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APPLICATION OF DIFFUSION BONDING TO ELECTRONIC INTERCONNECTION OF FLATPACK LEADS

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SUMMARY REPORT

JULY 1973

Prepared By
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V. F. Lardenoit

Contract No. NAS 8-28269

Prepared For

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National Aeronautics and Space Administration
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FR-73-01-580

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J. R. Shackleton for performing scanning electron microscopy and x-ray analyses

L. J. Yarber for making bonds and performing pull tests

J. L. Ewing for typing and preparation of the rough draft.

ABSTRACT

This investigation conducted under Contract No. NAS 8-28269 consisted of testing and evaluating diffusion bonds using low melting metals between gold-plated Kovar lead material and copper circuit pads. The investigation was conducted in three parts consisting of (1) an evaluation of the physical strength of resulting bonds at ambient and elevated temperature, (2) a metallurgical analysis of bonds using scanning electron microscopy and nondispersive x-ray analysis and (3) evaluation and development of various schemes for multiple lead flatpack bonding.

SUMMARY

Diffusion-bonded joints between gold-plated Kovar leads and indium-plated copper circuit pads offer some unique advantages for electronic circuit packaging. Test results show that consistent high strength bonds stronger than the copper circuit foil are achieved by parallel-gap bonding at relatively low power settings. The bonds are basically formed by the alloying of the gold, indium and copper at the bond interface. Other low melting metals such as tin can also be used; however, tin does not offer the ease of bonding that results in consistent separation of the copper foil during pull testing.

This investigation consisted of evaluating bonds made between gold-plated Kovar lead material and circuit boards plated with low temperature melting metals, i.e., indium, tin and tin-lead. The bonding was accomplished mainly by means of parallel-gap electrodes using a constant voltage D.C. power supply. The process is referred to as "diffusion bonding;" however, the bonding mechanism may not be what is normally considered as a true diffusion bond. It was the purpose of this investigation to obtain sufficient information on the diffusion bonding process to determine the following:

1. Consistency, elevated temperature strength and effects of aging.

2. Advantages over welding and soldering.

3. Feasibility as a production process.

4. Which of the three low melting metals, indium, tin or tin-lead is the optimum metal for bonding.

5. Adaptability to multiple lead bonding.

6. Applications where advantages of diffusion bonding could best be utilized.

The consistency, elevated temperature strength and effects of aging of the bonds were found to be excellent at temperatures as high as 175°C. Bond strengths were generally equal to or in excess of those obtained by soft solder and were limited by the strength of the copper foil and its bond strength to the epoxy circuit board.

Advantages of diffusion bonding over welding are less damage to the circuit board and the possible ability to bond a mixture of parts with gold-plated and tin-plated leads to the same circuit board with the same process. The advantages over soldering are identical with those of welding over soldering, i.e.:

1. A bond capable of higher temperature strength than solder.
2. Weight saving due to the amounts of tin-lead required for soldering.
3. Elimination of the necessity to pretin gold plated leads.

These advantages, however, do not ordinarily overcome three basic disadvantages of welding which are:

1. The permanency of the bond does not lend itself easily to component replacement.

2. The production speed is slower than multiple lead reflow soldering of flatpack leads.

3. Inspection to determine "acceptable" joints is more difficult than soldering and welding.

The process does not presently lend itself to production for two reasons:

1. A variation in circuit board processing would be required and the necessary procedures have not yet been developed.

2. It would not be competitive with reflow soldering unless a faster means of making the bonds could be developed. Single lead bonding requires 64 seconds for a single 14-lead flatpack. Multiple lead reflow soldering requires only 34 seconds.

Indium was found to be superior to tin and tin-lead as the low melting metal used in the bond interface. Lower power settings were required; the bonds were more consistent and resulted in removal of copper foil from the circuit board during pull testing.

An investigation of the adaptability of the process to multiple lead bonding resulted in design and fabrication of a tool for performing rapid parallel gap bonds. Further development, however, is required to completely develop the tool and associated mechanism.

Applications for the process other than flatpack lead bonding were considered. Two possible applications are (1) the attachment of lids to microelectronic packages and (2) the interconnection of beam lead devices.

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INTRODUCTION

This investigation consisted of evaluating bonds made between gold-plated Kovar lead material and circuit boards plated with low temperature melting metals. i.e., indium, tin, and tin-lead. The bonding was accomplished mainly by means of parallel-gap electrodes using a constant voltage D.C. power supply. The process is referred to as "diffusion bonding;" however, the bonding mechanism may not be what is normally considered as a true diffusion bond.

Bonding by true diffusion occurs when two metals are placed in intimate contact, usually under high pressure, but at temperatures below the melting point of either metal. Two metals with similar metallic crystal lattices brought into intimate physical contact will begin to interchange atoms and share metal lattice electron bonds. The more nearly identical the metals are in atomic size and lattice structure, the stronger will be the tendency to form bonds. Diffusion has been shown experimentally to follow an Arrhenius Law relationship to temperature; however, due to dependency on material and physical conditions, it is not presently possible to predict diffusion on a strictly mathematical and theoretical basis.

In this program, a low melting metal is preplaced (by plating) between the two metals to be joined. Heating causes melting of the intermediate metal and subsequent alloying with the base metals. With molten material present, such a process could be termed diffusion brazing or diffusion soldering depending on temperatures involved.

The term diffusion bonding, however, is used throughout the program for the following reasons:

1. Energy levels are below those used for welding.
2. The mechanism of joining was not fully understood at the outset of the program. It was not certain whether the intermediate material reacted with the material being joined to form the bond or if the intermediate metal was expulsed due to electrode pressure and a bond formed between the basis metals.

Previous work reported in References 1 and 2 showed that high strength bonds could be obtained between gold-plated Kovar leads and copper conductors using indium, tin, and tin-lead plated coatings. It was reported that bonds could be made with indium at temperatures close to its melting point (156.6^{o}C) that would subsequently melt at a higher temperature, thus providing a bonding mechanism capable of higher temperature strength than soft solder. Two advantages diffusion bonding would offer are: (1) no thermal damage to printed circuit board materials or temperature sensitive devices and (2) bonds capable of higher temperature applications than can be obtained with soft solder.

The purpose of this investigation was to determine the following with respect to diffusion bonding.

1. Consistency, elevated temperature strength, and effects of aging.
2. Advantages over welding and soldering.
3. Feasibility as a production process.

4. Which of the three low melting metals, indium, tin, or tin-lead is the optimum metal for bonding.

5. Adaptability to multiple lead bonding.

6. Applications where the advantages of diffusion bonding could best be utilized.

The test results and work necessary to satisfy the above objectives are reported in three parts which consist of the following:

SECTION 1 BOND EVALUATION

A bond evaluation was conducted to determine the consistency, elevated temperature strength and effects of aging. Of the three low melting metals selected (indium, tin, and tin-lead), the optimum metal and optimum plating thickness were determined. Various techniques for making the bonds were evaluated, advantages of the technique over welding and soldering were established, and applications where the advantages of diffusion bonding could best be utilized were identified.

SECTION 2 METALLURGICAL ANALYSIS

The analysis consisted of a determination of the diffusion bonding mechanism using scanning electron microscopy and x-ray analysis. Bonds that failed in different modes were examined to determine metallurgical characteristics of strong and weak bonds.

In addition to determining the bonding mechanism of gold-plated Kovar leads with tin and indium, the bonding mechanism between tin-plated leads and indium-plated copper was also analyzed.

SECTION 3 MULTIPLE LEAD DEVELOPMENT

The feasibility of diffusion bonding as a production process is dependent on its adaptability to making multiple lead bonds, single lead bonds in rapid succesion, or any combination of these. It was the purpose of this portion of the work to investigate multiple lead development or a means of making rapid diffusion bonds. During the course of the investigation, a design study was conducted to determine the most feasible approach from an economic standpoint. On the basis of the study. two prototype tools were designed, fabricated, and tested.

SECTION 1

BOND EVALUATION

BACKGROUND

The bonding of two materials is ideally achieved when their melting points and thermal and electrical conductivity values are reasonably matched. For a selected voltage, the amount of current flowing through a material is dependent on its electrical resistivity. The temperature rise and whether melting occurs are dependent upon the thermal conductivity and melting point of the material.

Presently, parallel-gap welding requires circuit boards to be finished with 300 microinches of nickel and 50 to 80 microinches of gold. The melting points of nickel, Kovar, copper and gold (Table 1-1) are 1455, 1450, 1083 and 1063°C, respectively. The Kovar lead reaches the highest temperature since it is in direct contact with the electrodes but because of its high melting point it does not melt. Gold, having the lowest melting point, is the first to melt. With proper selection of the pulse, amplitude, and duration, the gold is the only metal melting and forms a braze between the nickel on the conductor pad and the Kovar on the lead. The nickel acts as a barrier to prevent the copper from melting, thus extending the allowable range of power settings and preventing thermal damage to the printed wiring board.

Several methods can be used to explain the formation of high temperature bonds by use of a low melting intermediate material. One method is diffusion bonding where the low melting temperature material is fused in the bond area between the high melting metals and alloys with the metals by means of diffusion. The resulting alloy has a higher melting point than the original low melting temperature metal in the bond area. A second method is the formation of metallurgically clean surfaces by means of alloying and liquifying surface material and a resultant bond of clean surfaces by interatomic forces. A third method is the prevention of oxidation of the base metal, copper, by the low melting metal to enable simultaneous brazing with gold acting as the filler metal.

The low melting point metals of interest in this investigation were indium, tin, and tin-lead (electroplated 60-40), one purpose of the program being to determine which of the three coatings would be most suitable. Tin and tin-lead would be preferable from a production standpoint since they are low cost, well established and compatible with present circuit board fabrication procedures. Indium would present a problem in that it is not as well established in the industry, is not resistant to the etchants normally used in circuit board production and cannot be used as a resist. This would require special procedures; i.e., panel-plating the indium, applying an organic resist and etching. Since indium is expensive and panel-plating would result in considerable loss of the metal, a profitable means of recovery would be required.

The properties of the three metals selected are shown in Table 1-1. Of all the low melting metals, they appear the most practical. As previously mentioned, indium may present problems as far as expense and fabrication procedures are concerned, but they do not appear to be insurmountable.

The melting points of the three materials selected are five to seven times lower than the next highest metal, gold. If the gold must melt to achieve a bond, the low melting metal will be in an extremely fluid state, at least in the direct vicinity of the bond. Under the force of the electrodes, the low melting metal will tend to be depleted from the bond interface, with the lowest melting material, i.e., indium, being depleted to a greater extent than either tin or tin-lead. Of the three metals, indium has not only the lowest melting point, but also the lowest thermal conductivity and electrical resistivity. All three properties would favor it as the metal that would liquify at the lowest power setting. According to the properties listed in Table 1-1, tin-lead should require more power than indium and tin should require the most power of the three.

TABLE 1-1. PROPERTIES OF METALS AND ALLOYS USED IN BONDING INVESTIGATION

Metal or Alloy	Melting Point (^{o}C)	Thermal Conductivity ($Cal/Cm^2/Cm/Sec/^{o}C$)	Electrical Resistivity (Microohm-Cm)
Copper	1083	0.94	1.71
Gold	1063	0.71	2.44
Nickel	1455	0.16	9.5
Kovar	1450	0.046	50.5
Indium	157	0.057	9.0
Tin	232	0.155	11.5
Tin-Lead (63-37)	183	0.121	14.5

COMPARATIVE BOND STRENGTH OF SOLDERED AND WELDED JOINTS

Good quality soldered and welded flatpack leads consistently show joint strengths that exceed the ultimate strength of the lead material or circuit conductor. The effect of the process on the bond strength of the circuit pad to the board, however, is an important consideration. Bond tests reported in Reference 3 report soldered flatpack leads when pulled at an angle of 45 degrees as having a bond strength of 1.5 pounds when attached by parallel-gap soldering, but less than 0.1 pound when manually soldered. The mode of failure, however, was the circuit pad and not the soldered joint. Pull test values on Kovar leads welded to copper circuit boards are reported in Reference 4 as being stronger than the tensile strength of the materials tested.

An acceptable bond between a printed circuit board and flatpack lead should have a strength of more than half a pound and result in consistent failure of one of the joining materials. This was the criteria used throughout the investigation for determining the acceptability of diffusion bonded joints.

BOND TEST PROCEDURE

A bond test procedure was required that would discriminate between good and bad bonds and provide consistent reproducible results. A pull angle of 0 degree usually results in failure of the Kovar lead material at 6 pounds. A pull angle of 90 degrees and greater usually results in extreme notch stresses and fatiguing of the joint during the initial 90- to 180-degree bend. It was decided to use a 45-degree pull test to avoid these two extremes. A 45-degree pull test fixture was designed for use with a Missimers furnace and a Baldwin tensile test machine (Figure 1-1). The fixture utilizes a vacuum port to hold the board in place, thus enabling ease in placement and removal. A set of miniature grips was used to grip specimens with short leads without fatiguing or prestressing the bonds.

METHODS OF ACHIEVING THE BOND

For the purpose of the multiple lead bonding portion of the contract it was important to know whether it was necessary to use parallel-gap welding equipment to make diffusion bonds or whether a bond could be made using a resistance heated tip. If the bonding mechanism with indium was the formation of an alloy with gold at a low temperature that subsequently remelts at a significantly higher temperature, it could be possible to make the bond with a resistance heated tip with little or no damage to the board.

For initial bonding tests, a small resistance heated tip known as a "peg tip" was used. It consists of a small heater bar 0.035 inch wide and 0.100 inch long and can be used to reflow solder either one or two leads at a time depending on orientation. The rationale for using a resistance heated tip was as follows: first, the processing closely resembles existing reflow soldering techniques and equipment; second, the results generated would be applicable to multiple lead bonding since the tip is a variation of a multiple lead reflow soldering bar currently in production use. The tip can be used to bond two flatpack leads at a time or a single lead at a time depending on orientation. Both methods were tried. Better results were obtained with the single lead approach because of the larger bonding area that occurred.

The methods that were tried were: (1) resistance heated tip with D.C. power supply, (2) resistance heated tip with A.C. power supply, and (3) parallel-gap tip with D.C. power supply.

Test Boards

The initial set of boards was made with the three different types of plating: indium, tin, and tin-lead. Plating thicknesses were measured at the edge and center of each board to verify the specified thickness and determine variation from center to edge. The results are given in Table 1-2.

The plating thicknesses selected for investigation were 0.2, 0.4, 0.6 and 1 mil.

The gold plating thickness on the Kovar lead material was measured since it was expected to be a variable in the bonding process. Measurements established the gold thickness between 86 and 154 millionths of an inch.

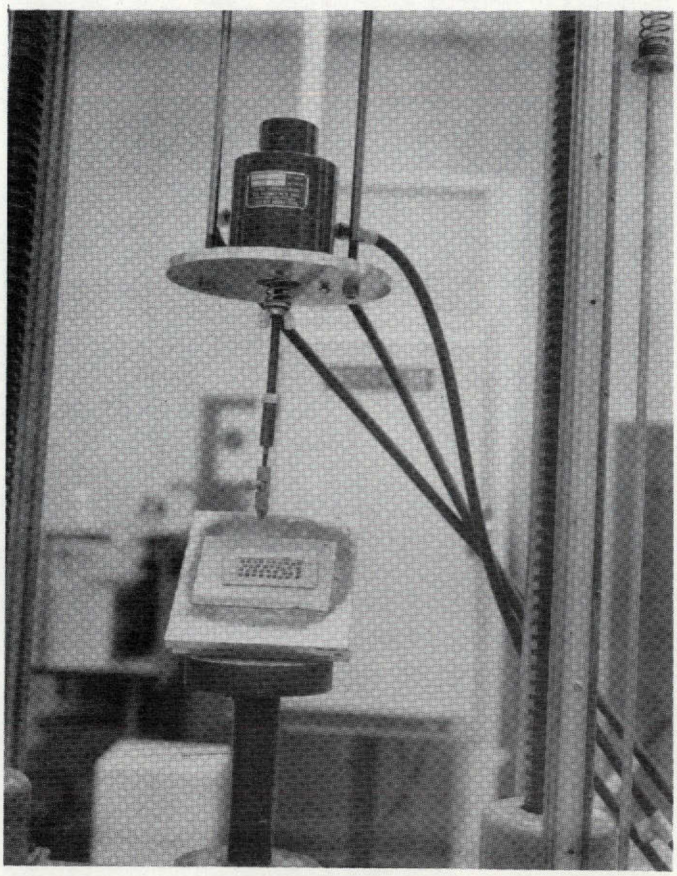


Figure 1-1. Bond Test Fixture Designed for Use With Missimers Furnace and Tensile Test Machine

TABLE 1-2. PLATING THICKNESS MEASUREMENTS ON TEST BOARDS

Board Number	Plating	Thickness	
		Edge	Center
1	Indium	.0012	.0010
2	Indium	.0006	.0006
3	Indium	.0004	.0004
4	Indium	.0003	.0003
5	Tin	.0052	.0031
6	Tin	.0040	.0039
7	Tin	.0015	.0009
8	Tin	.0002	.0006
9	Tin-Lead	.0019	.0017
10	Tin-Lead	.0014	.0010
11	Tin-Lead	.0012	.0006
12	Tin-Lead	.0008	.0010
13	Tin-Lead	.0004	.0003

Bond Results With Resistance Heated Tip and D.C. Power Supply

The initial bonds reported in Table 1-3 were made on the 1 mil indium-plated board, No. 1 in Table 1-2. The information recorded on each bond is as follows:

1. Board identification consisting of board number as given in Table 1-2 and row and column location of pad group, e.g., 1A1 = Board 1 (1 mil indium) Row A, Column 1.

