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CHARACTERIZATION OF THE THERMOSONIC WIRE BONDING TECHNIQUE

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ABSTRACT

This study was designed to evaluate the combination of ultrasonic energy and thermocompression techniques, i.e., thermosonic bonding, with regard to the bond response of thin film substrate metallization and thick film discrete component terminations. The object was to determine not only the quality of thermosonic gold wire bonds and the performance of these bonds when subjected to thermal environmental tests, but also to determine the process control parameters necessary to produce repeatable, reliable bonds. Comparison was made throughout the study with regard to results previously achieved on the same metallization systems using standard fine wire thermocompression bonding techniques.

It was concluded that the thermosonic wire bonding technique offered the advantages of lower bonding forces and lower substrate temperatures compared to the thermocompression process. In addition, it was determined that the thermosonic technique eliminates the need for special pre-bond etching and cleaning procedures presently used in production of Sandia hybrid microcircuits. Finally, a wide latitude in bonding parameters was realized with the thermosonic technique, and this was considered advantageous compared to the rigid process controls necessary for thermocompression bonding.

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INTRODUCTION

Solid phase bonding of metals involves the adhesion of contacting surfaces at temperatures below their melting points.[1,2] The interrelated variables of this process include the utilization of force - to promote plastic flow and intimate contact, elevated temperature - to promote contaminant dispersal while lowering flow stress and enhancing diffusion, and time - to promote solid state diffusion in the bond zone. The effects of these variables on the strengths of solid-phase bonds were reported by Bowden and Tabor,[3] Buckley,[4] Coucoulas,[5] Cuthrell and Tipping,[6] Faro and Vine,[7] and others. The enhancement of bonding as a result of lateral loading or wiping motion was reported by Bowden and Tabor,[3] by Coucoulas,[5] by Cuthrell and Tipping,[6] and by Faro and Vine.[7]

Thermosonic, or hot work ultrasonic, bonding employs the variables of thermocompression bonding (i.e., force, temperature, and time), and in addition introduces vibratory motion of one surface against the other. While hot work ultrasonic bonding is less well understood than other techniques, it is thought that the scrubbing motion promotes bonding by the mechanical displacement of surface contaminants and by the plastic deformation of surface asperities.[1,2,5,8] Thus this approach offers the potential advantage of increased intimate contact area without the gross heating and higher normal forces encountered in standard thermocompression bonding.[5,6,7,8]

A feasibility study was conducted at Sandia Laboratories to determine the gold wire bonding capabilities of the K&S 472Q thermosonic bonder to produce wire bonds on discrete components which previously had been considered "unbondable" by conventional thermocompression techniques without benefit of special surface cleaning.[9] Through the brief feasibility study, it was demonstrated that the thermosonic process was capable of producing wire bonds on the component metallized surfaces without requiring special cleaning procedures.

The present study was designed to further evaluate the contribution of the thermosonic technique to solid phase bonds on both thin film metallized substrates and thick film metallized component terminations.[10] This report discusses the materials and equipment utilized, the characterization of bond parameters as well as the development of bond envelopes, and the evaluation of as bonded as well as environmentally tested bonds.

EXPERIMENTAL

Materials

This study involved the thermosonic bonding of pure gold wire to thin film metallization and to thick film terminations on commercial discrete components. All components utilized for the study were mounted onto substrates with Ablestik 517 glass supported film adhesive. The specific materials which were used during the evaluation are described below.

A. Metallized Substrates. The Sandia Laboratories thin film technology employs a composite metallization of tantalum nitride, chromium, and gold films.[11] During resistor stabilization processing (300°C for 2 hours) the chromium migrates to the surface of the gold film with resultant decreased bondability when using the thermocompression wire bonding technique. Bondability can be improved or enhanced through the use of a surface etching technique to remove chromium oxide.[12]

For this study the substrates were processed at the resistor stabilization temperature. However, the surface etching process to remove contamination was not used. This eliminated a process step and, in addition, made possible a simple comparison between the thermosonic and thermocompression bonding processes.

B. Gold Wire. The gold wire used was 0.025 mm (0.001 inch) in diameter and had a purity of 99.99%. The breaking strength of the wire before bonding was approximately 10 grams with an elongation of 3 to 6%.

C. Discrete Components. The metallization for terminations on discrete components and other devices used included thick film gold, thick film platinum-gold, thick film palladium-silver, gold plated Kovar tabs, and aluminum on integrated circuits. These components included capacitors, resistors, thermistors, and integrated circuits, and were identical to those considered in the original bonding feasibility study.[9]

Equipment and Operations

The Kulicke and Soffa tailless thermosonic gold wire bonder, Model 472Q, was used exclusively for these bonding experiments. This bonder utilizes a heated substrate holder which is capable of providing temperatures variable from 25°C to 600°C. An unheated capillary bonding tool was directly attached to an ultrasonic horn to which the vibratory energy was furnished by a dual 10 watt ultrasonic generator (Uthe).

As shown schematically in Figure 1, the equipment for the system includes an electronic oscillator (60 KHz), a transducer, a velocity coupling system (horn), the bonding tool, and the heated substrate holder. The Uthe system employs a piezoelectric type of transducer to convert the electrical energy into vibratory motion to the bonding tip, thence to the work piece. The bonding system provides a dual clamping force to the materials which are being bonded.

The capability of the K&S 472Q to supply individual adjustments for the bond clamping force at both the first (ball) and second (tailless) bond represents an improvement, over similar bonding machines. Another significant improvement is that the bonding tool height can be adjusted to a maximum of 8.9 mm to accommodate variable height components.

For this study the search height was set at 2 to 3 wire diameters (i.e., .05 to .075 mm) for both the first and second bonds. This adjustment in height is

required to position or align the bond tool directly over the part or pad to be bonded. It was essential that tool and search height be maintained precisely at the set level to preserve uniformity of ball size and bond deformation. Figure 2 depicts a typical thermosonic ball bond and tailless wedge bond which might be obtained with a Microswiss profile 70 tailless bonding tool.

Thermosonic Bonding Parameters

The principle parameters for thermosonic bonding include ultrasonic power, ultrasonic bond time (dwell), bond forces, and substrate heating. Although other factors, such as generator frequency response, have to be considered, reliable bonds can generally be produced over a wide range of the established parameters. These ranges are shown in the bond schedule development section of this report.

Characterization of the bonding parameters for this study is discussed below. Figure 3 shows views of the bonding equipment and a close-up of the heated substrate holder.

A. Substrate Temperature. A BLH miniature Pt/Rh thermocouple, connected to a digital readout temperature indicator, was used to determine the temperature of the substrate holder. Temperatures were measured at six points over a 50 mm^2 area, and at 50°C increments to 550°C. Temperature measurements at the top surface of a metallized ceramic substrate were found to be stable to less than ± 6°C.

B. Bond Force. A Haldex force gauge was found to be sufficiently accurate for measurements of the clamping force. First bond forces ranged from 15 grams to 90 grams, and the second bond forces ranged from a minimum of 45 grams to 135 grams.

