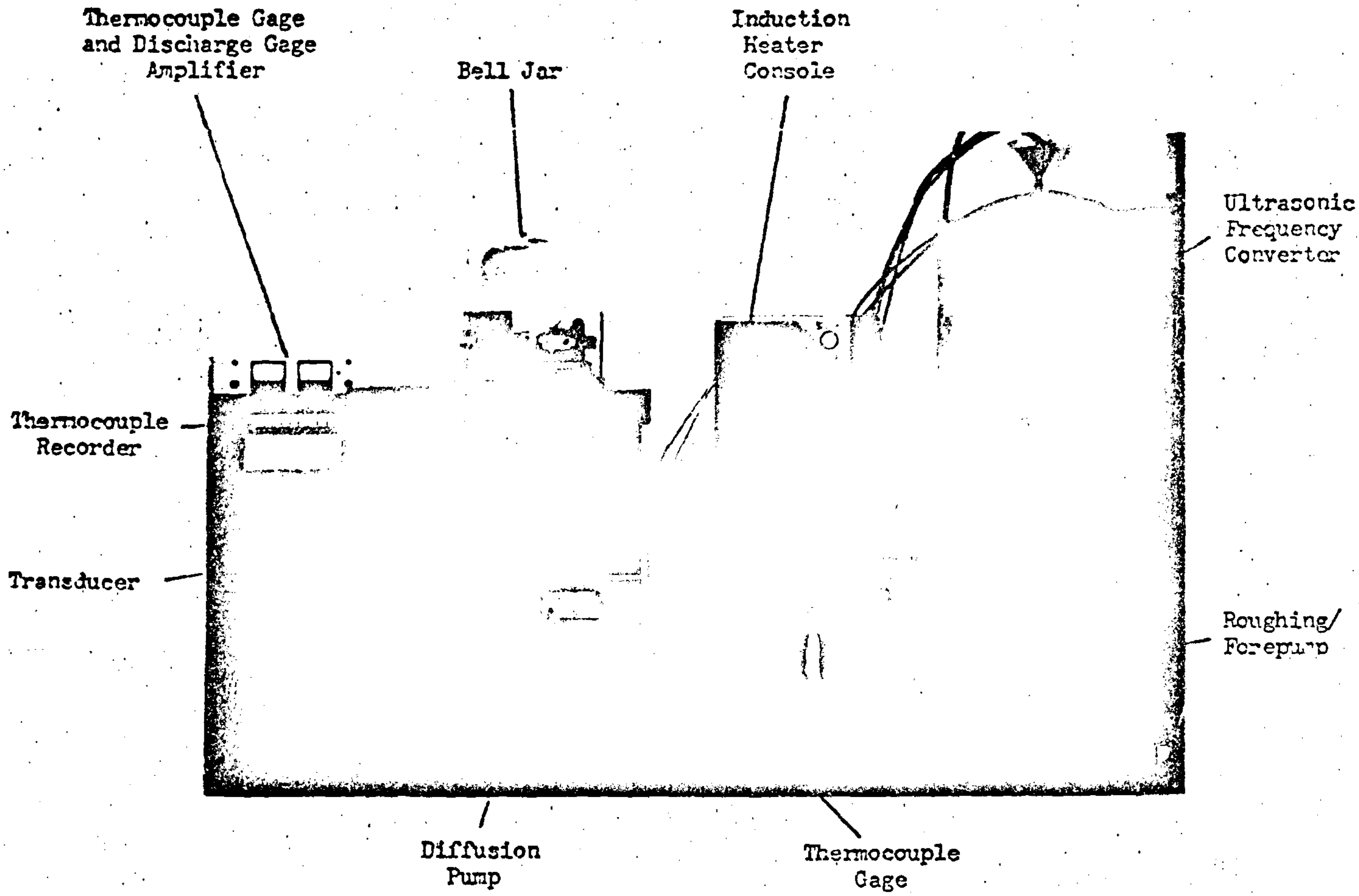

Figure 7

FINAL ARRAY OF ULTRASONIC DIFFUSION BONDING EQUIPMENT

The diffusion bonding apparatus allows experiments to be conducted in a vacuum (10^{-4} to 10^{-5} torr) at selected temperatures and bonding pressures with ultrasonic power inputs ranging from 0 to 2000 watts. Vacuum readout is provided by thermocouple and discharge gauges, and bonding temperature is recorded by a multipoint strip-chart recorder. Although a direct bonding pressure readout is not provided, calibration of the springs with suitable temperature compensation provide adequate control of the amount of pressure applied to the workpiece.

VI. CONCLUSIONS AND RECOMMENDATIONS

On the basis of the positive results of the bench tests performed with the ultrasonic flexural wedge-reed/coupler bonding system on the stacks of 0.005-inch-thick aluminum, it can be concluded that this equipment array represents a complete and functional bench model of an ultrasonic diffusion bonding system. This system is capable of subjecting simulated and/or actual laminated fluidic control devices to varying amounts of clamping pressure, ultrasonic power, and heat in a controlled atmosphere or vacuum.

It is strongly recommended that the work of this program be extended to confirm the initial results and to provide comprehensive data on ultrasonic diffusion bonding parameters for laminated titanium fluidic control devices.

Specific areas that require further study include the following:

a. Determination of bonding time and temperature dependence on ultrasonic energy input level and duration.

b. Determination of pressures required under conditions of good contact and impression.

c. Establishment of minimum diffusion bonding parameters for the ultrasonically assisted diffusion bonding of selected laminated fluidic control devices.

LITERATURE CITED