2. Voltage, time and force.

3. Visible board degradation caused by bonding (Yes or No).

4. Peel strength in pounds.

5. Type of separation during peel test.

   P/L = pad to lead

   P/B = pad to board

The bond results reported in Table 1-3 were made using the peg tip to bond two leads at a time. The results reported in Table 1-4 were made bonding one lead at a time with the tip oriented parallel to the pad.

TABLE 1-3. BOND RESULTS USING 35-100 PEG TIP TWO LEADS AT A TIME - D.C. POWER SUPPLY

Board Identification	Voltage	Time Ms	Force (Lbs)	Board Degradation		Peel Strength (Lbs)	Type of Separation*	
				Yes	No		P/L	P/B
1A1	.50	800	5		X			
1A2	.50	900	5		X			
1A3	.60	900	5	X				
1A4	.55	900	5	X		0.30	X	
						0.20	X	
						1.10	X	
						0.93	X	
1A5	.55	900	5	X		1.39	X	
						1.33		X
						1.22		X
1A6	.55	900	5	X		1.25		X
						0.60		X
						1.06		X
1A7	.53	900	5	X		0.47	X	
						0.23	X	
						0.42	X	
1B1	.52	1500	5	X				
1B2	.51	1200	5	X				
1B3	.50	1100	5	X				
1B7	.55	800	5	X		0.37	X	
						0.20	X	
						0.43	X	
1B8	.54	900	5	X		1.31		X
						1.09	X	
						1.35		X
1C1	.54	900	5	X		1.11		X
						0.97		X
						0.94		X
						1.39		X
						1.05		X
						0.51	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-3. (cont)

Board Identification	Voltage	Time Ms	Force (Lbs)	Board Degradation		Peel Strength (Lbs)	Type of Separation*	
				Yes	No		P/L	P/B
1C2	.54	900	5	X		1.03	X	
						0.95		X
						1.11		X
						0.57	X	
						0.97		X
						0.60	X	
1C3	.54	800	5	X		0.38	X	
						0.23	X	
						0.36	X	
						0.37	X	
						0.46	X	
						0.21	X	
1C4	.54	850	5	X		1.05		X
						1.03		X
						0.29		X
						0.93		
						---		X
						0.64		X
1C6	.54	900	3	X		0.55	X	
						0.56	X	
						0.26	X	
						0.39	X	
1C8	.54	900	3	X		0.88	X	
						0.67	X	
						0.67	X	
						0.60	X	
						0.73	X	
						0.73	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-4. BOND RESULTS USING 35-100 PEG TIP ONE LEAD AT A TIME - D.C. POWER SUPPLY

Board Identification	Voltage	Time Ms	Force (Lbs)	Board Degradation		Peel Strength (Lbs)	Type of Separation*	
				Yes	No		P/L	P/B
1D1	.40	900	3		X	0.17	X	
						0.15	X	
						0.12	X	
						0.15	X	
						0.22	X	
						0.09	X	
1D2	.45	900	3	X		0.33	X	
						0.39	X	
						0.41	X	
						0.41	X	
						0.38	X	
						0.18	X	
1D3	.47	900	3	X		0.97	X	
						0.77	X	
						0.57	X	
						0.60		X
						0.73		
						1.95		X
1D4	.47	1000	3	X		0.98		X
						1.28		X
						1.50		X
						0.83	X	
						0.59	X	
						1.24		X
1D5	.45	1100	3	X		0.49	X	
						0.73		X
						0.65		X
						0.66		
						0.34	X	
						1.01	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-4. (cont)

Board Identification	Voltage	Time Ms	Force (Lbs)	Board Degradation		Peel Strength (Lbs)	Type of Separation*	
				Yes	No		P/L	P/B
1D6	.45	1000	3	X		0.39	X	
						0.51	X	
						0.68	X	
						0.80	X	
						0.59	X	
2A1	.45	1100	3	X		1.67		X
						0.98	X	
						1.38		X
						1.40		X
						0.60	X	
						1.65		X
2A2	.45	1100	3	X		1.85		X
						0.74	X	
						1.58		X
						0.57	X	
						1.60		X
						1.45		X
						1.32		X

*P/L = Pad to Lead; P/B = Pad to Board

The work using the peg tip and MCW 550 D.C. power supply resulted in erratic and generally low strength bonds. It was felt that better results may be achieved with an alternating current power supply.

Bond Results With Resistance Heated Tip and A.C. Power Supply

The A.C. power supply (HAC-1) has a time control for 1 to 9.9 seconds and an amplitude control from 1 to 100 percent for each of five different ranges. The amplitude control is the percentage of output for each given range setting. The Hughes ERL 35-100 peg tip (.035" x .100") was used with a thermocouple attached. Tip temperature was monitored by means of a strip chart recorder. The results are given in Table 1-5. Each value is an average of six bonds. The results are generally lower than those achieved with D.C. power supply since an effort was made to achieve an adequate bond strength at as low a temperature as possible to prevent board damage. Board damage generally occurred at settings required to obtain bond strengths of over 0.5 pound. Because the results were not encouraging, further work with the peg tip was discontinued.

TABLE 1-5. BOND RESULTS USING 35-100 PEG TIP AND A.C. POWER SUPPLY
(ONE LEAD AT A TIME)

Board Identification	Range and Percent	Time Sec.	Temperature °F	Board Damage		Peel Strength (Lbs)	Type of Separation*	
				Yes	No		P/L	P/B
(1) In (1.0)	1-90	0.1	420		X	0.25	X	
	1-95	0.1	470		X	0.19	X	
	1-98	0.1	500		X	0.54		X
	1-71	0.7	700		X	0.52	X	
	1-71	0.9	800	X		1.04		X
(2) In (0.6)	1-71	0.8	740	X		0.80		X
	1-67	0.9	750		X	0.25	X	
	1-65	1.0	780		X	0.18	X	
	1-55	5.0	790		X	0.32	X	
	1-67	1.0	810		X	0.47	X	X
	1-70	1.0	840		X	0.48	X	X
	1-67	1.1	845		X	0.38	X	
(3) In (0.4)	2-78	0.1	320		X	0.10	X	
	2-85	0.1	390		X	0.19	X	
	2-90	0.1	460		X	0.10	X	
	1-98	0.1	515		X	0.37		X
	2-95	0.1	530		X	0.10	X	
	2-96	0.1	535	X		0.50		X
(8) Sn (0.2)	1-85	0.2	490		X	0.20	X	
	1-87	0.2	500		X	0.23	X	
	1-98	0.1	510		X	0.38	X	
	1-88	0.2	520		X	0.26	X	
	1-25	9.9	520		X	0.32	X	
	1-71	0.9	800	X		0.37		X

*P/L = Pad to Lead; P/B = Pad to Board

CONSTANT VOLTAGE VS. CONSTANT CURRENT POWER SUPPLY

Parallel-gap welding was originally a delicate operation. Using capacitor discharge-type power supplies only a fine line in welder settings separated under-strength welds from complete blow-outs. Small changes in material cross-sections produced equally drastic effects. The MCW/EL welder developed by Hughes was developed to provide a broader operating range and automatic compensation for material variations. It incorporates a welding circuit of constant voltage design, as distinguished from the nearly constant current operation of the capacitor-discharge welder. This design provides a broad latitude compared to constant current operation. Quality welds of 4 x 17 mil Kovar can be made to copper circuit paths ranging from 21 to 70 square mils with the same schedule (Reference 3). Constant current welds of Kovar to Kovar require a different schedule if the cross-section changes 3 or 4 square mils. Constant voltage operation decreases the current as the resistance of the joint increases which occurs as welding heat increases. Control is maintained and does not result in a burn-out. Variations in cross-sectional areas of materials result in different resistances. A separate sensing circuit "feeds back" from the electrodes and automatically controls the power supply to maintain a constant pre-set voltage. The changes in cross-sectional area result in changes in total current so that the same current density and the same power density are maintained. For example, a cross-sectional area of 40 square mils has a resistance of 3 milliohms at 0.6 volt. Pulse current is 200 amps, current density is 5 amps per square mil, and power density is 3 watts per square mil. For a cross-sectional area of 80 square mils the resistance is 1.5 milliohms. At 0.6 volt, pulse current is 400 amps, current density is 5 amps per square mil and power density is 3 watts per square mil. Since both large and small joints receive equal current and power density, there is equal heating at the bondline.

At a constant current of 300 amps the constant current power supply would result in 3.75 amps/sq. mil and 1.69 watts/sq. mil for the 80 square mil area and 7.5 amps/sq. mil and 6.75 watts/sq. mil for the 40 square mil area (a possible blowout).

Since a uniform current density could be achieved regardless of lead geometry and size, the constant voltage power supply was selected for the investigation.

PARALLEL-GAP TIP AND CONSTANT VOLTAGE POWER SUPPLY

Work proceeded with the parallel-gap tip and MCW 550 power supply shown in Figure 1-2. A schedule was established that provided relatively high bond strengths with tin. Ideally, separate schedules should be established for each plating and thickness to be truly meaningful in determining which plating type and thickness would be optimum for diffusion bonding. An attempt was made to accomplish this, but the results did not appear to warrant using different schedules. The schedule established was just below the level that would melt the Kovar or cause board damage: i.e., 0.5 volt, 5 ms, 0.005-inch gap and 5 pounds of force. Test boards were prepared with fourteen leads each and pulled at room temperature. The results are recorded in Table 1-6. The second series of tin-plated boards (24 thru 27) were prepared because the thickness on the first series (5 thru 8) was incorrect.

Reasons for obtaining higher bond strengths with tin plating rather than indium are not readily apparent. In both cases half the pad was torn from the board and the strength was less for the indium-plated boards than for the tin-plated ones. The values recorded in Table 1-6, however, are from a small sample size.

It was expected that there would be problems in obtaining meaningful data from elevated temperature peel tests and after aging for 1000 hours at 120°C. Preliminary tests indicated that at 120°C, lower bonds were obtained because of pad-to-board separation.

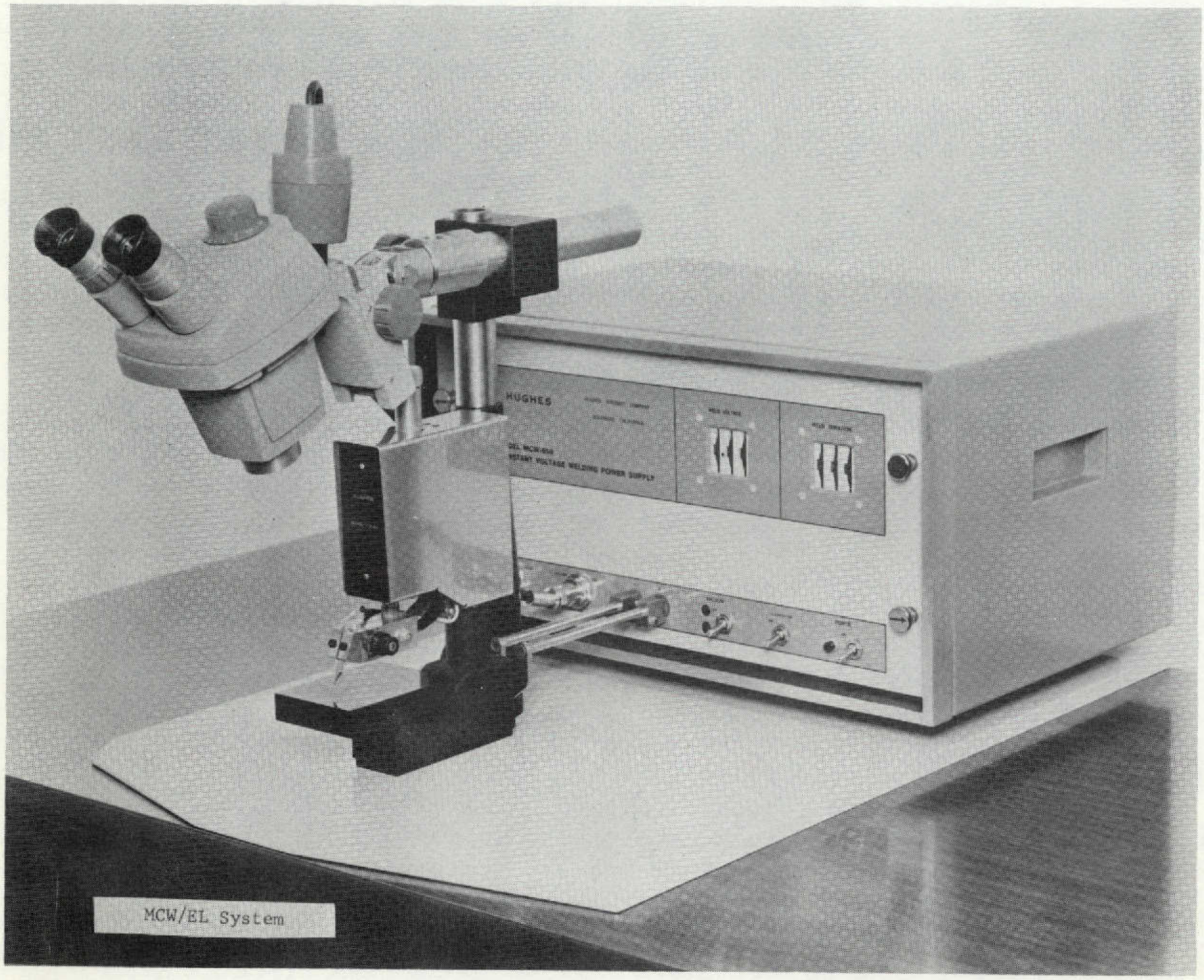


Figure 1-2. Constant Voltage D.C. Power Supply

Preliminary Bond Test Results

The preliminary bond tests reported in Table 1-6 showed that the highest values were obtained with 0.6 mil of tin. The indium-plated boards did not show much difference in bond strength between 0.4 and 1.0 mil. Results with tin-lead plating were too low to be of further interest; therefore it was eliminated from further tests. All preliminary tests were done using boards with 0.030 x 0.100 etched pads. Relatively high bond strengths were obtained at room temperature, but the tests at elevated temperature were too low to be meaningful because of loss of adhesion between the pad and board. In order to eliminate this problem and to determine the potential of the technique exclusive of pad size, it was decided to use plated copper clad boards with no pad pattern. Because of the larger heat-sinking characteristics of the solid copper cladding, it was necessary to adjust the schedule upward from 0.5 volt 5 ms to 0.62 volt 5 ms for tin and 0.62 volt 6 ms for indium. An electrode gap of 0.005 inch and 3 pounds of force was maintained. The test boards were plated to a thickness of approximately 0.6 mil for both the tin and the indium based on the test results reported in Table 1-6.

TABLE 1-6. PRELIMINARY BOND RESULTS USING PARALLEL-GAP TIP AND D.C. POWER SUPPLY

Board No.	Plating	Thickness Mils	Peel Strength	Type of Separation*	
				P/L	P/B
1	In	1.0	1.47		X
2	In	0.6	1.36		X
3	In	0.4	1.38		X
4	In	0.3	1.14		X
5	Tin	3.0	1.02	X	
6	Tin	4.0	0.65	X	
7	Tin	1.0	0.76	X	
8	Tin	0.6	2.60		X
9	Tin-Lead	1.7	--		
10	Tin-Lead	1.0	0.35	X	
11	Tin-Lead	0.6	0.31	X	
12	Tin-Lead	1.0	0.43	X	
13	Tin-Lead	0.3	--		
24	Tin	0.2	2.28		X
25	Tin	0.4	2.51		X
26	Tin	0.6	3.22		X
27	Tin	1.0	1.34		X

*P/L = Pad to Load; P/B = Pad to Board

High Temperature Bond Tests

Test temperatures of 125 and 175°C were chosen for the following reasons. At 125°C tin-lead solder has only 40 percent of its strength at room temperature, and makes a convenient point to compare strength data of diffusion-bonded joints. The higher temperature, 175°C, was considered the upper limit of the epoxy circuit board material.