C. Bond Time (dwell) and Bonding Power (Amplitude). A magnetic pickup and an oscilloscope were used to calibrate time width (with relative dial setting on the power supply) and the ultrasonic power amplitude and frequency to insure that these

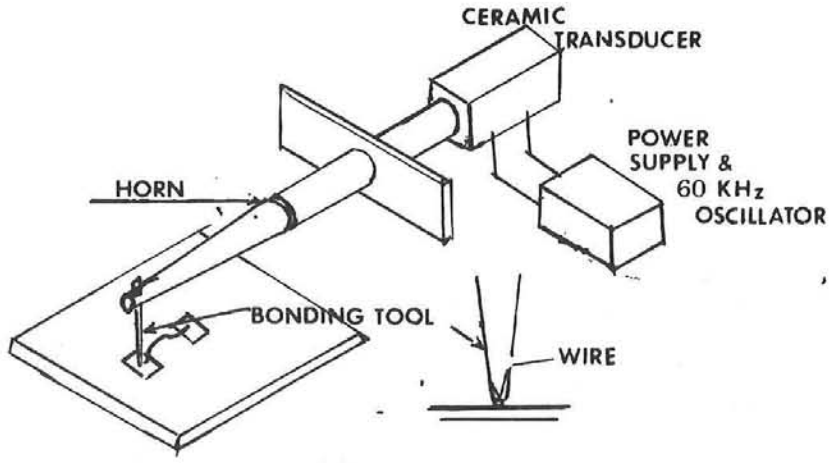


Figure 1. Ultrasonic Bonding Basic Set-Up. The signal from the ultrasonic power supply develops a mechanical movement which is transmitted along the tuned horn through the bonding tool and to the work piece.

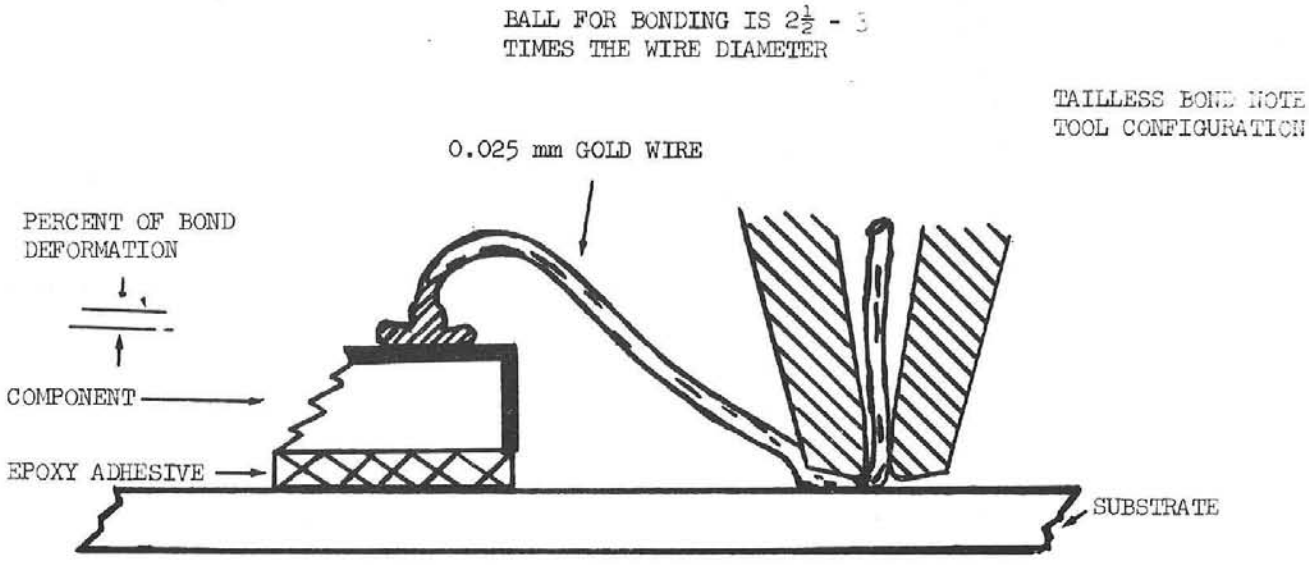
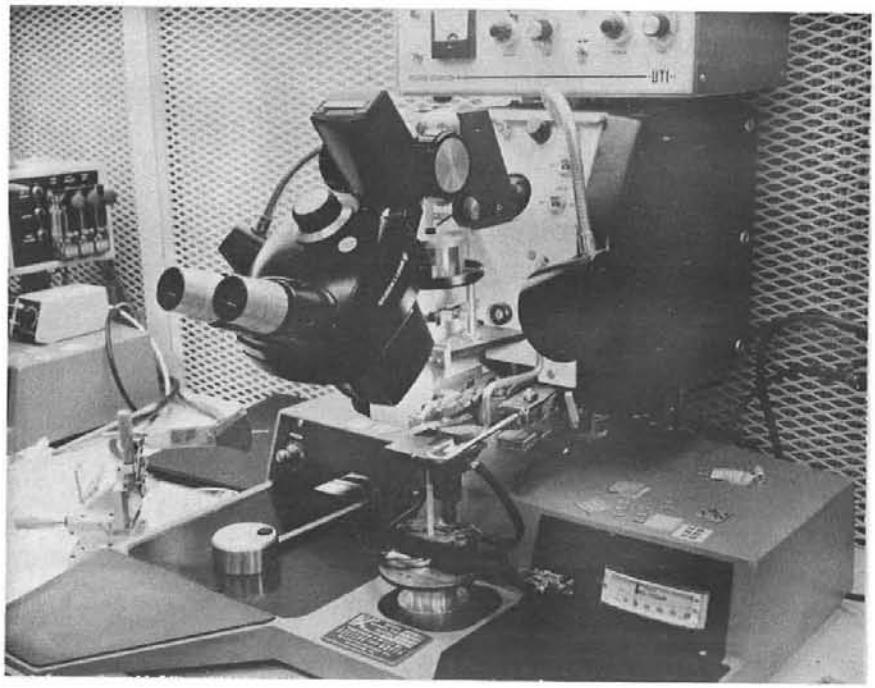


Figure 2. Thermosonic Ball Bond and Tailless Bond with Type 70 Profile Bond Tool.



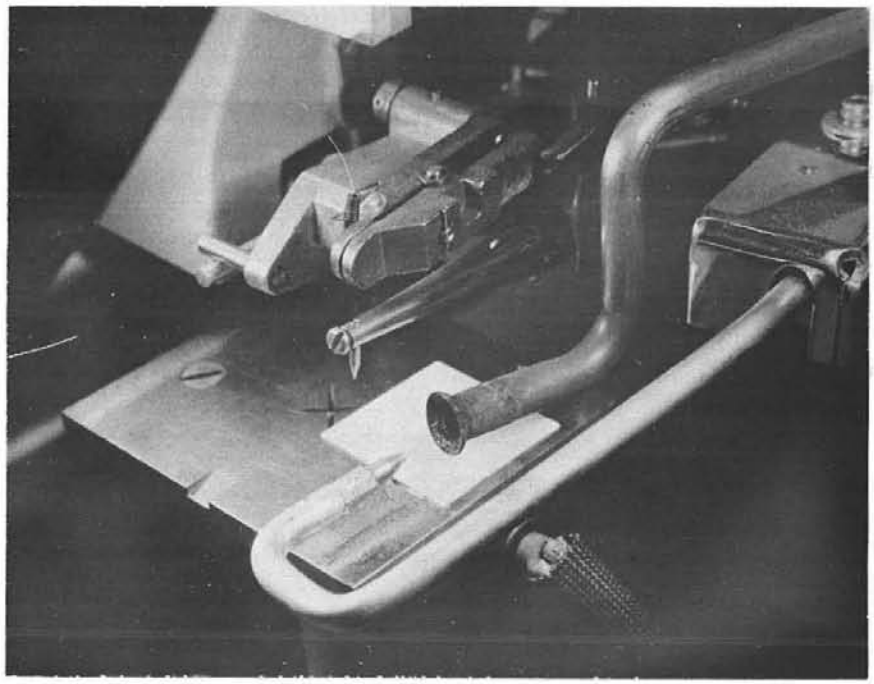


Figure 3. Wire Bonding Equipment. Bottom view - close up of bonding capillary and ball forming flame-off tool. Capillary is attached to the ultrasonic horn.

settings were consistent. Additionally, these calibration steps were repeated after replacement of bond tools and other machine adjustments. The ultrasonic generator frequency was checked for resonance periodically, with only minor shifts in frequency observed at the various test intervals.