1. Metcalfe, A. G., "Modern Diffusion Bonding Meets Space Age Needs." SAE Journal, April 1964, p. 53-57.

2. Carriere, S. H. and R. V. Wolf, "Solid Phase Welding of Nodular Iron to Low Carbon Steel." Welding Journal, Vol. 44, September 1965, p. 398s-401s.

3. Blaha, F., B. Langenecker, and D. Oelschlagel, "Zum plastischen Verhalten von Metallen unter Schalleinwirkung." Zeitschrift fur Metallkunde, Vol. 51, 1960, p. 636-638.

4. Al'ftan, E. A., "Ultrasonic Treatment of Solid Metals and Alloys for Accelerated Diffusional and Diffusionless Processes." Nauchnye Doklady Vysshei Shkoly, Metallurgiya, No. 1, 1959, p. 19-24.

5. Tarpley, W. B. and H. Kartluke, "Ultrasonic Hot Pressing of Metals and Ceramics." NYO-10007, Aeroprojects Incorporated, AEC Contract AT(30-1)-1836, December 1961.

6. Jones, J. B., N. Maropis, J. G. Thomas, and D. Bancroft, "Fundamentals of Ultrasonic Welding, Phase I." Research Report 59-105, Aeroprojects Incorporated, Navy Contract NOas-108-c, May 1959; Phase II, Research Report 60-91, Navy Contract NOas 59-6070-c, December 1960.

7. Rhines, F. N., "Study of Changes Occurring in Metal Structure During Ultrasonic Welding." Summary Report TP 82-162, Metallurgical Research Laboratory, University of Florida, Gainesville, Florida, April 1962.

8. Personal Communication, H. L. McKaig of Aeroprojects Incorporated with Bell Telephone Laboratories, Murray Hill, New Jersey.

9. Jones, J. B. and E. E. Weismantel, "Ultrasonic Welding of Structural Aluminum Alloys." Research Report 57-13, Aeroprojects Incorporated, Navy Contract NOas 56-161-c, January 1957.

10. Thomas, J. G., "Ultrasonically Accelerated Diffusion Bonding of Beryllium." Research Report 71-22, Aeroprojects Incorporated, Navy Contract N00156-70-C-1513, July 1971.

11. Gerken, J. M. and W. A. Owczarski, A Review of Diffusion Welding, Welding Research Council Bulletin 109, October 1965.