Seventy pull tests each were made for tin and indium on the unetched clad boards at three different temperatures - ambient temperature, 125°C and 175°C. The results are tabulated in Tables 1-7 thru 1-12.

The predominant mode of separation in the pull tests was a section of copper in the bond region being torn out and away from the board. There were a significant number of pad to lead failures, however, that occurred with the tin-plated boards during the elevated temperature tests. At 125°C, 59 percent of the pull tests on tin-plated boards resulted in pad to lead failures. The failures occurred as high as 2.5 pounds and the average P/L failure was 1.1 pounds with 50 percent over 1 pound. At 175°C, 27 percent of the pull tests resulted in P/L failures. Pad to lead failures occurred as high as 1.9 pounds. The average was 1 pound with 50 percent of the P/L failures over that value.

Frequency distribution graphs for each set of values were plotted and are shown in Figures 1-3 thru 1-8. The bond strengths for both tin and indium fall off slightly at elevated temperature, but since the failure is not the bond between the copper cladding and the Kovar lead the real value in the peel tests is (1) that they show indium and tin to be practically equal, (2) tin shows some lower values at all temperatures and results in pad to lead failures at elevated temperatures, and (3) the tests serve as a reference for the identical tests run on samples aged for 1000 hours at 150°C.

TABLE 1-7. BOND TESTS
TIN - AMBIENT TEMPERATURE

Mean: 1.8 Std. Dev: 0.65

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	2.07		X	36	2.25		X
2	2.06		X	37	2.7		X
3	2.61		X	38	1.1		X
4	0.76		X	39	1.3		X
5	1.81		X	40	2.42		X
6	2.38		X	41	1.52		X
7	3.21		X	42	0.52		X
8	1.64		X	43	1.22		X
9	3.3		X	44	2.04		X
10	2.7		X	45	2.13		X
11	2.4		X	46	2.10		X
12	3.4		X	47	1.07		X
13	2.13		X	48	2.88		X
14	1.51		X	49	1.88		X
15	1.66		X	50	1.56		X
16	2.16		X	51	0.80		X
17	1.72		X	52	2.14		X
18	2.47		X	53	2.39		X
19	1.68		X	54	0.61		X
20	2.64		X	55	2.02		X
21	1.90		X	56	1.17		X
22	1.97		X	57	1.78		X
23	1.88		X	58	1.7		X
24	2.12		X	59	1.58		X
25	1.98		X	60	2.04		X
26	1.92		X	61	2.02		X
27	1.48		X	62	1.0		X
28	1.23		X	63	2.11		X
29	1.33		X	64	1.0		X
30	0.97		X	65	1.3		X
31	2.05		X	66	0.98		X
32	2.31		X	67	2.47		X
33	1.48		X	68	1.0		X
34	2.48		X	69	1.38		X
35	0.53		X	70	1.21		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-8. BOND TESTS
INDIUM - AMBIENT TEMPERATURE

Mean: 1.6 Std. Dev: 0.31

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0			36	1.87		X
2	1.49		X	37	2.22		X
3	1.61		X	38	2.08		X
4	1.80		X	39	1.95		X
5	1.55		X	40	1.90		X
6	1.68		X	41	1.70		X
7	1.62		X	42	1.68		X
8	1.66		X	43	1.72		X
9	2.9		X	44	1.82		X
10	1.59		X	45	1.62		X
11	1.40		X	46	1.41		X
12	1.53		X	47	1.69		X
13	1.50		X	48	1.67		X
14	1.52		X	49	1.34		X
15	1.50		X	50	1.65		X
16	1.56		X	51	1.69		X
17	1.57		X	52	1.41		X
18	1.99		X	53	1.44		X
19	1.77		X	54	1.63		X
20	1.73		X	55	1.82		X
21	1.71		X	56	1.62		X
22	1.71		X	57	1.36		X
23	1.62		X	58	1.37		X
24	1.87		X	59	1.52		X
25	1.70		X	60	1.48		X
26	1.68		X	61	1.72		X
27	1.68		X	62	1.55		X
28	1.58		X	63	1.80		X
29	1.61		X	64	1.68		X
30	1.39		X	65	1.61		X
31	1.86		X	66	1.45		X
32	1.68		X	67	1.61		X
33	1.48		X	68	1.47		X
34	2.1		X	69	1.67		X
35	2.1		X	70	1.49		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-9. BOND TESTS
TIN 125°C

Mean: 1.3 Std. Dev: 0.59

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.95	X		31	0.75	X	
2	1.91	X		32	0.78	X	
3	2.52	X		33	1.38		X
4	1.48	X		34	0.84	X	
5	2.32	X		35	1.71		X
6	1.48	X		36	0.68	X	
7	2.06	X		37	1.48		X
8	2.35	X		38	1.39		X
9	0.95		X	39	1.32		X
10	1.01		X	40	1.66		X
11	1.2	X		41	1.69		X
12	0.72	X		42	1.55		X
13	2.3		X	43	1.53		X
14	0.95	X		44	0.42	X	
15	2.21		X	45	1.52		X
16	1.66	X		46	0.62	X	
17	1.84		X	47	0.84	X	
18	0.03	X		48	0.68	X	
19	0.03	X		49	0.61	X	
20	1.44	X		50	0.38	X	
21	1.18	X		51	1.28		X
22	1.35	X		52	1.05		X
23	1.19	X		53	1.38		X
24	1.87		X	54	0.46	X	
25	1.12	X		55	2.22		X
26	1.4	X		56	0.94	X	
27	2.4		X	57	1.46		X
28	1.37		X	58	1.75	X	
29	0.94	X		59	2.01		X
30	1.24	X					

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-10. BOND TESTS
INDIUM 125°C

Mean: 1.6 Std. Dev: 0.38

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	1.46		X	36	1.57		X
2	1.59		X	37	1.41		X
3	1.29		X	38	1.38		X
4	1.36		X	39	1.5		X
5	1.30		X	40	1.28		X
6	1.20		X	41	1.42		X
7	1.34		X	42	1.36		X
8	1.6		X	43	1.16		X
9	0.78		X	44	1.89		X
10	1.06		X	45	2.12		X
11	1.24		X	46	1.76		X
12	1.25		X	47	1.99		X
13	1.23		X	48	1.74		X
14	1.5		X	49	2.21		X
15	1.23		X	50	1.9		X
16	1.46		X	51	1.82		X
17	1.22		X	52	2.0		X
18	1.16		X	53	1.76		X
19	1.13		X	54	1.69		X
20	1.35		X	55	1.6		X
21	1.1		X	56	1.78		X
22	1.09		X	57	1.74		X
23	1.29		X	58	1.77		X
24	1.28		X	59	1.88		X
25	1.34		X	60	2.02		X
26	1.28		X	61	2.12		X
27	1.5		X	62	2.91		X
28	1.55		X	63	1.95		X
29	1.6		X	64	2.06		X
30	1.63		X	65	2.5		X
31	1.46		X	66	2.08		X
32	1.49		X	67	2.07		X
33	1.43		X	68	1.87		X
34	1.41		X	69	2.24		X
35	1.64		X	70	2.08		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-11. BOND TESTS
TIN 175°C

Mean: 1.3 Std. Dev: 0.43

Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B
1	0.50	X	
2	0.40	X	
3	0.93	X	
4	1.14		X
5	1.12		X
6	1.3		X
7	1.44		X
8	1.02		X
9	1.38		X
10	1.13		X
11	1.48		X
12	1.42		X
13	1.36		X
14	1.3		X
15	1.3		X
16	1.04		X
17	1.39		X
18	1.48		X
19	1.71		X
20	1.48		X
21	1.60		X
22	1.39	X	
23	1.61	X	
24	1.58		X
25	1.38	X	
26	1.04		X
27	1.62		X
28	1.49	X	
29	0.86		X
30	1.69		X
31	0.46		X
32	1.68		X
33	1.24		X
34	1.35	X	
35	1.23	X	
36			
37	1.27		X
38	0.54	X	
39	0.39	X	
40	0.13		X
41	1.4		X
42	0.5		X
43	1.22		X
44	1.49		X
45	1.55		X
46	1.77		X
47	1.46		X
48	0.52	X	
49	1.72		X
50	1.32		X
51	1.38		X
52	0.63	X	
53	1.45	X	
54	1.18		X
55	1.85		X
56	1.3	X	
57	1.69		X
58	1.7	X	
59	1.38		X
60	1.36		X
61	1.91		X
62	1.65		X
63	1.62		X
64	1.63		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-12. BOND TESTS
INDIUM 175°C

Mean: 1.2 Std. Dev: 0.27

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.91		X	35	1.72		X
2	0.98		X	36	1.4		X
3	0.96		X	37	1.55		X
4	1.3		X	38	1.3		X
5	0.95		X	39	1.42		X
6	0.91		X	40	1.67		X
7	0.92		X	41	2.14		X
8	1.2		X	42	1.78		X
9	1.32		X	43	1.8		X
10	0.80		X	44	1.7		X
11	0.79		X	45	1.21		X
12	1.07		X	46	1.35		X
13	1.02		X	47	1.2		X
14	0.80		X	48	1.3		X
15	0.81		X	49	1.2		X
16	0.96		X	50	1.1		X
17	0.98		X	51	1.12		X
18	0.94		X	52	1.3		X
19	1.28		X	53	1.21		X
20	0.91		X	54	1.12		X
21	1.0		X	55	1.08		X
22	0.96		X	56	1.22		X
23	0.95		X	57	1.2		X
24	0.97		X	58	1.1		X
25	1.12		X	59	1.23		X
26	1.2		X	60	1.2		X
27	1.47		X	61	1.16		X
28	1.41		X	62	1.07		X
29	1.58		X	63	1.08		X
30	1.62		X	64	1.20		X
31	1.63		X	65	1.26		X
32	1.28		X	66	1.23		X
33	1.29		X	67	1.33		X
34	1.21		X				