D. Bond Tools. Bonding tools used for this thermosonic bond evaluation included a titanium carbide capillary, a quartic capillary, and a ceramic capillary. Although the bond tool material and configuration are generally considered bond parameter variables, this evaluation showed that the three bonding capillaries produced bonds of identical appearance with little or no difference in the strength. Bond settings were basically the same for all three of these capillaries.

Bond Schedule Development

The data obtained from previous investigations of the thermosonic process indicated the feasibility of producing bonds of good quality to discrete components and to metallized substrates.[13,14] Preliminary bond parameters derived from these previous studies were as follows:

1st. Bond (ball)	Bond Force $\geq$ 50 grams
2nd. Bond (tailless)	Bond Force $\leq$ 115 grams
Substrate Temperature	100°C
Ultrasonic Energy (both bonds)	$<$ 1.0 watt

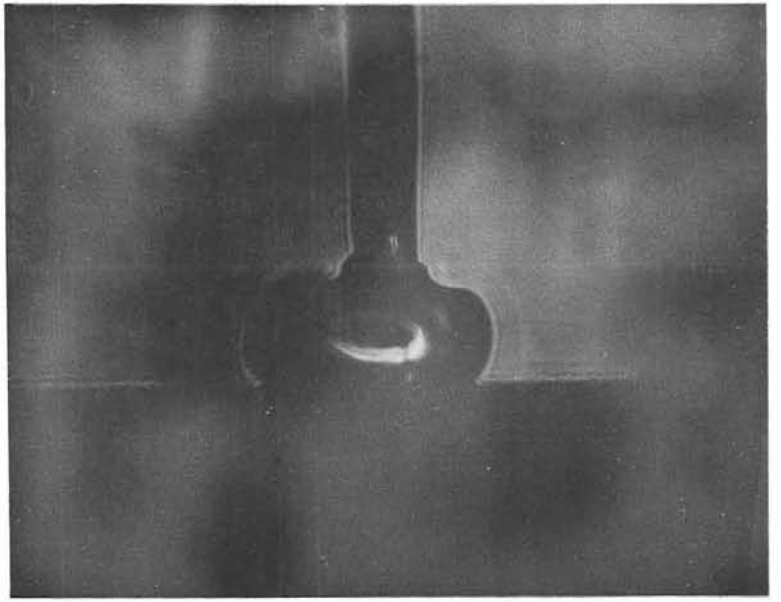
Subsequently, to initiate a full range bond schedule for this evaluation, it was necessary to arbitrarily choose a bond force known to produce acceptable bonds. From the preliminary bond force figures shown above, the settings chosen were 55 grams for the 1st bond and 95 grams for the 2nd bond. These high bond forces provided the necessary clamping force between the bond tool and the workpiece, i.e., the gold wire and metallization, to compensate for external vibratory movements

which could affect the ultrasonic energy at the bond tool surface. Additional criteria for the bond schedule included the following:

1. Ball size was maintained at approximately 2-1/2 times the wire diameter (0.06 mm). The ball bond deformation ranged from 50 to 60% of the ball size.
2. Bonds were made to metallized terminated ends on discrete components, and to metallized substrates. These included ball bonds to the tabs and tailless wedge bonds to the substrates.
3. The substrate heat was maintained at 100°C.

Utilizing the above as non-variable parameters, an initial attempt to optimize a bond schedule was made by independently varying the ultrasonic power and time settings. Figure 4 illustrates the deformation in the ball bond at various power settings; 4.c. is representative of an acceptable ball bond of approximately 50% deformation (note also the tailless bond profile).

Figure 5 presents the strength plots for both ball and tailless bonds which were obtained over the range of settings. Only two ultrasonic power settings (0.025 watt and 0.150 watt) are shown for each time. The bond dwell time setting was varied from two through seven on the power supply dial (equivalent to 0.020 milliseconds through 0.210 milliseconds). From the tailless bond plot in this figure, it is significant that an increase in the power level improves the bond strength at the minimum setting for bond dwell time (dial set at 2). At the minimum time and minimum power (0.025 watt) many tailless bond lifts from the substrate metallization were observed. Tailless bond strength at the 0.025 watt level was significantly lower because of the inability to obtain consistent bond deformation at this setting. Figure 6 shows the difference in deformation for the tailless bonds at the minimum and maximum power settings.



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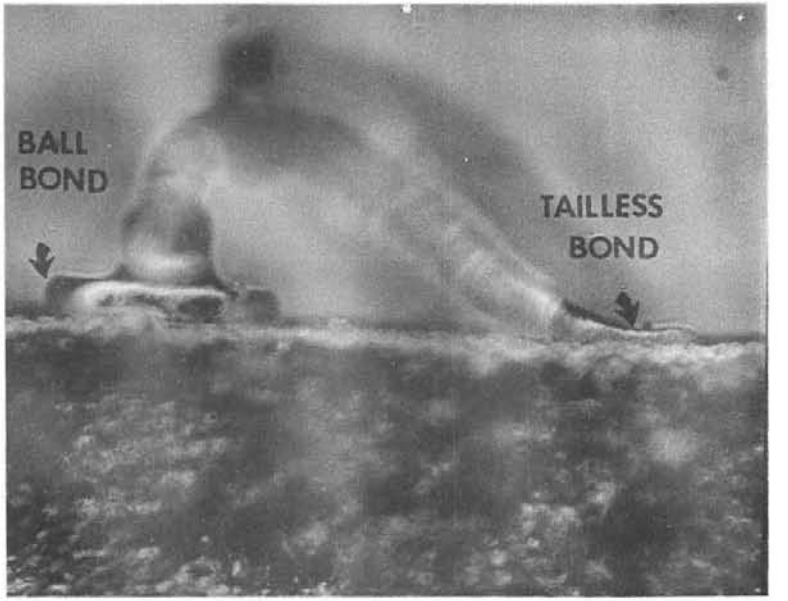

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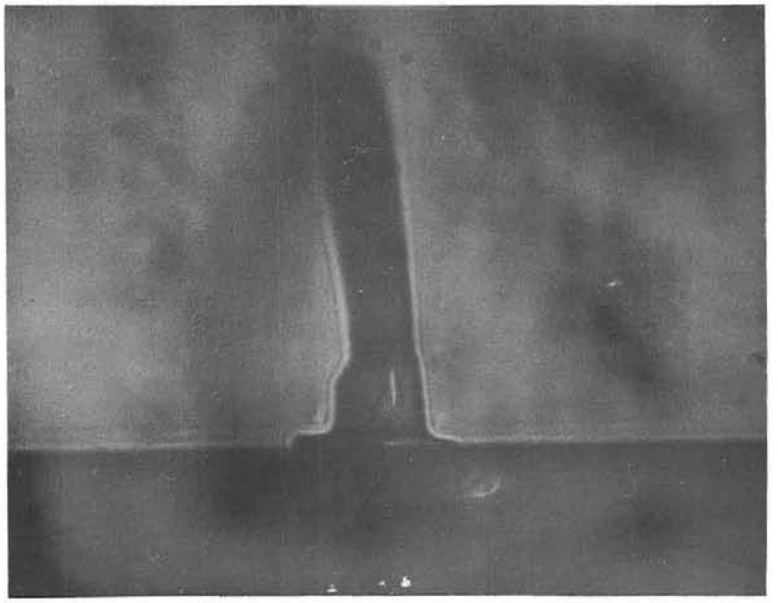


B

Figure 4. Ball Bonds. These were bonded at various power settings and illustrate varying deformation.