*P/L = Pad to Lead; P/B = Pad to Board

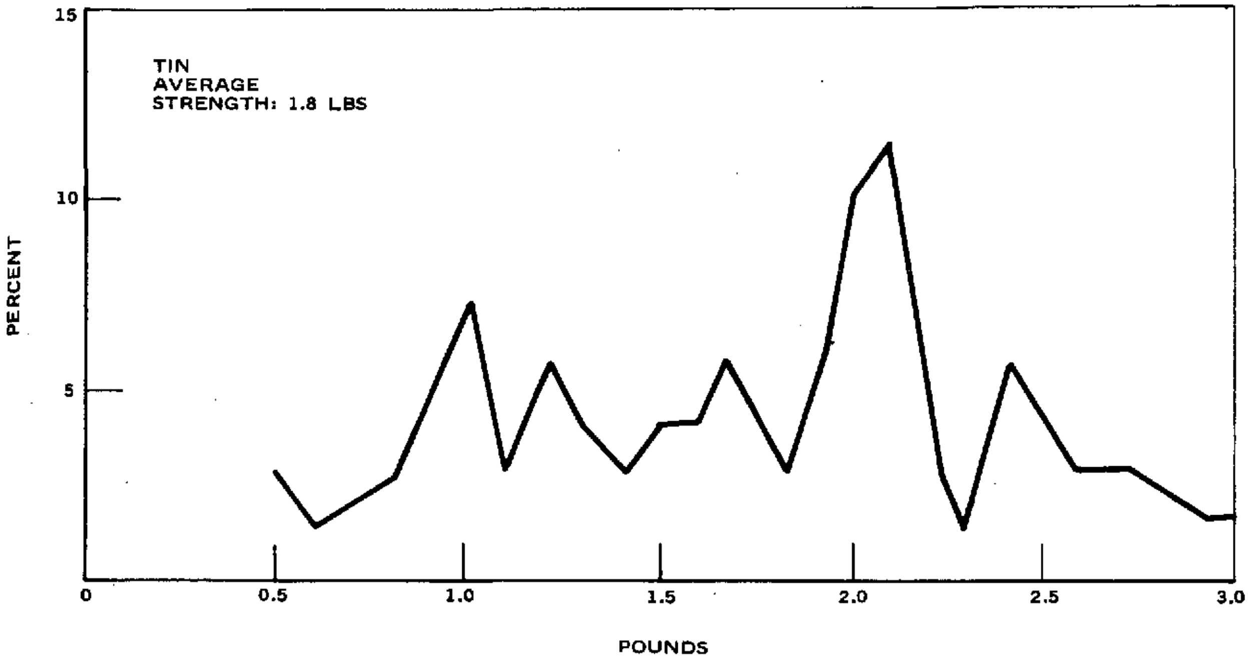


Figure 1-3. Frequency Distribution of Bond Tests at Ambient Temperature - Tin

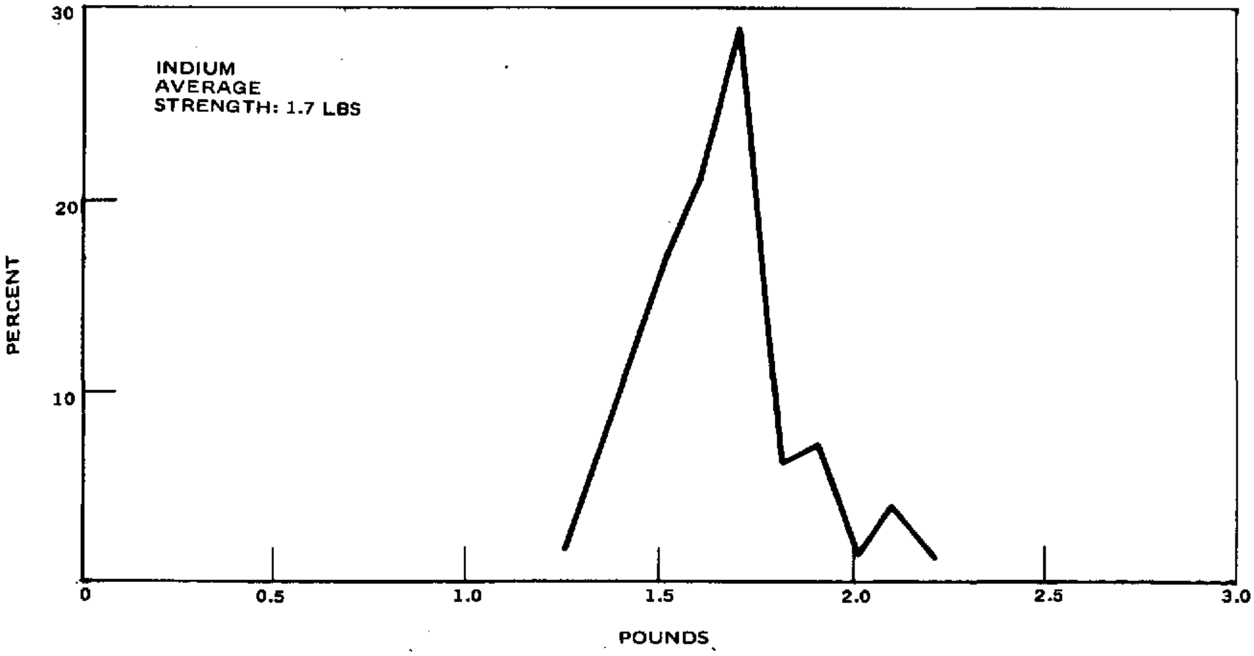


Figure 1-4. Frequency Distribution of Bond Tests at Ambient Temperature - Indium

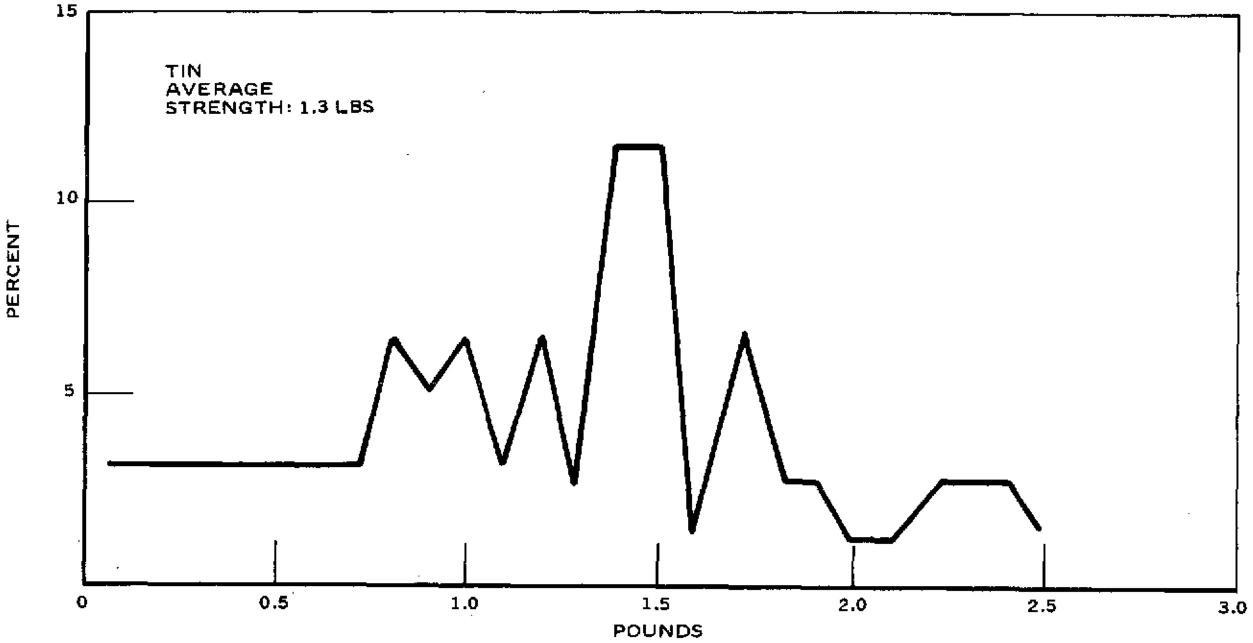


Figure 1-5. Frequency Distribution of Bond Tests at 125°C - Tin

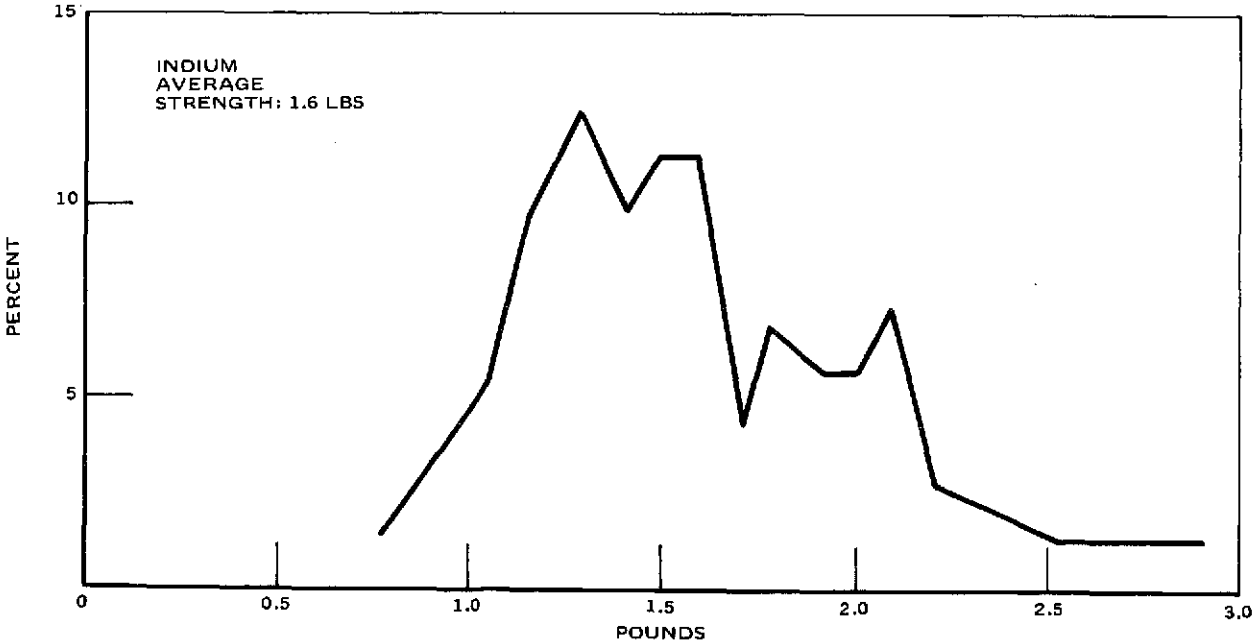


Figure 1-6. Frequency Distribution of Bond Tests at 125°C - Indium

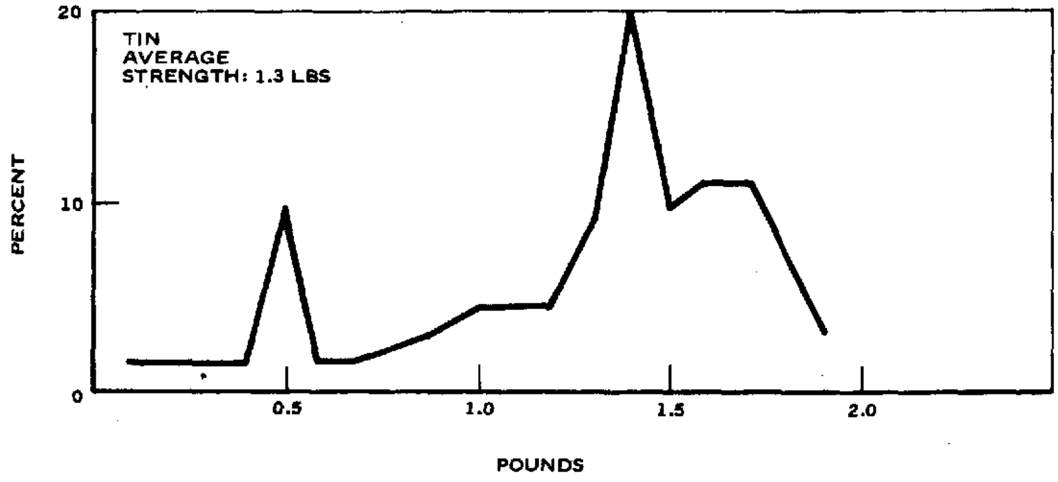


Figure 1-7. Frequency Distribution of Bond Tests at 175°C - Tin

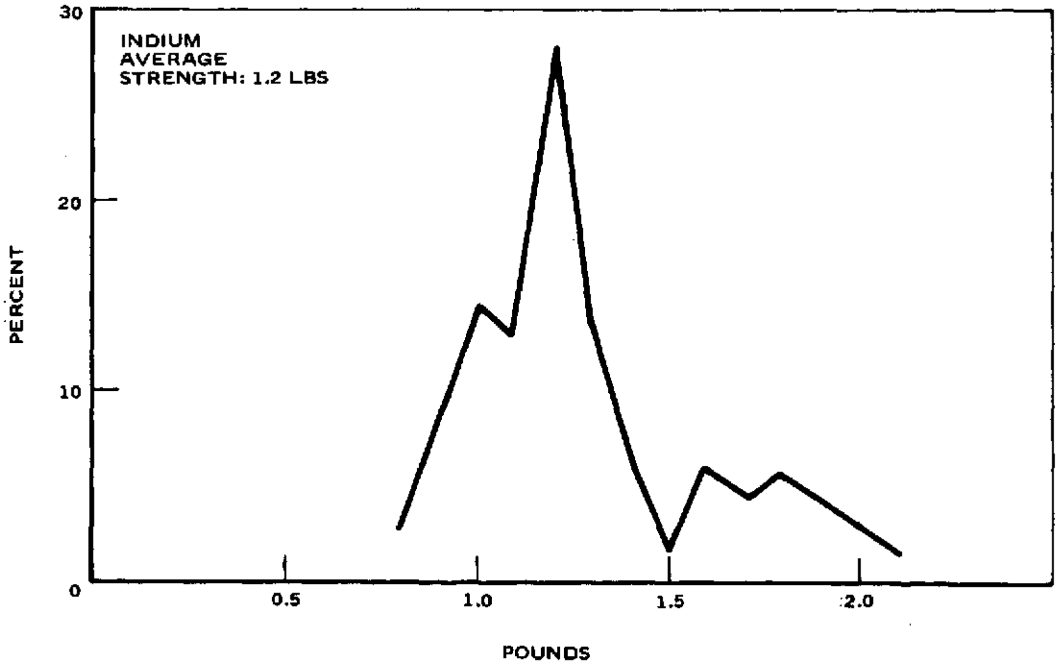


Figure 1-8. Frequency Distribution of Bond Tests at 175°C - Indium

Bond Tests on Aged Specimens

Bond tests were made on specimens that had been aged for 1000 hours at 150°C. The tin-plated boards suffered considerable damage during aging in that the foil and individual plies of the boards were partially delaminated. The indium-plated boards showed no evidence of delamination; however, the reason one set of boards fared better than the other is not known. They were aged in the same oven and made from the same circuit board stock. The results are given in Tables 1-13 thru 1-18. Frequency distributions of the bond results are given in Figures 1-9 thru 1-15. In comparing the bond strength for tin in Figures 1-9, 1-11 and 1-13 with that of unaged specimens, Figures 1-3, 1-5 and 1-7, there appears to be a deterioration in the tin bond from long-term aging at elevated temperature. The same tests for indium, shown in Figures 1-10, 1-12 and 1-14, compared to Figures 1-4, 1-6 and 1-8, show no such deterioration from aging.

It appeared that tin bonds were degraded by long-term aging at elevated temperature. Considerable board degradation occurred during the aging tests particularly in the case of the tin specimens which casts doubt on the veracity of those results. Since tin has many advantages over indium it was important that adverse data be conclusive. For this reason it was decided to obtain lower temperature aging information on tin bonds that would be more consistent with the upper temperature limit of G-10 epoxy boards.

An additional set of bonds was made with tin-plated boards and aged at a lower temperature, 125°C, for a shorter period of time, 500 hours. Bond tests were again made at room temperature, 125°C and 175°C, and the results shown in Tables 1-19, 1-20 and 1-21. Frequency distributions of the bond results are shown in Figures 1-15, 1-16 and 1-17. There was basically no overall change in average bond strength when compared to unaged specimens; however, the predominant mode of failure was pad to lead rather than pad to board. The predominant mode of failure with indium was pad to board which indicated a stronger bond with indium than with tin.

In the case of indium, all bond failures were between the pad and the board; therefore, the bond strengths recorded are dependent on the strength between the copper foil and epoxy board.

TABLE 1-13. BOND TESTS - AMBIENT TEMPERATURE
TIN
BONDS AGED 1000 HOURS AT 150°C

Mean: 0.50 Std. Dev: 0.23

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.35	X		30	1.11	X	
2	0.27	X		31	0.46	X	
3	0.36	X		32	0.94	X	
4	0.43	X		33	0.36	X	
5	0.35	X		34	1.10	X	
6	0.30	X		35	0.74	X	
7	0.32	X		36	0.94		X
8	0.32	X		37	0.28	X	
9	0.35	X		38	0.69		X
10	0.45	X		39	0.42	X	
11	0.42	X		40	0.55		X
12	0.29	X		41	0.50	X	
13	0.94	X		42	0.54		X
14	0.30	X		43	0.53	X	
15	0.80	X		44	0.10	X	
16	0.24	X		45	0.44	X	
17	0.30	X		46	0.70		X
18	0.48	X		47	0.59	X	
19	0.50	X		48	0.92		X
20	0.30	X		49	0.48	X	
21	0.46	X		50	0.80		X
22	0.39	X		51	0.89		X
23	0.36	X		52	0.58	X	
24	0.61	X		53	0.56	X	
25	0.34	X		54	0.43	X	
26	0.58	X		55	0.50	X	
27	0.20	X		56	0.44	X	
28	0.41	X		57	0.39	X	
29	0.44	X					

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-14. BOND TESTS - AMBIENT TEMPERATURE
INDIUM
BONDS AGED 1000 HOURS AT 150°C

Mean: 1.13 Std. Dev: 0.12

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	1.18		X	30	1.16		X
2	1.21		X	31	1.00		X
3	1.29		X	32	1.08		X
4	1.25		X	33	1.02		X
5	1.26		X	34	1.34		X
6	1.39		X	35	1.04		X
7	1.38		X	36	1.32		X
8	1.20		X	37	1.10		X
9	1.13		X	38	1.22		X
10	1.24		X	39	0.94		X
11	1.04		X	40	1.19		X
12	1.05		X	41	1.04		X
13	1.19		X	42	1.10		X
14	0.97		X	43	1.03		X
15	1.19		X	44	1.00		X
16	1.13		X	45	1.01		X
17	1.16		X	46	1.18		X
18	1.14		X	47	1.00		X
19	1.22		X	48	1.21		X
20	1.03		X	49	1.10		X
21	1.00		X	50	1.06		X
22	0.98		X	51	1.32		X
23	1.11		X	52	1.30		X
24	0.99		X	53	1.10		X
25	1.10		X	54	1.45		X
26	0.95		X	55	1.16		X
27	1.19		X	56	1.10		X
28	0.96		X	57	1.00		X
29	1.06		X				

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-15. BOND TESTS 125°C
TIN
BONDS AGED 1000 HOURS AT 150°C

Mean: 1.31 Std. Dev: 0.46

Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B
1	1.58		X
2	1.48		X
3	1.34		X
4	1.75		X
5	1.84		X
6	1.65	X	
7	1.55		X
8	1.50		X
9	1.23		X
10	1.52		X
11	1.48		
12	1.39		X
13	1.24		X
14	1.18		X
15	1.51		X
16	1.58		X
17	0.32	X	
18	0.50	X	
19	0.26	X	

Bond tests were incomplete. Foil delaminated from board due to damage from aging.

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-16. BOND TESTS 125°C
INDIUM
BONDS AGED 1000 HOURS AT 150°C

Mean: 2.2 Std. Dev: 0.34

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	2.76		X	34	2.62		X
2	2.44		X	35	2.19		X
3	2.58		X	36	2.40		X
4	2.54		X	37	2.57		X
5	2.42		X	38	2.49		X
6	2.60		X	39	2.43		X
7	2.30		X	40	2.42		X
8	2.58		X	41	2.46		X
9	2.50		X	42	2.26		X
10	2.77		X	43	2.17		X
11	1.15	X		44	1.91		X
12	2.33		X	45	1.89		X
13	2.20		X	46	1.79		X
14	2.00		X	47	1.62		X
15	2.09		X	48	1.48		X
16	2.42		X	49	1.46		X
17	2.20		X	50	2.54		X
18	2.30		X	51	2.03		X
19	2.23		X	52	2.46		X
20	2.40		X	53	1.90		X
21	2.07		X	54	2.00		X
22	2.14		X	55	2.18		X
23	2.03		X	56	1.92		X
24	2.16		X	57	2.22		X
25	2.24		X	58	1.87		X
26	2.00		X	59	1.63		X
27	2.29		X	60	1.62		X
28	2.16		X	61	1.89		X
29	2.03		X	62	1.71		X
30	2.29		X	63	1.73		X
31	2.54		X	64	2.00		X
32	2.34		X	65	1.75		X
33	2.52		X	66	1.78		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-17. BOND TESTS 175°C
TIN
BONDS AGED 1000 HOURS AT 150°C

Mean: 0.68 Std. Dev: 0.21

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.82		X	36	0.46		X
2	0.69		X	37	0.48		X
3	0.70		X	38	0.60		X
4	0.84		X	39	0.50		X
5	0.63		X	40	0.46		X
6	0.72		X	41	0.41		X
7	0.82		X	42	0.57		X
8	0.68		X	43	0.60		X
9	0.60		X	44	0.61		X
10	0.51		X	45	0.59		X
11	0.20		X	46	1.08		X
12	0.70		X	47	0.83		X
13	0.70		X	48	0.50		X
14	0.63		X	49	0.48		X
15	0.68		X	50	0.68		X
16	0.59		X	51	0.84		X
17	0.65		X	52	0.96		X
18	0.39		X	53	0.92		X
19	0.68		X	54	0.40		X
20	0.60		X	55	0.85		X
21	0.78		X	56	0.60		X
22	0.82		X	57	1.22		X
23	0.58		X	58	0.67		X
24	0.87		X	59	1.30		X
25	0.85		X	60	0.99		X
26	0.69		X	61	1.06		X
27	0.50		X	62	1.30		X
28	0.69		X	63	0.67		X
29	0.42		X	64	0.50		X
30	0.72		X	65	0.42		X
31	0.68		X	66	0.97		X
32	0.54		X	67	0.46		X
33	0.63		X	68	0.48		X
34	0.64		X	69	0.70		X
35	0.68		X	70	0.38		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-18. BOND TESTS 175°C
INDIUM
BONDS AGED 1000 HOURS AT 150°C

Mean: 1.3 Std. Dev: 0.26

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	1.11		X	35	1.36		X
2	0.99		X	36	1.36		X
3	1.09		X	37	1.37		X
4	0.93		X	38	1.38		X
5	0.40		X	39	1.53		X
6	0.98		X	40	1.60		X
7	1.12		X	41	1.51		X
8	1.01		X	42	1.44		X
9	0.85		X	43	1.43		X
10	0.86		X	44	1.50		X
11	0.97		X	45	1.64		X
12	1.33		X	46	1.84		X
13	1.31		X	47	1.48		X
14	1.27		X	48	1.39		X
15	1.08		X	49	1.61		X
16	1.16		X	50	1.60		X
17	1.35		X	51	0.62		X
18	1.05		X	52	1.08		X
19	1.32		X	53	1.20		X
20	1.54		X	54	1.27		X
21	1.72		X	55	1.20		X
22	1.65		X	56	1.31		X
23	1.64		X	57	1.21		X
24	1.50		X	58	1.47		X
25	1.49		X	59	1.17		X
26	1.42		X	60	1.49		X
27	1.83		X	61	1.35		X
28	1.22		X	62	1.33		X
29	1.51		X	63	1.48		X
30	1.30		X	64	1.53		X
31	1.54		X	65	1.47		X
32	1.49		X	66	1.53		X
33	1.21		X	67	1.48		X
34	1.26		X	68	1.42		X