Bond No. A indicates a need for an increase in energy level.

Bond No. B. Excessive deformation.

Bond No. C shows acceptable ball and tailless bond made at the optimized parameters.

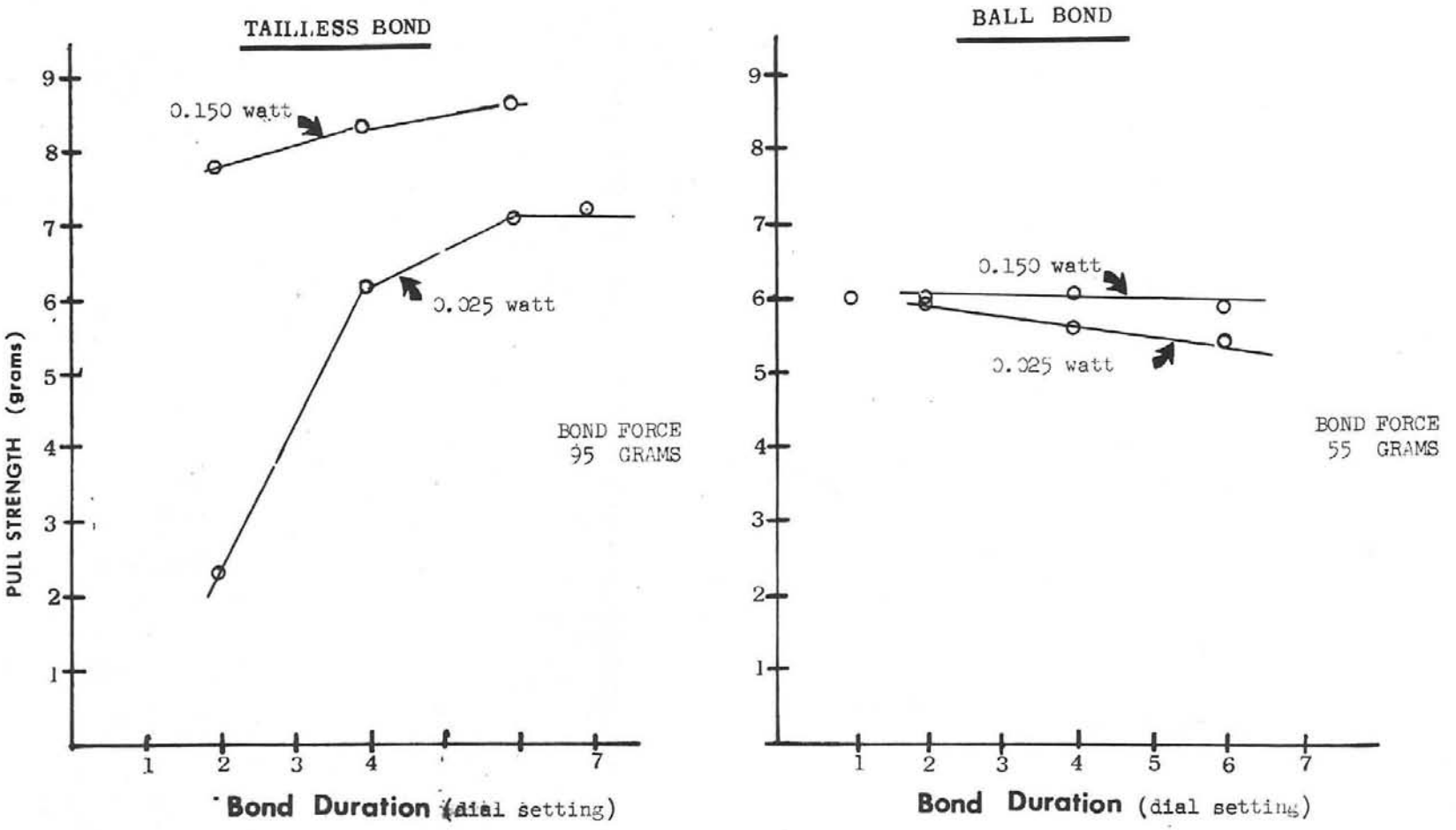


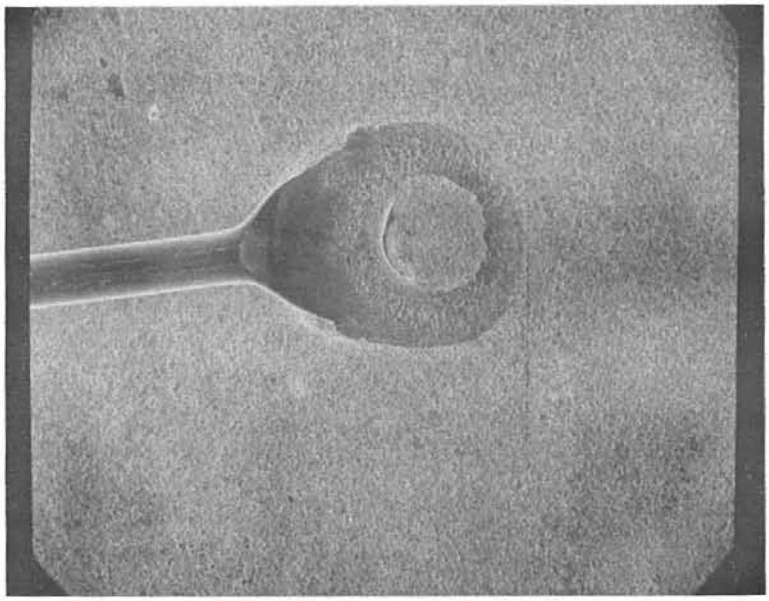
Figure 5. Power and time settings varied with the respective bond forces held at constant level of 55 grams and 90 grams. Bond made to Cr-Au metallized substrates and discrete components.

At the 0.150 watt power setting the majority of failures (95%) were recorded as wire fractures, with some failures resulting from heel fractures. However, the strengths of these heel fractures were as high as the tensile pull strengths of the gold wire. As shown in Figure 5, the tailless bond pull strength was approximately 2 grams higher than the ball bond pull strength. Since a hydrogen flame-off is required to form the ball, the gold wire is annealed at this point, resulting in a decrease in tensile strength at the immediate neck area of the ball.