*P/L = Pad to Lead; P/B = Pad to Board

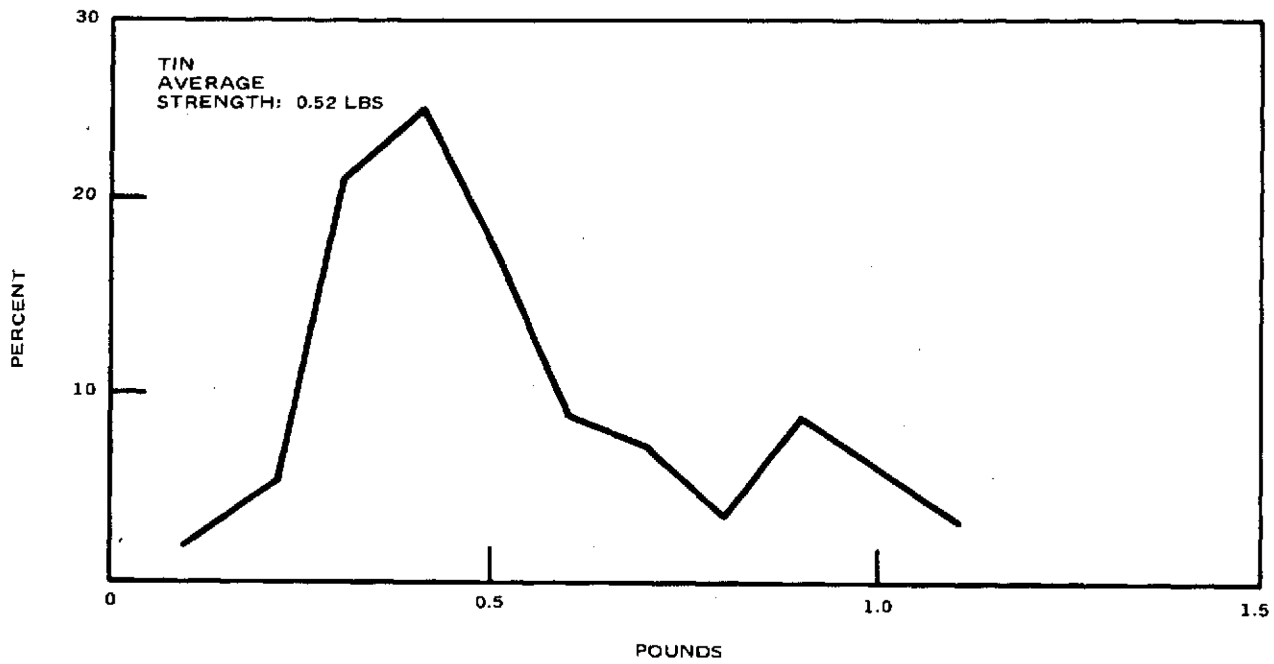


Figure 1-9. Frequency Distribution of Bond Tests at Ambient Temperature on Samples Aged for 1000 Hours at 150°C - Tin

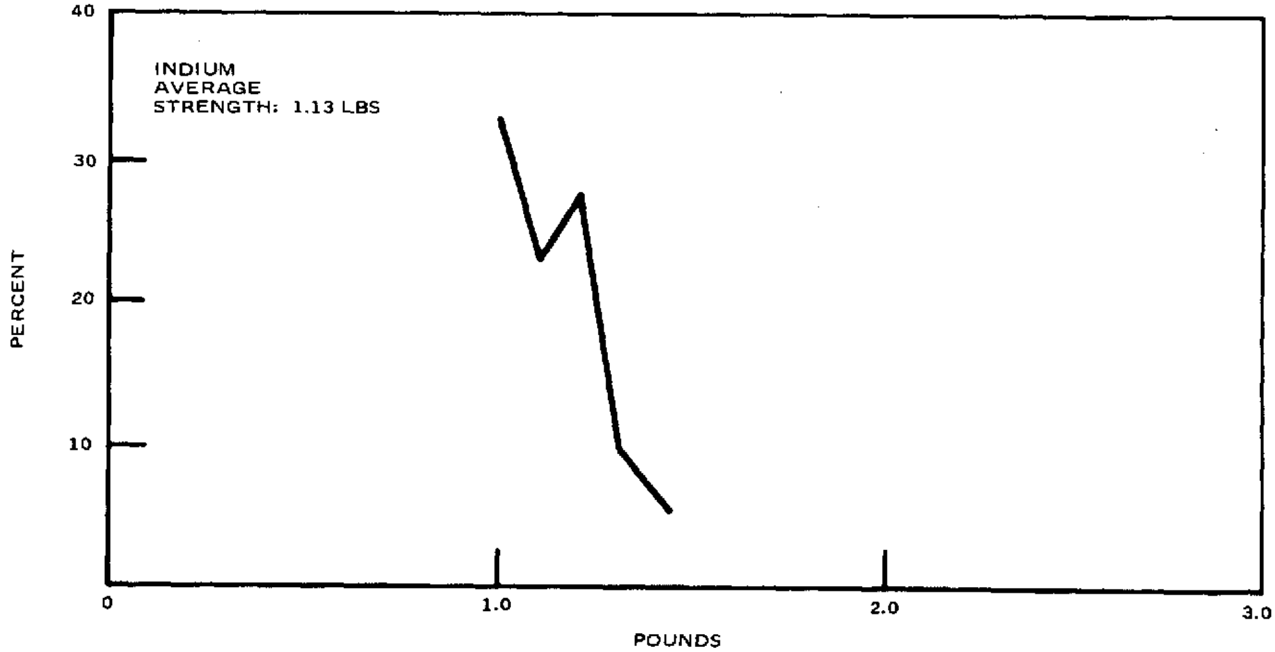


Figure 1-10. Frequency Distribution of Bond Tests at Ambient Temperature on Samples Aged for 1000 Hours at 150°C - Indium

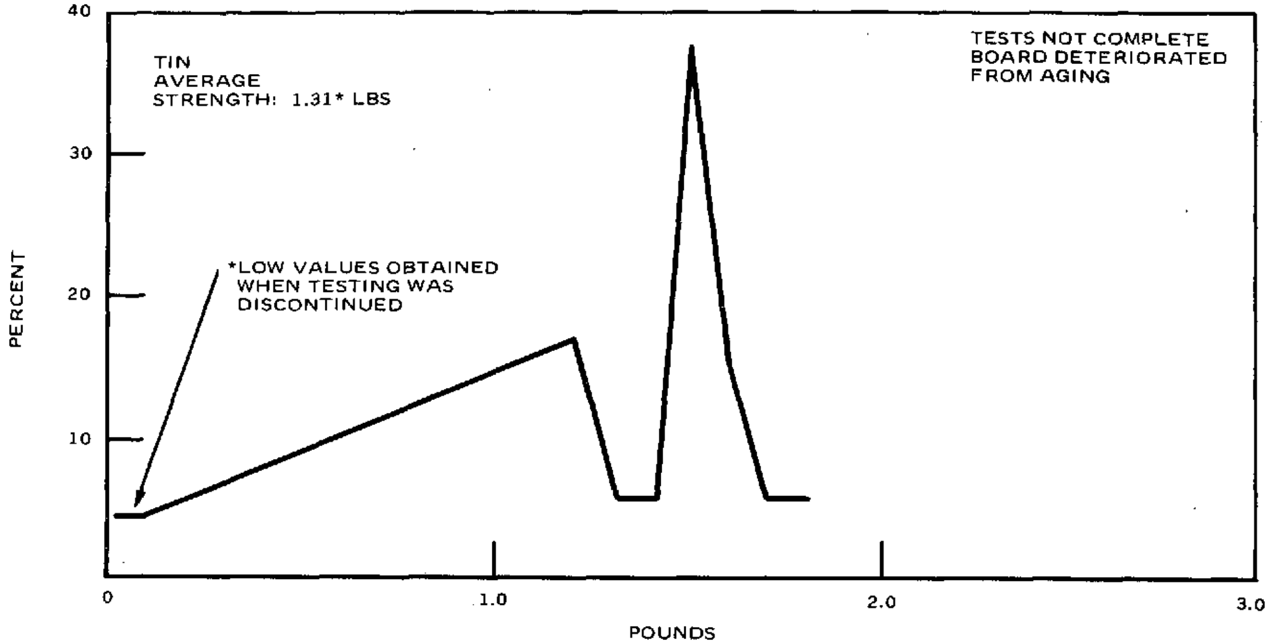


Figure 1-11. Frequency Distribution of Bond Tests at 125°C on Samples Aged for 1000 Hours at 150°C - Tin

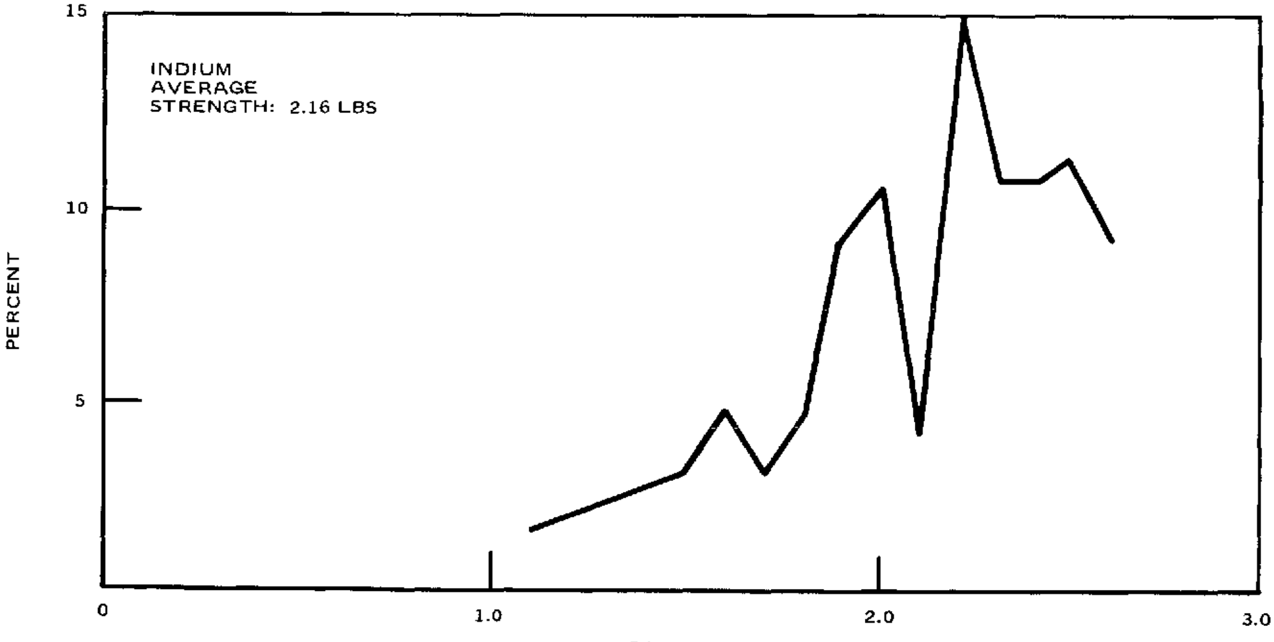


Figure 1-12. Frequency Distribution of Bond Tests at 125°C on Samples Aged for 1000 Hours at 150°C - Indium

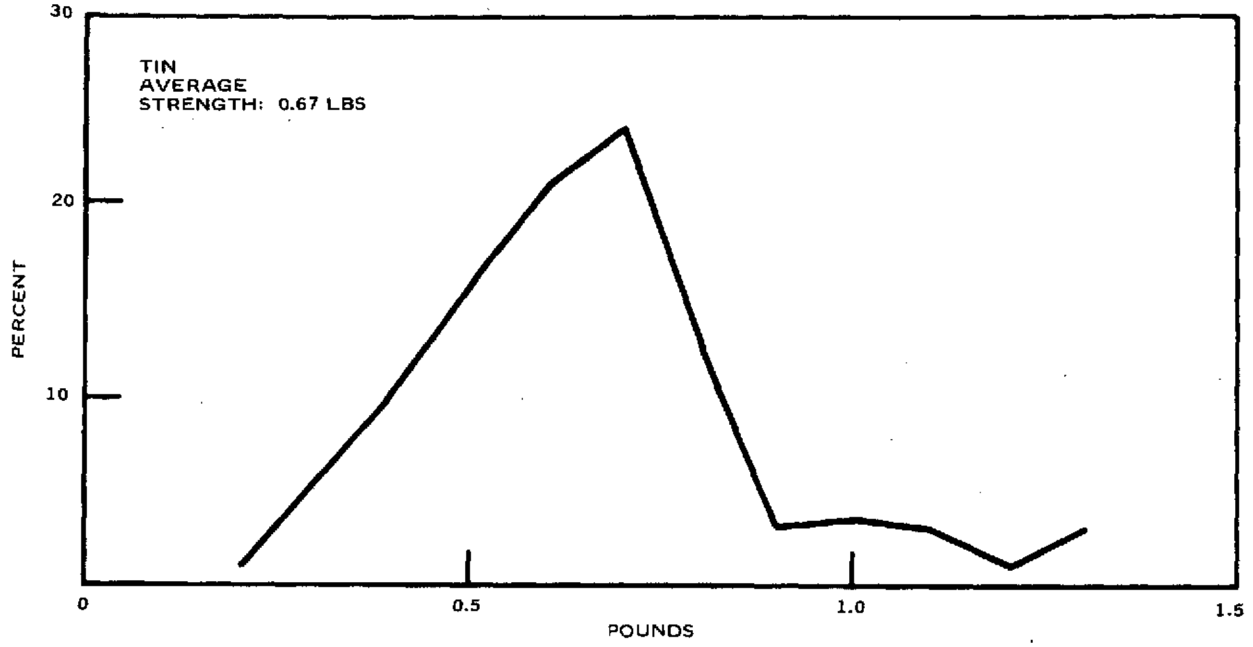


Figure 1-13. Frequency Distribution of Bond Tests at 175°C on Samples Aged for 1000 Hours at 150°C - Tin

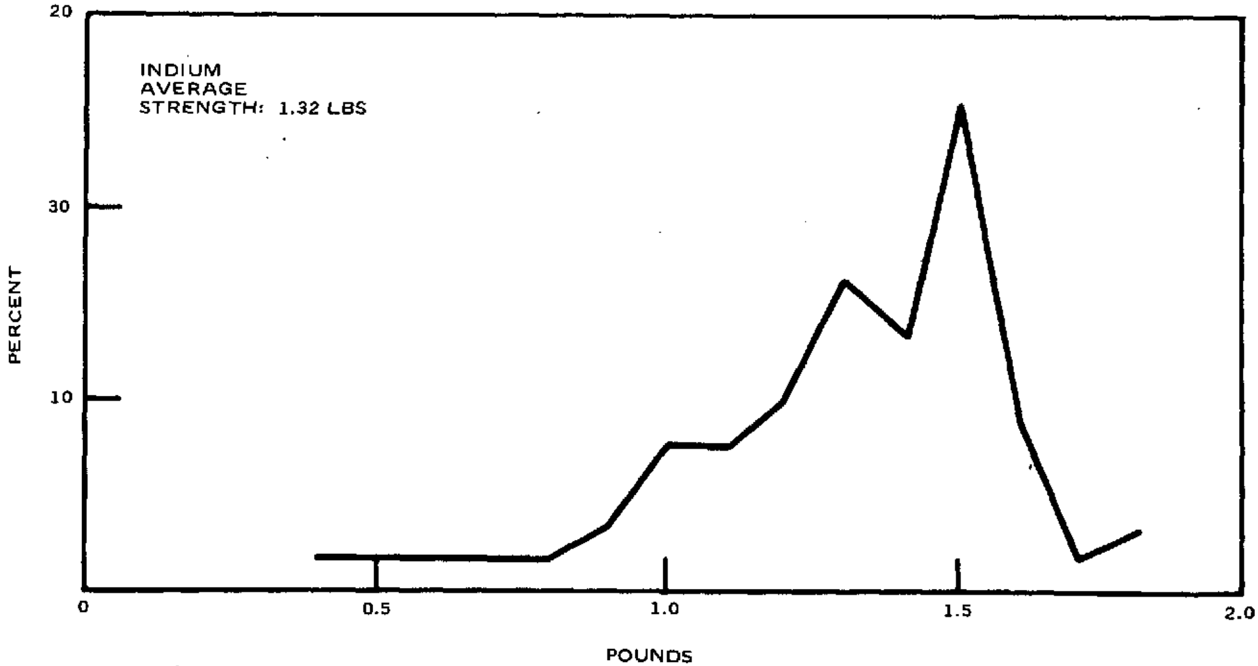


Figure 1-14. Frequency Distribution of Bond Tests at 175°C on Samples Aged for 1000 Hours at 150°C - Indium

TABLE 1-19. BOND TESTS
AMBIENT TEMPERATURE - TIN
BONDS AGED 500 HOURS AT 125°C

Mean: 1.9 Std. Dev: 0.74

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.35	X		31	1.71	X	
2	1.17	X		32	1.56	X	
3	0.81	X		33	1.46	X	
4	0.94	X		34	2.29		X
5	1.67	X		35	2.54		X
6	1.47	X		36	2.18		X
7	2.03	X		37	2.50		X
8	1.22	X		38	2.30		X
9	2.55		X	39	2.30		X
10	2.20	X		40	2.18		X
11	1.96		X	41	2.40		X
12	2.30		X	42	1.92		X
13	2.03		X	43	2.10		X
14	2.16		X	44	2.68		X
15	2.68		X	45	2.60		X
16	2.47		X	46	2.45		X
17	2.10		X	47	0.48	X	
18	2.06		X	48	2.54		X
19	2.44		X	49	2.37		X
20	2.94		X	50	2.60		X
21	2.28		X	51	2.37		X
22	2.11		X	52	2.74		X
23	0.53	X		53	2.50		X
24	1.63		X	54	2.74		X
25	2.49		X	55	1.70	X	
26	0.62	X		56	1.10	X	
27	0.69	X		57	3.70		X
28	0.76	X		58	0.92	X	
29	1.42	X		59	0.78	X	
30	1.23	X		60	0.91	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-20. BOND TESTS 125°C
TIN
BONDS AGED 500 HOURS AT 125°C

Mean: 1.0 Std. Dev: 0.41

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.55	X		36	0.76	X	
2	0.79	X		37	0.59	X	
3	0.50	X		38	0.98	X	
4	0.82	X		39	0.81	X	
5	1.46	X		40	0.93	X	
6	0.85	X		41	0.96	X	
7	0.79	X		42	0.64	X	
8	0.71	X		43	0.56	X	
9	0.69	X		44	0.80	X	
10	0.93	X		45	0.96	X	
11	0.98	X		46	0.97	X	
12	0.83	X		47	1.29		X
13	0.82	X		48	0.99	X	
14	1.44	X		49	1.93	X	
15	1.03	X		50	1.77	X	
16	0.87	X		51	1.40	X	
17	1.03	X		52	1.69	X	
18	1.38	X		53	1.50	X	
19	0.88	X		54	0.94	X	
20	0.58	X		55	1.93	X	
21	0.89	X		56	1.86	X	
22	1.08	X		57	1.60	X	
23	0.96	X		58	2.42		X
24	0.90	X		59	2.00	X	
25	0.83	X		60	1.39	X	
26	0.91	X		61	0.77	X	
27	0.87	X		62	1.19	X	
28	0.95	X		63	0.82	X	
29	0.83	X		64	0.94	X	
30	0.76	X		65	1.53	X	
31	0.88	X		66	0.55	X	
32	0.83	X		67	0.53	X	
33	0.76	X		68	0.39	X	
34	0.88	X		69	0.78	X	
35	0.83	X		70	0.68	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-21. BOND TESTS 175°C
TIN
BONDS AGED 500 HOURS AT 125°C

Mean: 1.2 Std. Dev: 0.56

Number	Bond Strength (Lbs)	Type of Separation*		Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B			P/L	P/B
1	0.57	X		36	0.40	X	
2	0.73	X		37	0.24	X	
3	0.49	X		38	0.70	X	
4	0.66	X		39	0.49	X	
5	0.75	X		40	0.95	X	
6	0.92	X		41	0.50	X	
7	0.79	X		42	0.69	X	
8	0.95	X		43	0.90	X	
9	1.01	X		44	0.92	X	
10	2.13		X	45	0.78	X	
11	1.84		X	46	0.67	X	
12	1.60		X	47	1.82		X
13	1.81		X	48	1.10	X	
14	1.30	X		49	1.70		X
15	1.80		X	50	1.98	X	
16	1.79		X	51	1.59		X
17	1.73		X	52	2.10		X
18	1.80		X	53	0.58	X	
19	0.58	X		54	1.87		X
20	1.76		X	55	1.97		X
21	1.78		X	56	1.48		X
22	1.74		X	57	1.59		X
23	1.78		X	58	0.71	X	
24	0.84	X		59	2.00		X
25	2.12		X	60	0.95	X	
26	1.88		X	61	0.85	X	
27	2.18		X	62	1.20	X	
28	1.14	X		63	0.69	X	
29	1.44	X		64	0.82	X	
30	1.02	X		65	0.72	X	
31	0.94	X		66	1.07	X	
32	0.70	X		67	0.75	X	
33	0.70	X		68	0.82	X	
34	0.38	X		69	0.71	X	
35	0.39	X		70	0.52	X	

*P/L = Pad to Lead; P/B = Pad to Board

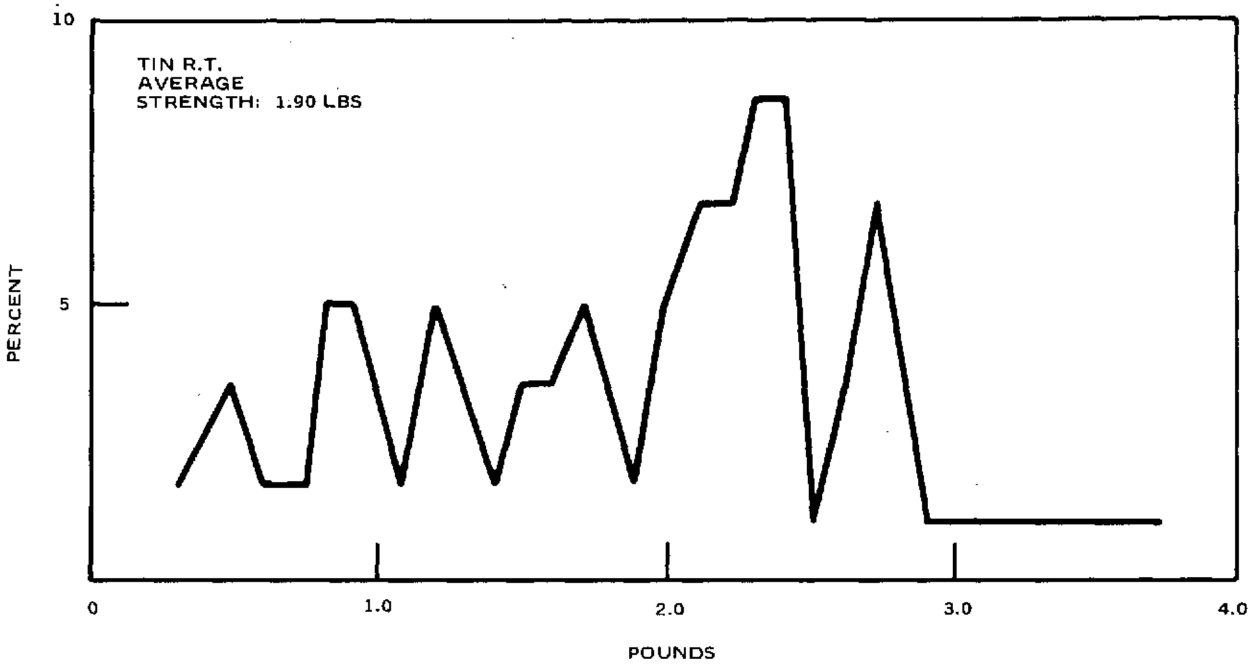


Figure 1-15. Frequency Distribution of Bond Tests at Ambient Temperature on Samples Aged for 500 Hours at 125°C - Tin

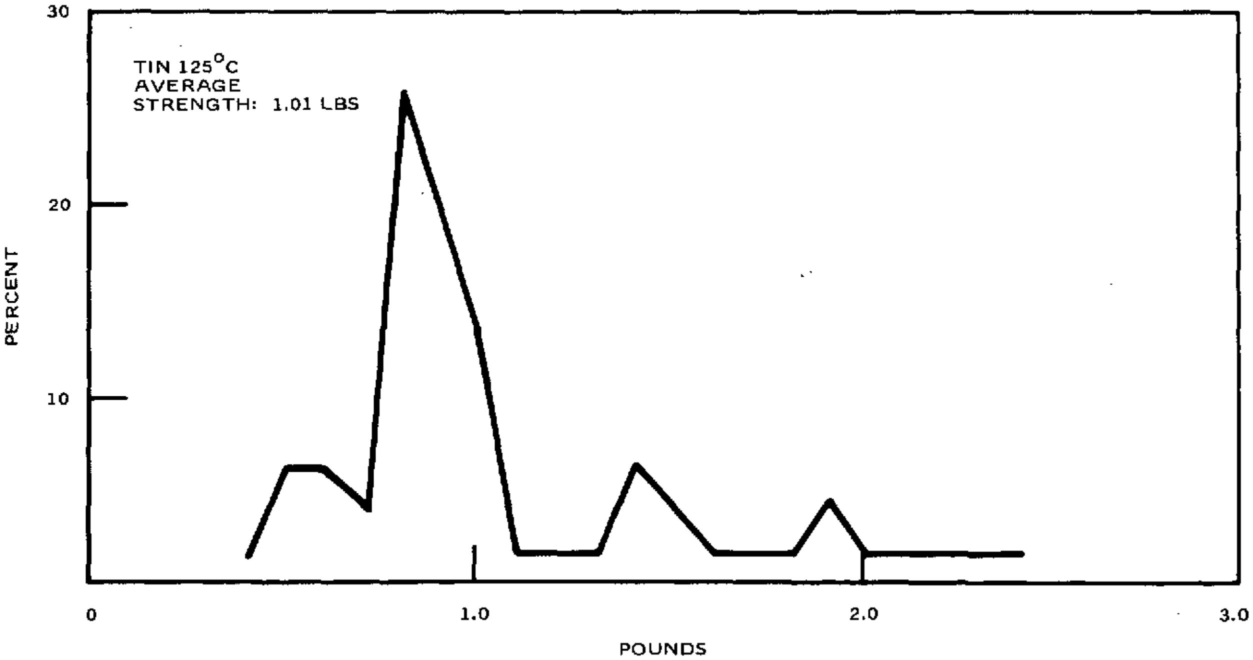


Figure 1-16. Frequency Distribution of Bond Tests at 125°C on Samples Aged for 500 Hours at 125°C

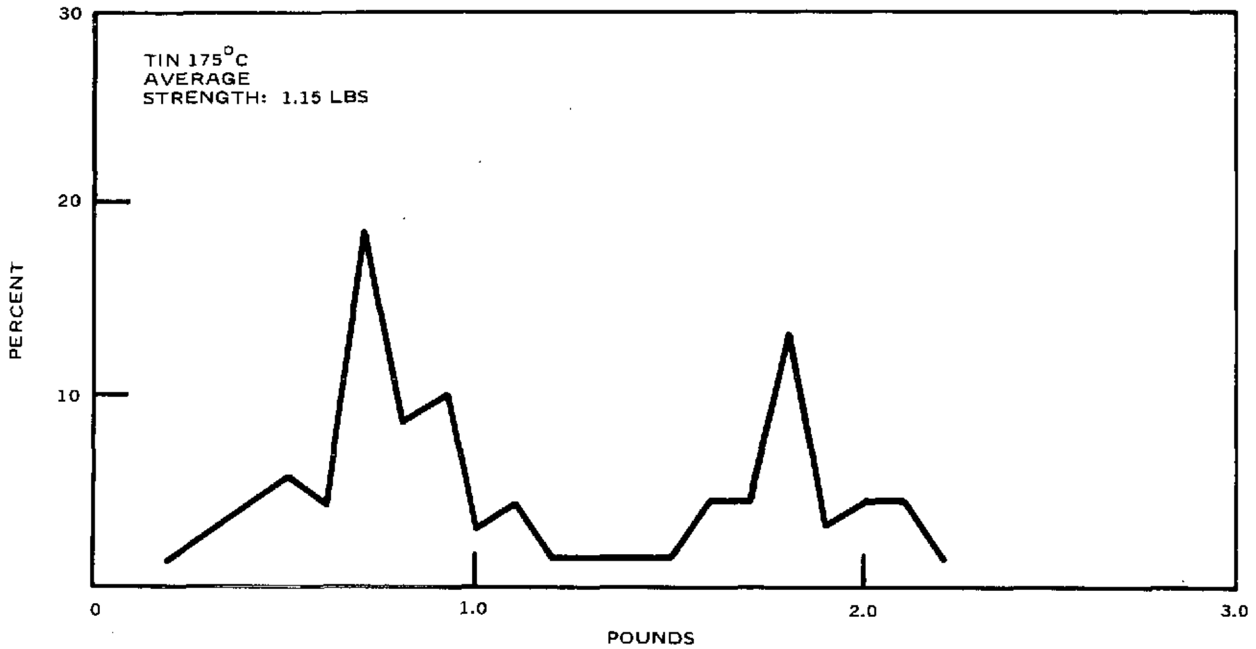


Figure 1-17. Frequency Distribution of Bond Tests at 175°C on Samples Aged for 500 Hours at 125°C

Bond Tests On Production Boards

A production board design was selected for bond testing to determine the repeatability of given machine settings with variations in circuit paths. Boards were made with both indium and tin plating and one and two ounce copper cladding. An additional mil of copper was plated prior to final plating to duplicate the copper added during through-hole plating. The results of bond tests are given in Tables 1-22 thru 1-25.

In all cases, a schedule of 0.5 volt, 5 milliseconds was tried first because it had been established for boards having pads only without circuitry. It was necessary to increase the voltage to 0.62 to 0.65 to obtain consistent bonds. More difficulty was experienced in obtaining consistent bonds to the indium-plated boards. This difficulty was due to impurities in the deposit on this particular set of boards. In one case more consistent bonds were obtained when the pressure was increased from 3 pounds to 8 pounds. The problem of consistency is not due to circuit configuration because the weak bonds did not occur consistently on the same pads.