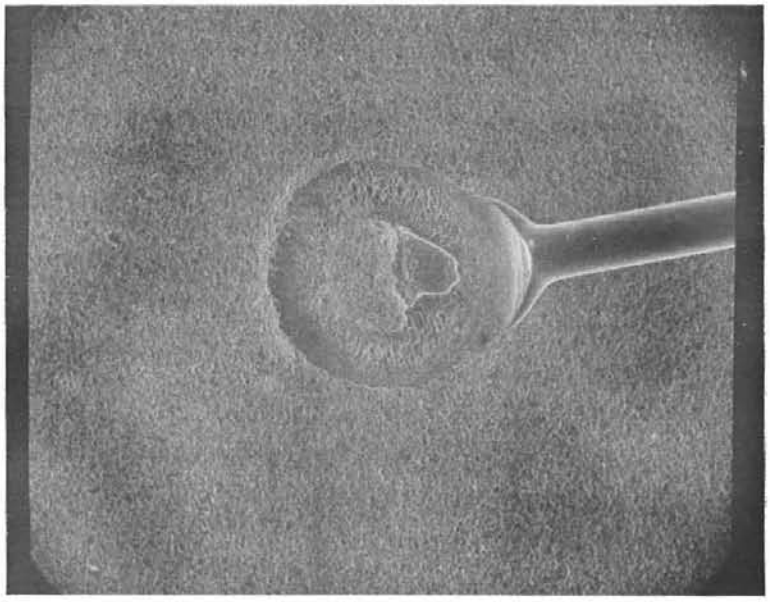
As a result of the bond schedule development, the parameters for both the tailless bond and the ball bond appear to fall between the bond duration dial setting range of 2 to 6, with energy levels of 0.025 watt to 0.150 watt (and bond forces remaining at 90 and 55 grams respectively). From Figure 5, the optimum schedule for each bond was determined to be an ultrasonic power setting of 0.100 watt and a bond duration dial setting of 3-1/2. These parameter points were reasonably situated to allow for normal power and time variations of the power supply.

Next, with the ultrasonic power set at 0.100 watt and the bond duration dial setting at 3-1/2 (approximately 100 milliseconds), the bond clamping force was varied over the range of 15 to 135 grams. The response of both ball bonds and tailless bonds to this range of clamping forces is shown in Figure 7. This range represents the minimum and maximum force capabilities of the bonder.

The apparently optimum points for the bond forces, 60 grams first bond and 90 grams second bond (stars on Figure 7), substantiate the closeness of the bond forces which were arbitrarily chosen to optimize the power and duration parameters. The bonding parameter settings derived from the bond strength plots in Figures 5 and 7 were utilized to bond all subsequent test samples.



Minimum Power Setting Levels



Maximum Power Setting Level

Figure 6. Tailless Wedge Bonds At Different Power Setting Levels

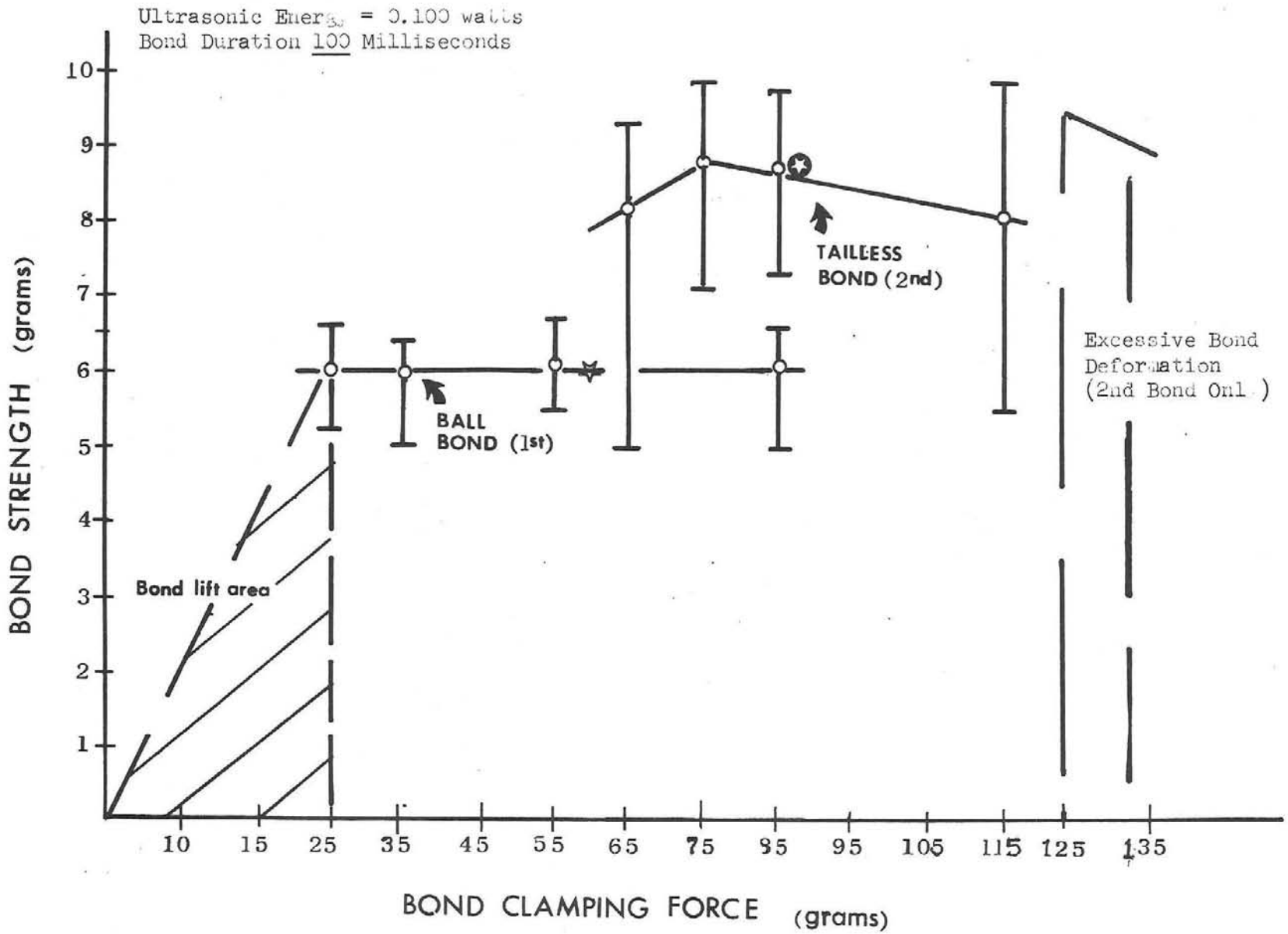


Figure 7. Optimizing Bond Force by Maintaining the Ultrasonic Energy and Bond Duration Constatn As Shown.

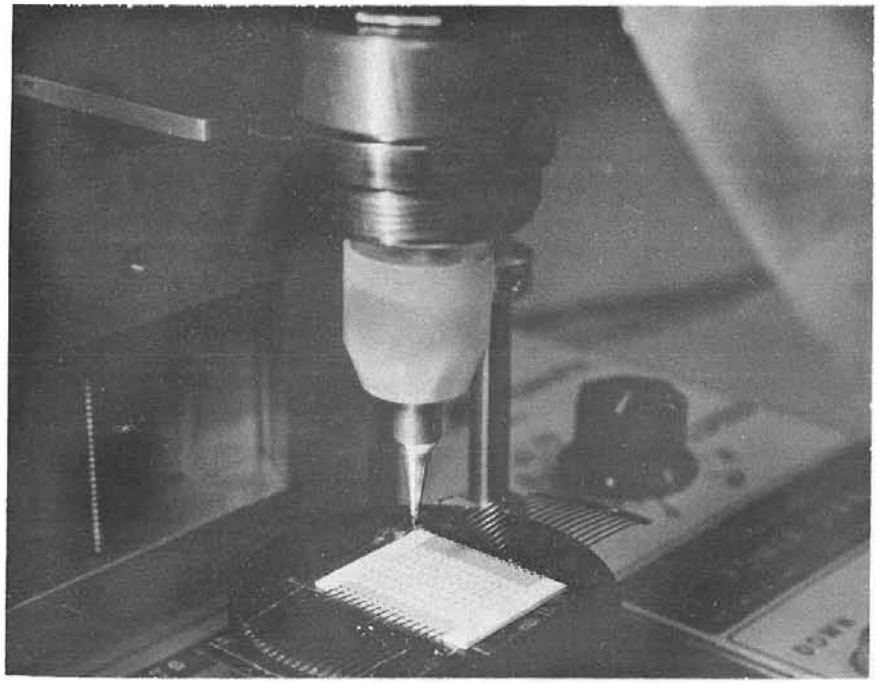
Bond Evaluation

The discrete components and metallized substrates previously mentioned were all used for bondability testing and verification of the bond schedules. Bonds were made to these components as received from the manufacturer.

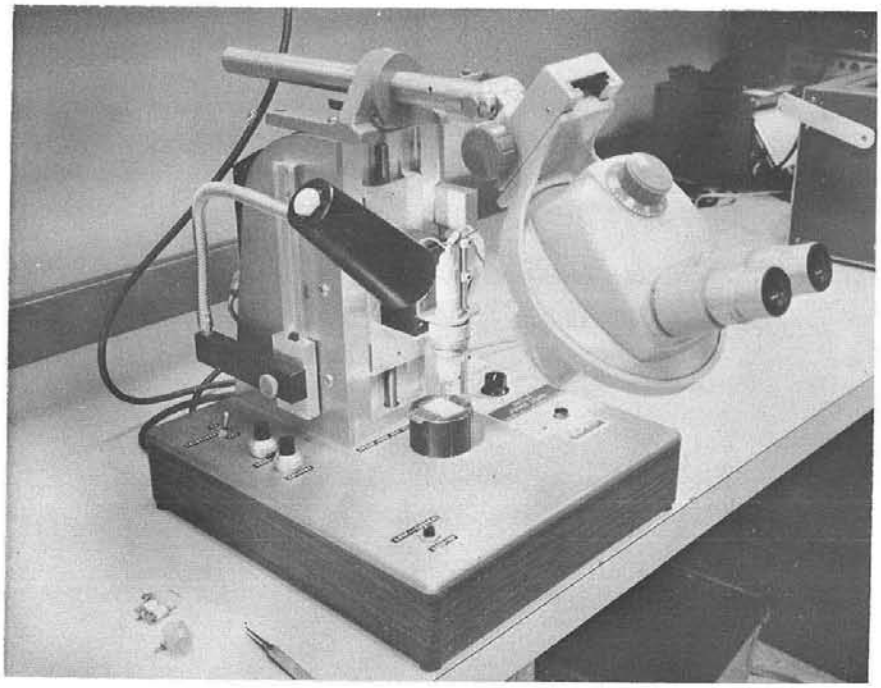
Bonds were destructively pull tested at 90° to determine the bond strength. The failure mode criterion was based solely on wire fractures, and lift offs and bond misses were not permitted within the previously identified optimized bond schedule. Following bonding, the wires were cut between the ball and tailless bonds so each could be evaluated individually. The free wire end was attached to a loop heater which was coated with polyvinyl acetate to facilitate pulling. The opposite end of the loop heater was connected to a force transducing cell which was coupled to a strip-chart recorder. Figure 8 shows an overall view and a close-up view of the pull testing set up.

In addition to pull testing, ball bonds were also evaluated by a shear test. This was performed by exerting a shearing force on the side of a ball by a finely machined push rod. In order to confirm the previously selected bonding parameters, one metallized substrate, with ball bonds made at four different force levels, was prepared for shear strength testing. With the ultrasonic power and bond duration set at the optimized points of 0.100 watt and 3-1/2, the bonding forces selected were 25, 35, 60, and 85 grams. The force required to shear the ball bonds was directly related to the bonding parameters. The shear strength results are presented in Table I.

The results in Table I show that the maximum shear strength occurred at the 85 gram force level. However, it should be noted that at this force level the bond deformation is greater than at the other levels. Therefore, a large bond area is created which acts to produce a higher shear strength. The next high value for



Close-up View of Strain Gauge Fixturing
On Bond Pull Tester



Bond Tester Used to Destructively
and Non-Destructively Test Wire Bonds

Figure 8. Bond Pull Tester

shear strength occurred at 60 grams bonding force which also resulted in normal bond deformation (i.e., 50 to 60% deformation). These shear strength results provide a favorable comparison with the tensile strength of the ball bonds at each force level as shown in Figure 7, and further confirm the validity of the bonding schedule chosen.

TABLE I

Ball Bond Force Vs. Shear Strength

Bond Force (grams)	Average Shear Strength (Grams)	High Shear (Grams)	Low Shear (Grams)
25	40	56	25
35	73.4	84	54
60	82.9	95	62
85	95.3	112	73

Environmental Tests

Further evaluation of the thermosonic bonds was conducted after subjecting bonds made to the discrete components to various thermal environments. These thermal environments included elevated temperature aging and thermal cycling as listed in Table II.

TABLE II

Thermal Environments for Thermosonic Bond Evaluation

A. Control Group, as bonded, no thermal age

B. 300°C age for two hours

C. 150°C age for 100 hours

D. 150°C age for 850 hours

E. Temperature cycling sequence
(20 cycles at each of three exposures 1, 2, and 3)

Cycles		Temp., °C	Time (Minutes)
Exposure 1	20*		
Step a		-55	10 Min
b		25	5 Max
c		125	10 Min
d		25	5 Max

*One cycle consists of steps a through d

Exposure 2	20		
a		-65	10 Min
b		25	5 Max
c		150	10 Min
d		25	5 Max
Exposure 3	20		
a		-65	10 Min
b		25	5 Max
c		200	10 Min
d		25	5 Max