TABLE 1-22. PRODUCTION BOARD BOND TESTS
TIN PLATING - 1 OUNCE COPPER

Mean: 1.9 Std. Dev: 0.31

Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*		Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*	
			P/L	P/B				P/L	P/B
.5v 5 ms	1	0.45	X		.65v 5 ms	27	1.84		X
.5v 5 ms	2	0.38	X		.65v 5 ms	28	1.86		X
.5v 5 ms	3	0.48	X		.65v 5 ms	29	1.86		X
.5v 5 ms	4	0.40	X		.65v 5 ms	30	1.87		X
.5v 5 ms	5	0.41	X		.65v 5 ms	31	1.90		X
.5v 5 ms	6	0.52	X		.65v 5 ms	32	1.84		X
.5v 5 ms	7	0.37	X		.63v 5 ms	33	1.70		X
.5v 5 ms	8	0.42	X		.63v 5 ms	34	2.03		X
.5v 5 ms	9	0.28	X		.63v 5 ms	35	2.13		X
.65v 5 ms	10	2.03		X	.63v 5 ms	36	2.30		X
.65v 5 ms	11	1.80		X	.63v 5 ms	37	1.40	X	
.65v 5 ms	12	2.50		X	.63v 5 ms	38	1.66		X
.65v 5 ms	13	2.50		X	.63v 5 ms	39	1.50		X
.65v 5 ms	14	2.39		X	.63v 5 ms	40	0.68	X	
.65v 5 ms	15	2.20		X	.63v 5 ms	41	1.79		X
.65v 5 ms	16	2.46		X	.63v 5 ms	42	2.04		X
.65v 5 ms	17	2.22		X	.63v 5 ms	43	2.00		X
.65v 5 ms	18	1.80		X	.63v 5 ms	44	1.98		X
.65v 5 ms	19	1.83		X	.63v 5 ms	45	2.00		X
.65v 5 ms	20	1.66		X	.63v 5 ms	46	1.80		X
.65v 5 ms	21	1.66		X	.63v 5 ms	47	1.62		X
.65v 5 ms	22	1.96		X	.63v 5 ms	48	1.80		X
.65v 5 ms	23	1.74		X	.63v 5 ms	49	1.78		X
.65v 5 ms	24	1.70		X	.63v 5 ms	50	1.86		X
.65v 5 ms	25	1.90		X	.63v 5 ms	51	1.84		X
.65v 5 ms	26	1.84		X	.63v 5 ms	52	1.78		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-23. PRODUCTION BOARD BOND TESTS
TIN PLATING - 2 OUNCE COPPER

Mean: 1.5 Std. Dev: 0.37

Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*		Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*	
			P/L	P/B				P/L	P/B
.5v 5 ms	1	0.15	X		.62v 5 ms	28	1.68		X
.5v 5 ms	2	0.24	X		.62v 5 ms	29	1.61		X
.5v 5 ms	3	0.38	X		.62v 5 ms	30	1.70		X
.5v 5 ms	4	0.30	X		.62v 5 ms	31	1.88		X
.5v 5 ms	5	0.30	X		.62v 5 ms	32	1.90		X
.5v 5 ms	6	0.41	X		.62v 5 ms	33	1.50		X
.5v 5 ms	7	0.30	X		.62v 5 ms	34	2.03		X
.5v 5 ms	8	0.27	X		.62v 5 ms	35	1.12	X	
.5v 5 ms	9	0.40	X		.62v 5 ms	36	1.90		X
.5v 5 ms	10	0.68	X		.62v 5 ms	37	0.82	X	
.62v 5 ms	11	1.51		X	.62v 5 ms	38	1.78		X
.62v 5 ms	12	1.54		X	.62v 5 ms	39	1.73		X
.62v 5 ms	13	1.76		X	.62v 5 ms	40	1.82		X
.62v 5 ms	14	1.42		X	.62v 5 ms	41	1.70		X
.62v 5 ms	15	1.02		X	.62v 5 ms	42	1.45		X
.62v 5 ms	16	1.39		X	.62v 5 ms	43	1.68		X
.62v 5 ms	17	1.64		X	.62v 5 ms	44	0.32	X	
.62v 5 ms	18	1.49		X	.62v 5 ms	45	1.80		X
.62v 5 ms	19	1.95		X	.62v 5 ms	46	1.70		X
.62v 5 ms	20	1.78		X	.62v 5 ms	47	1.50		X
.62v 5 ms	21	1.88		X	.62v 5 ms	48	1.79		X
.62v 5 ms	22	1.82		X	.62v 5 ms	49	1.80		X
.62v 5 ms	23	1.82		X	.62v 5 ms	50	0.94	X	
.62v 5 ms	24	1.80		X	.62v 5 ms	51	0.68	X	
.62v 5 ms	25	1.52		X	.62v 5 ms	52	1.02		X
.62v 5 ms	26	1.72		X	.62v 5 ms	53	1.02	X	
.62v 5 ms	27	1.90		X	.62v 5 ms	54	1.50		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-24. PRODUCTION BOARD BOND TESTS
INDIUM PLATING - 1 OUNCE COPPER

Mean: 1.0   Std. Dev: 0.73

Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*		Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*	
			P/L	P/B				P/L	P/B
.5v 5 ms	1	0	X		.62v 5 ms	28	1.70		X
.5v 5 ms	2	0.06	X		.62v 5 ms	29	0.69	X	
.5v 5 ms	3	0	X		.62v 5 ms	30	1.64		X
.5v 5 ms	4	0.19	X		.62v 5 ms	31	1.68		X
.5v 5 ms	5	0.07	X		.62v 5 ms	32	1.54		X
.5v 5 ms	6	0.28	X		.62v 5 ms	33	1.96		X
.5v 5 ms	7	0	X		.62v 5 ms	34	0.02	X	
.5v 5 ms	8	0.42	X		.62v 5 ms	35	0.02	X	
.5v 5 ms	9	0.09	X		.62v 5 ms	36	1.45		X
.62v 5 ms	10	1.80		X	.62v 5 ms	37	0.62	X	
.62v 5 ms	11	1.78		X	.62v 5 ms	38	0.02	X	
.62v 5 ms	12	1.42		X	.62v 5 ms	39	1.53		X
.62v 5 ms	13	1.12		X	.62v 5 ms	40	1.43		X
.62v 5 ms	14	1.93		X	.62v 5 ms	41	0.30	X	
.62v 5 ms	15	2.10		X	.62v 5 ms	42	0.64		X
.62v 5 ms	16	1.38		X	.62v 5 ms	43	0.02	X	
.62v 5 ms	17	2.00		X	.62v 5 ms	44	0.83		X
.62v 5 ms	18	2.15		X	.62v 5 ms	45	0.94		X
.62v 5 ms	19	2.30		X	.62v 5 ms	46	1.52		X
.62v 5 ms	20	1.79		X	.62v 5 ms	47	0.80		X
.62v 5 ms	21	0.88	X		.62v 5 ms	48	0.01	X	
.62v 5 ms	22	0.59	X		.62v 5 ms	49	1.14	X	
.62v 5 ms	23	0.57	X		.62v 5 ms	50	1.36		X
.62v 5 ms	24	1.48		X	.62v 5 ms	51	0.02	X	
.62v 5 ms	25	0.02	X		.62v 5 ms	52	0.04	X	
.62v 5 ms	26	0.44	X		.62v 5 ms	53	0.64	X	
.62v 5 ms	27	0.12	X		.62v 5 ms	54	0	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-25. PRODUCTION BOARD BOND TESTS
INDIUM PLATING - 2 OUNCE COPPER

Mean: 1.2 Std. Dev: 0.69

Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*		Bond Schedule	Number	Bond Strength (Lbs)	Type of Separation*	
			P/L	P/B				P/L	P/B
.5v 5 ms	1	0	X		.65v 5 ms	28	0.62	X	
.5v 5 ms	2	1.40	X		.65v 5 ms	29	0.26	X	
.5v 5 ms	3	0.09	X		.65v 5 ms	30	1.10	X	
.5v 5 ms	4	0	X		.65v 5 ms	31	0.49	X	
.5v 5 ms	5	0	X		.65v 5 ms	32	0.52	X	
.5v 5 ms	6	0	X		.65v 5 ms	33	0.34	X	
.5v 5 ms	7	0	X		.65v 5 ms	34	1.80	X	
.5v 5 ms	8	0.20	X		.65v 5 ms	35	0	X	
.5v 5 ms	9	0	X		.65v 5 ms	36	0.46	X	
.62v 5 ms	10	1.04	X		.65v 7 ms	37	1.53	X	
.62v 5 ms	11	0.04	X		.65v 7 ms	38	2.88		X
.62v 5 ms	12	0	X		.65v 7 ms	39	1.38	X	
.62v 5 ms	13	0.88	X		.65v 7 ms	40	0.92	X	
.62v 5 ms	14	1.00	X		.65v 7 ms	41	0.55	X	
.62v 5 ms	15	0.81	X		.65v 7 ms	42	1.63	X	
.62v 5 ms	16	0.88	X		.65v 7 ms	43	0.90	X	
.62v 5 ms	17	0.02	X		.65v 7 ms	44	0.82	X	
.62v 5 ms	18	0.72	X		.65v 7 ms	45	1.43	X	
.65v 5 ms	19	0.87	X		.65v 7 ms	46**	2.91		X
.65v 5 ms	20	0.88	X		.65v 7 ms	47	1.72		X
.65v 5 ms	21	1.31	X		.65v 7 ms	48	1.98	X	
.65v 5 ms	22	0.59	X		.65v 7 ms	49	0.98		X
.65v 5 ms	23	1.20	X		.65v 7 ms	50	2.74	X	
.65v 5 ms	24	1.37	X		.65v 7 ms	51	1.22	X	
.65v 5 ms	25	0.72	X		.65v 7 ms	52	1.70		X
.65v 5 ms	26	0.80	X		.65v 7 ms	53	1.12		X
.65v 5 ms	27	1.32	X		.65v 7 ms	54	1.08	X	

*P/L = Pad to Lead; P/B = Pad to Board

**Pressure was increased from 3 pounds to 8 pounds from numbers 46 thru 54.

Evaluation of Higher Power Setting for Bonding to Tin

In comparing the tin and indium bond separation, it was observed that there was a fairly high percentage of pad to lead separations with tin and practically none with indium. Since it is desirable to obtain bonds that result in consistent pad to board separation, it was decided to increase the power output for the tin bonds. The schedule was changed from 0.62 volt 5 ms to 0.75 volt 5 ms. Electrode gap and force remained at 0.005 inch and 3 pounds. Consistent pad to board separation did result as shown in Table 1-26. This higher power setting, however, caused visible melting of epoxy between the pads. The standard deviation of 0.3 for this set of bonds compared to 0.31 for indium at the lower power setting.

TABLE 1-26. RESULTS OF INCREASED POWER SETTING FOR TIN-PLATED BOARDS

Mean: 1.8 Std. Dev: 0.30

Number	Bond Strength (Lbs)	Type of Separation*	
		P/L	P/B
1	1.72		X
2	1.7		X
3	1.6		X
4	1.71		X
5	1.8		X
6	1.78		X
7	1.5		X
8	1.53		X
9	1.48		X
10	1.55		X
11	0.87		X
12	1.64		X
13	2.24		X
14	1.44		X
15	2.02		X
16	1.55		X
17	1.48		X
18	1.64		X
19	2.6		X
20	1.72		X
21	1.62		X
22	1.88		X
23	1.98		X
24	1.5		X
25	1.9		X
26	1.71		X
27	1.77		X
28	2.1		X
29	2.0		X
30	1.75		X
31	1.8		X
32	1.64		X
33	2.04		X
34	1.94		X
35	2.03		X
36	2.22		X
37	1.9		X
38	2.26		X
39	1.93		X
40	2.03		X
41	2.46		X
42	1.76		X
43	1.86		X
44	1.92		X
45	1.72		X
46	2.23		X
47	2.16		X
48	1.75		X
49	1.46		X
50	1.9		X

*P/L = Pad to Lead; P/B = Pad to Board

Bond Tests With Tin-Plated Kovar Leads

Since there is a trend in the industry to replace gold-plated Kovar with tin-plated Kovar lead devices, it was of interest to attempt diffusion bonding with the tin-plated lead material. The results with indium-plated boards are given in Table 1-27 and with tin in Table 1-28. As evident from the bond values and power settings, bonding with tin was difficult, but encouraging with indium.

This supports the selection of indium as the optimum material for diffusion bonding. It should be noted that tin and indium form a low melting entectic (117°C), thus less board damage occurs as opposed to pure tin interfaces which melt at a higher temperature.

TABLE 1-27. BOND TESTS OF TIN-PLATED LEADS TO INDIUM-PLATED BOARDS

Schedule	Bond Strength	Type of Separation*	
		P/L	P/B
.75v - 5.0 ms	0.3	X	
	0.65	X	
	0.9	X	
	0.84	X	
	1.49		X
	1.23		X
.76v - 5.0 ms	1.58		X
	1.23		X
Mean: 1.4	1.18		X
Std. Dev: 0.29	1.94		X
	1.44		X
	1.7		X
	1.23		X
	1.68		X
	1.54		X
	1.25		X
	0.91		X
	1.31		X
	0.74		X
	1.19		X
	1.5		X
	1.19		X
	1.64		X
	1.29		X
	1.51		X

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 1-28. BOND TESTS OF TIN-PLATED LEADS TO TIN-PLATED BOARDS

Schedule	Bond Strength	Type of Separation*		Comments
		P/L	P/B	
.9v - 14.0 ms	0.4	X		
	1.32		X	
	0.7	X		
	1.08		X	
	1.48		X	
	1.5		X	
	1.4	X		
.8v - 15.0 ms	1.68		X	
	0.79	X		
Mean: 0.66	1.5		X	
Std. Dev: 0.45	0.56	X		
	0.69	X		
	0.3	X		
	0.4	X		
	0.93	X		
	0.5	X		
	0.38	X		
	0.54	X		
	0.77	X		
	0.54	X		
	1.54		X	
	0.49	X		
	0.92		X	
	1.44	X		
	0.39	X		
	0.2	X		
	0.3	X		
	0.38	X		
	0.33	X		
	0.16	X		
	0.24	X		
1.1v - 5.0 ms	1.9		X	Board Damage
	2.51		X	Board Damage
	2.5		X	Board Damage
	2.22		X	Board Damage
	2.24		X	Board Damage
1.0v - 5.0 ms	0.74	X		
	1.56		X	
	0.6	X		
	2.2		X	
	0.68	X		
	0.75	X		
	1.92	X		
	0.6	X		
	1.98	X		

*P/L = Pad to Lead; P/B = Pad to Board

SUMMARY OF BOND TESTS

Indium was found to be superior to tin as the low melting metal used in the bond interface. Lower power settings were required; the bonds were more consistent and resulted in removal of copper foil from the circuit board during pull testing.

The bond test results for indium are summarized in Table 1-29. In all cases the type of separation was between the copper foil and the board. The average bond strength for the unaged specimens decreased slightly with increased temperature due to the lower bond strength of the copper foil to the circuit board at elevated temperature. The number of bonds that were less than one pound increased from 0 at ambient to 1.4 percent at 125°C and 25.5 percent at 175°C for the same reason. The bond strengths of the aged specimens also resulted in pad to board separation, except for one instance, and averaged over one pound at all test temperatures. The apparent discontinuity in average bond strengths is probably due to the additional cure which gives higher elevated temperature strength but a lower ambient temperature bond between the copper and the circuit board. The bonds with indium were consistent, resulted in good elevated temperature strength, and were accomplished at low power settings.

TABLE 1-29. SUMMARY OF BOND TESTS FOR INDIUM

Condition	Test Temperature	Mean	Standard Deviation	Type of Separation*		Separation at <1.0 lb.		
				P/L	P/B	P/L	P/B	% Total
Unaged	Ambient	1.7	0.31	0	69	0	0	0
	125°C	1.6	0.38	0	70	0	1	1.4%
	175°C	1.2	0.27	0	67	0	17	25.5%
1000 Hours at 150°C	Ambient	1.1	0.12	0	57	0	6	10.5%
	125°C	2.2	0.34	1	65	0	0	0
	175°C	1.4	0.26	0	68	0	8	12.0%

*P/L = Pad to Lead; P/B = Pad to Board

The bond test results for tin are summarized in Table 1-30. Although the average bond strengths are in the same range as those with indium the range of values is wider and the percentage of bonds less than one pound is higher. The standard deviation for tin bonds is 25 to 50 percent higher than those for indium. Also there is a high percentage of bonds that separated between the lead and copper foil (P/L) which account for most of the values below one pound. It is felt that the values on the samples aged at 150°C for 1000 hours are invalid, except for the 125°C test, because of degradation of the boards during aging. The reason for the degradation of these particular specimens was not known but for the sake of expediency a second set of samples was prepared and aged for 500 hours at 125°C. Unlike the aged indium bonds all the bonds that were less than one pound, of which there was a relatively high percentage, were a result of separation between the copper foil and Kovar lead (P/L). Although the average bond strength was good there was more scatter and more lower strength bonds with tin than with indium. The data therefore shows indium to be superior to tin as the low melting metal used in the bond interface.

TABLE 1-30. SUMMARY OF BOND TESTS FOR TIN

Condition	Test Temperature	Mean	Standard Deviation	Type of Separation*		Separation at <1.0 lb.		
				P/L	P/B	P/L	P/B	% Total
Unaged	Ambient	1.8	0.65	0	70	0	7	10.0%
	125°C	1.3	0.59	35	24	18	1	57.0%
	175°C	1.3	0.43	16	48	8	3	22.0%
1000 Hours at 150°C	Ambient	0.5	0.23	49	8	47	8	96.0%
	125°C	1.3	0.46	4	15	3	0	15.0%
	175°C	0.6	0.21	0	70	0	65	93.0%
500 Hours at 125°C	Ambient	1.9	0.74	24	36	11	0	18.3%
	125°C	1.0	0.41	68	2	50	0	71.4%
	175°C	1.1	0.56	46	24	37	0	52.8%

*P/L = Pad to Lead; P/B = Pad to Board

SECTION 2

METALLURGICAL ANALYSIS OF BONDS

METHOD OF ANALYSIS

Metallurgical analysis of the bondline was conducted using the scanning electron microscope and nondispersive x-ray analyzer and the electron microprobe analyzer (early in the program). The SEM permitted high magnification, resolution and depth of field for viewing the bonded areas and obtaining bondline thickness measurements. The x-ray analyzer and electron microprobe were used to give the concentration and distribution of elements along the bondline. Use of the electron microprobe analyzer was discontinued early in the program as discussed under the section entitled Initial Analysis.

X-Ray Analysis

X-ray analysis utilizes the fact that when high energy electrons strike a material, x-rays are generated which are characteristic of the elements in the material. Instruments have been developed to exploit this phenomena for the analysis, which can be conducted in various ways.

Element Map

If the sensor is adjusted to sense only one element of a specimen and then the electron beam is scanned over the specimen synchronously with a cathode ray tube display, the picture that results is an element map showing the distribution of the selected element over the surface of the specimen, as in Figure 2-1A.