THERMOSONIC BOND STRENGTHS (90° PULLS) TABLE III

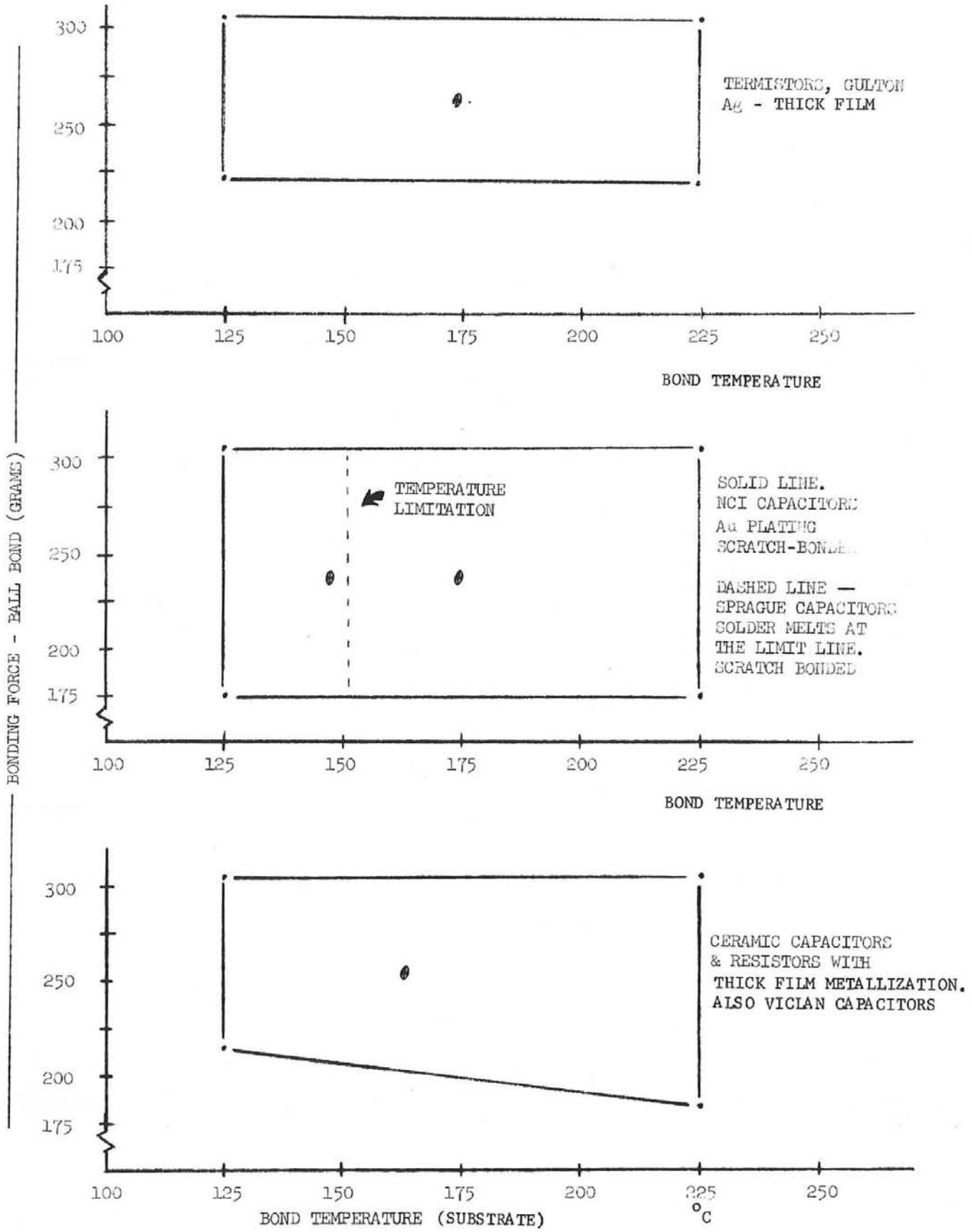
MANUFACTURER	METALLIZATION	BOND TYPE	CONTROL GROUP	AFTER 300°C 2 HRS	150°C 100 HRS	150°C 850 Hrs.	TEMP CYCLE
USCC CAPACITOR, BCN	Au T.F.	Ball	σ = .22 $\bar{x}$ = 6.27		σ = .16 $\bar{x}$ = 6.1	σ = .20 $\bar{x}$ = 6.0	σ = .31 $\bar{x}$ = 5.84
USCC CAPACITOR FH142	Au T.F.	Ball	σ = .41 x = 6.2	σ = .47 $\bar{x}$ = 5.9	σ = .40 $\bar{x}$ = 6.0		
USCC CAPACITOR CAN 3413	Au T.F.	Ball	σ = .37 $\bar{x}$ = 6.0		σ = .42 $\bar{x}$ = 6.3		
ISCC CAPACITOR CAN 7212	Au T.F.	Ball			σ = .42 $\bar{x}$ = 6.0	σ = .34 $\bar{x}$ = 6.2	σ = .27 $\bar{x}$ = 6.0
VICLAN CAPACITOR	Au T.F.	Ball	σ = .39 $\bar{x}$ = 6.1			σ = .35 $\bar{x}$ = 5.8	
NCI TANTALUM BNS206P020K	AuPt NiTAB	Ball	σ = .43 x = 6.05		σ = .38 $\bar{x}$ = 6.19	σ = .31 $\bar{x}$ = 5.4	σ = .37 $\bar{x}$ = 5.7
SPRAGUE TANTALUM SA2243-3	AuPt KoTAB	Ball	σ = .53 $\bar{x}$ = 6.19	σ = .42 $\bar{x}$ = 5.46		σ = .33 $\bar{x}$ = 5.9	σ = .22 $\bar{x}$ = 5.6
GULTON 55F 41 THERMISTORS	Ag T.F.	Ball	σ = .42 $\bar{x}$ = 5.4	σ = .41 $\bar{x}$ = 5.5	σ = .29 $\bar{x}$ = 5.28	σ = .30 $\bar{x}$ = 5.6	
DALE RESISTOR 99-82	Au T.F.	Ball	σ = .56 $\bar{x}$ = 6.23		σ = .34	σ = .34 $\bar{x}$ = 5.5	σ = .35 $\bar{x}$ = 6.0
DALE-RC550-27 RESISTOR	Pd-Ag T.F	Ball	σ = .45 $\bar{x}$ = 6.4			σ = .31 $\bar{x}$ = 5.8	σ = .50 $\bar{x}$ = 6.17
GOLD PLATED KOVAR TAB	Au KoTAB	Ball	σ = .86 $\bar{x}$ = 6.05	σ = .50 $\bar{x}$ = 5.4	σ = .41 $\bar{x}$ = 6.1	σ = .29 $\bar{x}$ = 5.9	σ = .50 $\bar{x}$ = 6.0
I.C.'s Aℓ METAL	Aℓ PAD	Tailless	σ = 1.7 $\bar{x}$ = 7.9		σ = .83 $\bar{x}$ = 8.0	σ = 1.4 $\bar{x}$ = 7.3	σ = .73 $\bar{x}$ = 6.8
SANDIA THIN FILM SUBSTRATE	Cr-Au	Tailless	σ = 1.8 $\bar{x}$ = 7.9	σ = 1.7 $\bar{x}$ = 7.34	σ = .90 $\bar{x}$ = 8.1	σ = 1.2 $\bar{x}$ = 7.9	σ = 1.5 $\bar{x}$ = 7.4
SANDIA THIN FILM SUBSTRATE	Cr-Au	Ball	σ = .33 $\bar{x}$ = 6.32	σ = .39 $\bar{x}$ = 5.72	σ = .25 $\bar{x}$ = 5.8	σ = .28 $\bar{x}$ = 6.1	σ = .20 $\bar{x}$ = 5.9

EXPERIMENTAL RESULTS AND DISCUSSION

The optimized bonding schedule derived from the parametric plots for thermosonic bonding of 0.025 mm gold wire to various discrete components was defined by a bonding power of 0.100 watts, a dwell time of 100 ms, and a substrate temperature of 100°C for both ball and tailless bonds. The bond clamping force was set at 60 grams for the first (ball) bond, and at 90 grams for the second (tailless) bond. These settings were used to produce the bonds for the control and environmental test groups evaluated in this study. All of the discrete components bonded readily in the as received condition without requiring either special cleaning procedures or surface conditioning. In addition, both ball and tailless bonds were readily produced on the thin film (Cr-Au) substrate metallization which had been resistor stabilized but not pre-bond etched. The results of the bond strength evaluation for each type of component or metallization is presented in Table III. Each average strength used represents a minimum of 15 bonds.

In contrast, Figure 9 shows the bond envelopes which were previously developed for these same discrete components using the thermocompression process.[9] This technique required pre-bond cleaning. Although successful bonds were made at temperatures as low as 125°C, it was necessary to increase the bond forces to levels of 175 grams and higher. As a result these high forces produced ball bonds with deformation well in excess of 50% of the diameter of the ball. Invariably, an increase in deformation of the ball bond tends to weaken the gold wire at the extreme end of the neck, immediately adjacent to the top of the ball. This condition is primarily a result of the bonding capillary configuration which, at high bond force levels, has the tendency to push or draw the wire up into the capillary. Consequently, this stretching effect reduces the diameter of the wire at the neck of the ball which results in wire fractures with low tensile strength. Normally the bond forces are maintained at a nominal level to prevent this condition.

FIGURE 9 - BOND ENVELOPES



By elevating the temperature it was possible to produce acceptable bonds at reduced force levels. However, these temperature increases were limited by the hybrid circuit metallization temperature constraints[11] as well as by discrete components described as temperature sensitive. In addition, the thermocompression process requires more rigid control of the processing parameters to accomplish satisfactory bonding at elevated temperatures and high bond forces.

The results from the thermal aging tests indicated little degradation in the bond strengths. However, a slight reduction in tensile strength of the wire was noted after subjecting the test samples at each aging condition. Undoubtably this can be attributed to the slight annealing of gold wire at these elevated temperatures. The test results for thermal environmental aging are listed in Table III, and are plotted in Figure 10.

SUMMARY/CONCLUSIONS

The objective of the study described herein was to evaluate the contribution of the thermosonic bonding technique to solid phase bonds on both thin film metallized substrates and thick film metallized component terminations. The experimental materials and procedures, the bonding parameters, and the test results have been presented.

Based on the results of this evaluation, it was concluded that an improvement to the thermocompression bonding technique was realized by the introduction of ultrasonic energy, i.e., the thermosonic process. The bond forces required for thermosonic bonding are relatively low as compared to the forces required for the thermocompression technique (60 and 90 grams versus 175 grams and higher). In addition, the thermosonic wire bonding process can be performed at reduced substrate

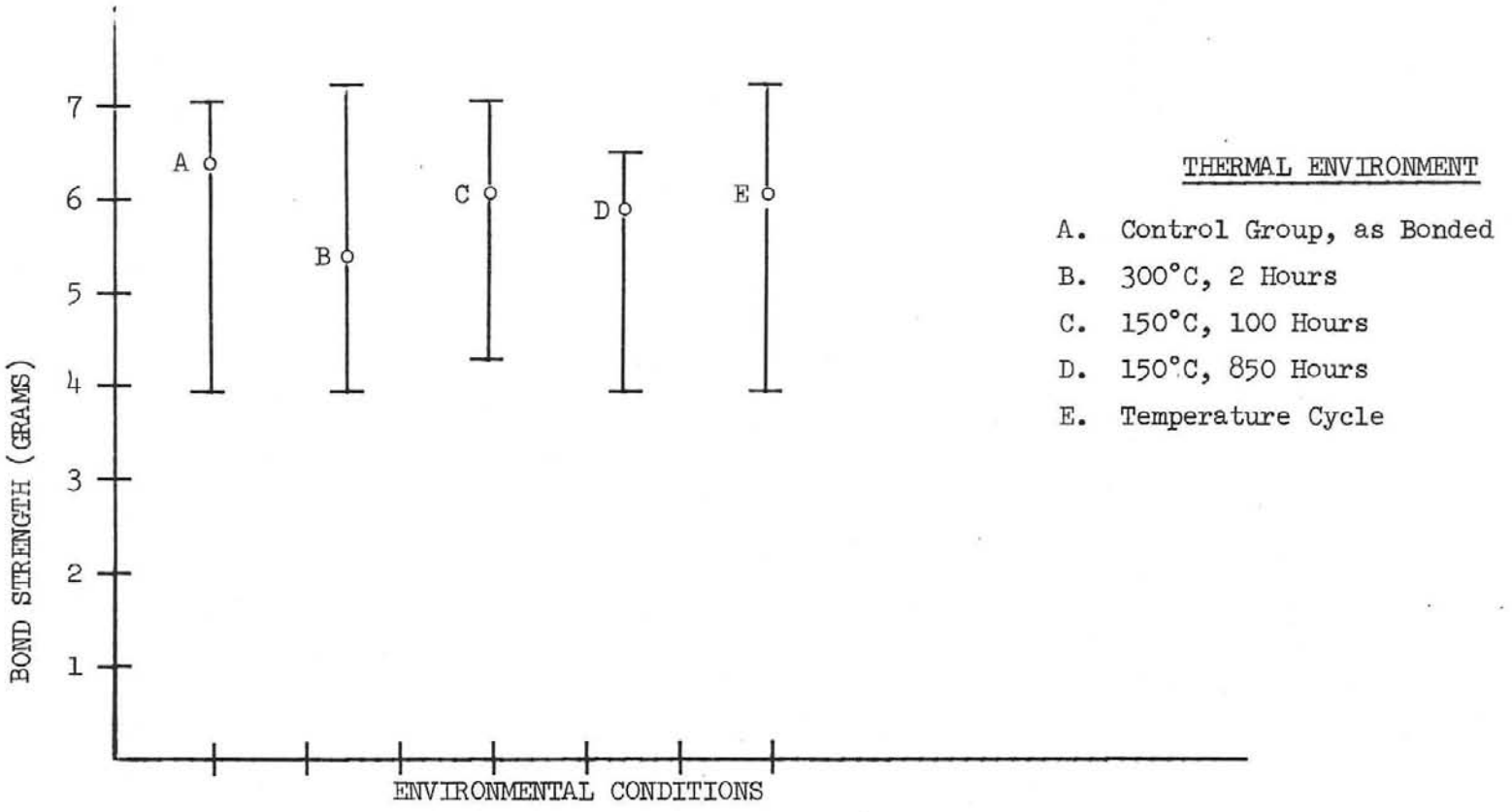


Figure 10. Results of Bond Pull Tests at Each Environmental Condition

temperatures (100°C versus 125°C and higher) which in effect removes the thermal bonding constraints which are encountered in the thermocompression process.

Perhaps even more important, this study revealed that the thermosonic wire bonding technique essentially eliminates the need for special pre-bond cleaning and pre-bond etching of either the discrete components or the metallized substrates used in Sandia's hybrid microcircuit applications. Further, as was shown in the bond schedule plots (Ref. Figures 5 and 7), the usable bonding envelope is sufficiently extended to compensate for fluctuations in parameter settings, thereby minimizing rigid processing controls. Thus the thermosonic process appears to offer the greater process flexibility which is desired in the hybrid microcircuit area.

The thermosonic bonds showed little or no change in tensile strength as a result of the thermal environmental aging tests conducted during this evaluation.

Using the procedures and basic bond parameters developed for this evaluation, the present study has demonstrated that the thermosonic bonding process is capable of producing fine wire gold bonds to a variety of thin and thick film metallized surfaces. These bonds exhibited excellent metal to metal adherence and high tensile strengths. On the basis of the results obtained in this study, it is recommended that the thermosonic wire bonding technique be incorporated as an in-house capability for Sandia's hybrid microcircuit interconnection applications. Further, the advantages of this process suggest that the thermosonic technique should be considered for production line utilization during component manufacturing. Additional investigation of this technique, for both development and production applications, should be pursued, especially with regard to comparison with other techniques such as pulsed thermocompression bonding.

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