Line Scan

An alternative mode of operation is the line scan. In this mode, the output from the x-ray sensor and the electron beam scan drive signal is connected to an X-Y recorder. The electron beam is scanned in one direction only; thus it produces a line scan as in Figure 2-1B (left) rather than a surface scan. The line scans record the count rate in counts per second of the specific x-ray. In general, on the line scan charts, the indicated count rate is 100 counts per second per major grid division. In a few cases, a scale multiplier has been used so that the count rate scale factor is 50 counts per second per major grid line. Operation of the analyzer in the line scan mode is much more amenable to quantitative analysis than is the element map.

In this report, the line scan data was further analyzed by creating element distribution plots as in Figure 2-1B (right). Here, the relative data from the line scan is calculated into elemental percentages utilizing the line scan plot and known count rates for each element. To do so, some curve fitting is used, thus the resulting distribution plots are not of extreme accuracy, but are useful in analyzing the data.

X-Ray Counts

A third mode of analysis using the x-ray analyzer is to record the number of element counts during the analysis (used as a means of specimen comparision, showing relative differences in quantities of elements present). The quantity of the x-rays of a specific element is proportional to the amount of that element present in the specimen. The x-ray counts listed in the various tables of this report indicate the number of x-rays detected for the specific element in a fixed period of time.

INITIAL ANALYSIS

Initially, it was felt that bonding occurred by diffusion of the indium or tin into the gold and copper with excess of the low melting metal squeezed out of the bondline. The resulting bond would be essentially a braze consisting of a mixture of the three metals. The initial analyses were conducted on bonds selected at random from three sources:

1. Indium-plated boards using parallel-gap bonding.
2. Indium-plated boards using peg tip bonding.
3. Tin-plated boards using parallel-gap bonding.

These examinations were made on untested bonds to compare the relative bond characteristics for each type. Consequently, bond strengths were not known and could only be correlated to pull test data on bonds made under the same conditions. During the first portion of the program an electron microprobe analyzer was used for bondline analysis. As a result, only three elements (gold, indium or tin, and copper) are recorded for the following reasons:

1. Only those three elements were considered important to bond analysis.
2. The microprobe analyzer is limited to analyzing three elements at one time.

Indium Bonds

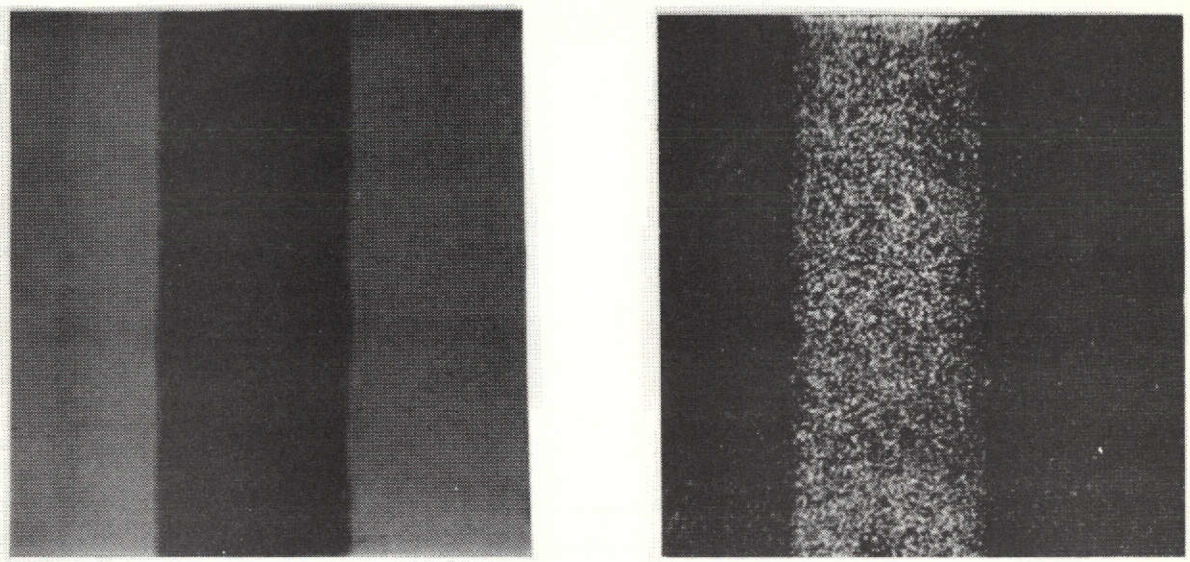
Analysis of indium bonds encompassed two types of joining methods as mentioned above. The data relative to these bonds are shown in Figure 2-1A and 2-1B for parallel-gap bonding and Figures 2-2A and 2-2B for peg tip.

Figures 2-1A and 2-2A are x-ray maps of 3 mil square areas of the bonds discussed. The first picture in each series is a scanning electron micrograph - absorbed electron mode - of the specimen. The light area along the right edge is the epoxy-glass board material, the medium gray band adjacent is the copper, the dark band is the gold-indium and the gray bond on the left is the Kovar lead material. The other three pictures in each figure show the distribution of the indicated elements throughout the interface.

Figures 2-1B and 2-2B reproduce the line scan records of each specimen for the materials of interest and also show graphically the distribution of materials as deduced from these line scans. In these distribution charts, the left edge corresponds to the surface of the Kovar. The right edge is in the copper foil. The horizontal scale is approximately 2.5 microns per inch.

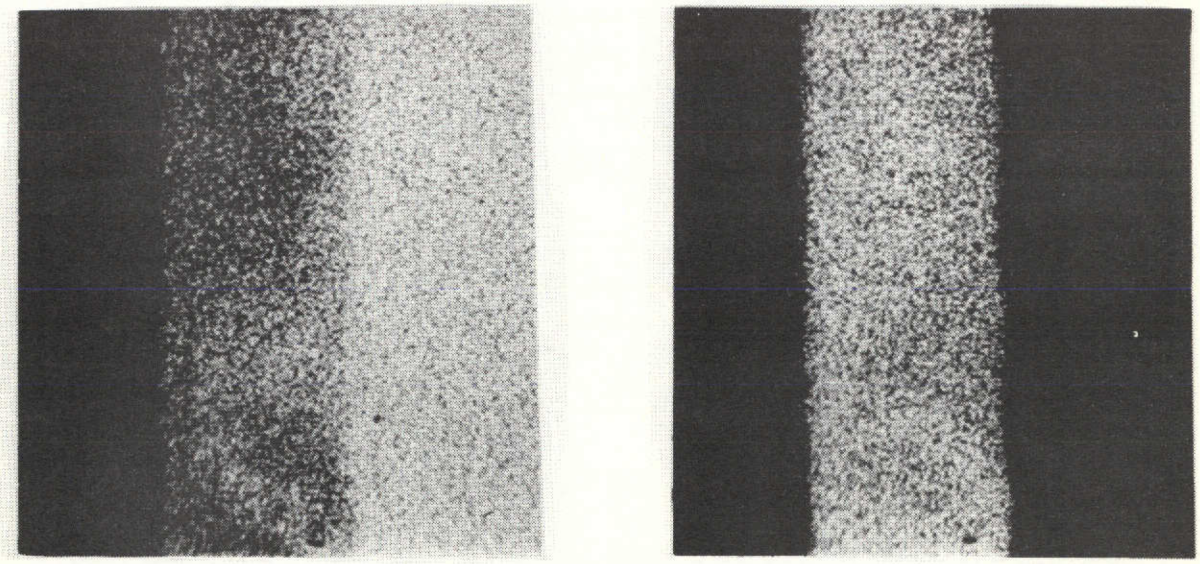
The indium-gold bond shown in Figure 2-1A and 2-1B shows copper from the edge of the Kovar or gold side of the bond gradually increasing in concentration. The concentration of gold and indium is fairly constant at 40 percent each throughout most of the bond in the same region that copper remains constant at about 20 percent.

The indium-gold bond shown in Figure 2-2A and 2-2B shows very little copper except for the region close to the circuit pad. The concentration of the gold and indium is relatively constant across most of the bond similar to Figures 2-1A and 2-1B.



Positive Absorbed Electrons

Bondline Showing
Distribution of Gold



Bondline Showing
Diffusion of Copper

Bondline Showing
Distribution of Indium

Figure 2-1A. X-Ray Maps - Indium-Gold-Copper Bond - Parallel-Gap Bonded

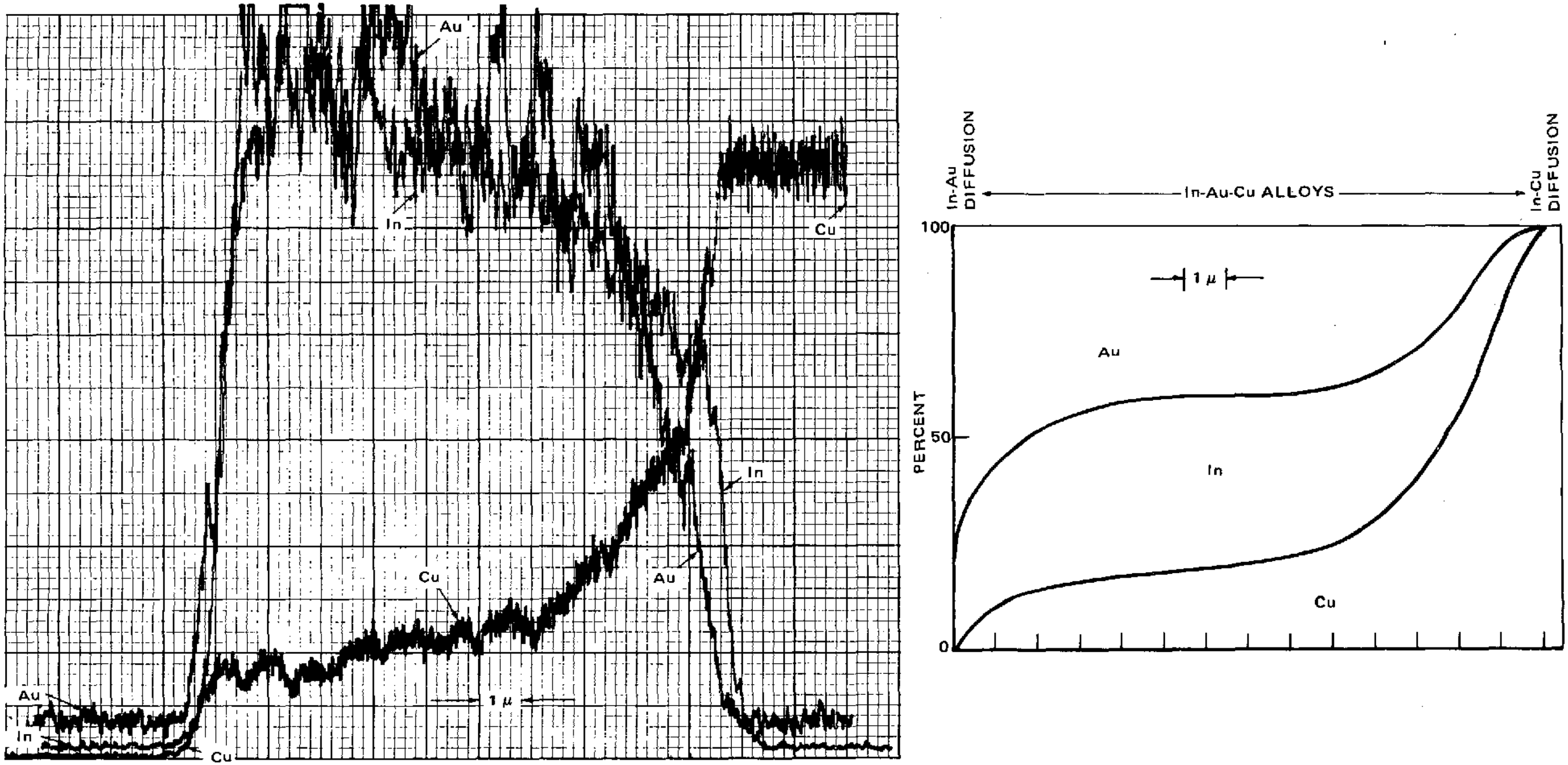
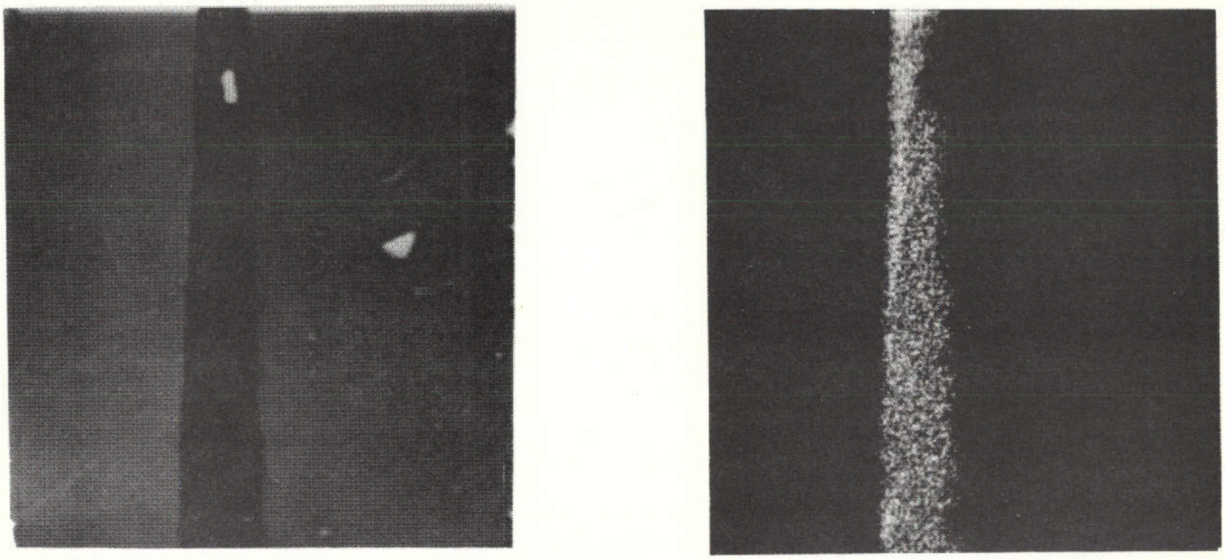
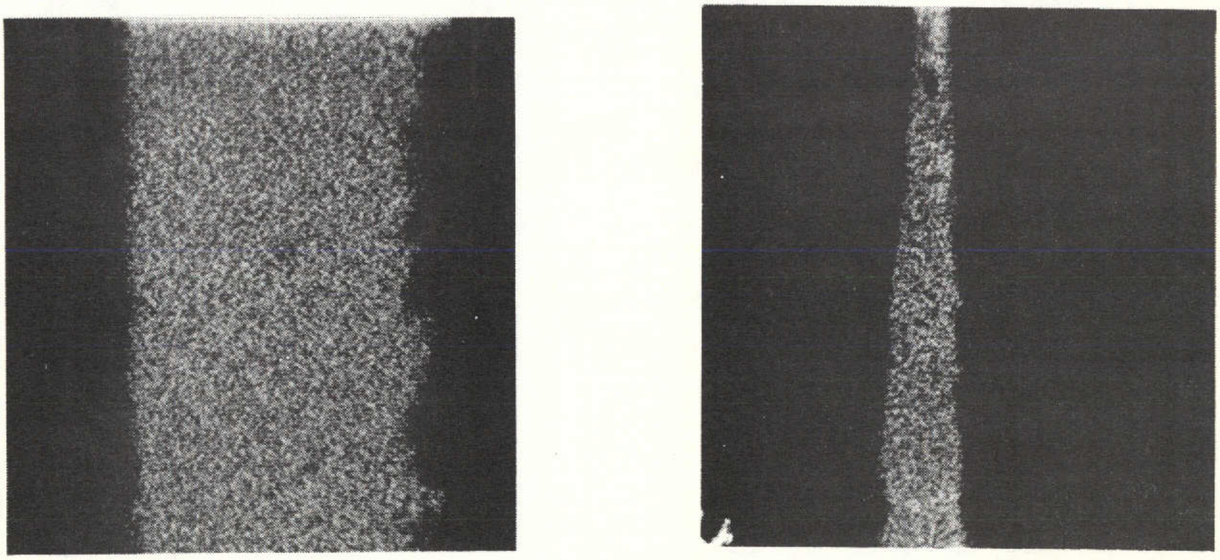


Figure 2-1B. Relative and Percentage Concentration of Elements in Indium-Bonded Flatpack Lead - Parallel-Gap Bonded



Absorbed Electrons Showing Bond Interface

Bondline Showing Distribution of Gold



Bondline Showing Diffusion of Copper

Bondline Showing Distribution of Indium

Figure 2-2A. X-Ray Maps - Indium-Gold-Copper Bond - Peg Tip Bonded

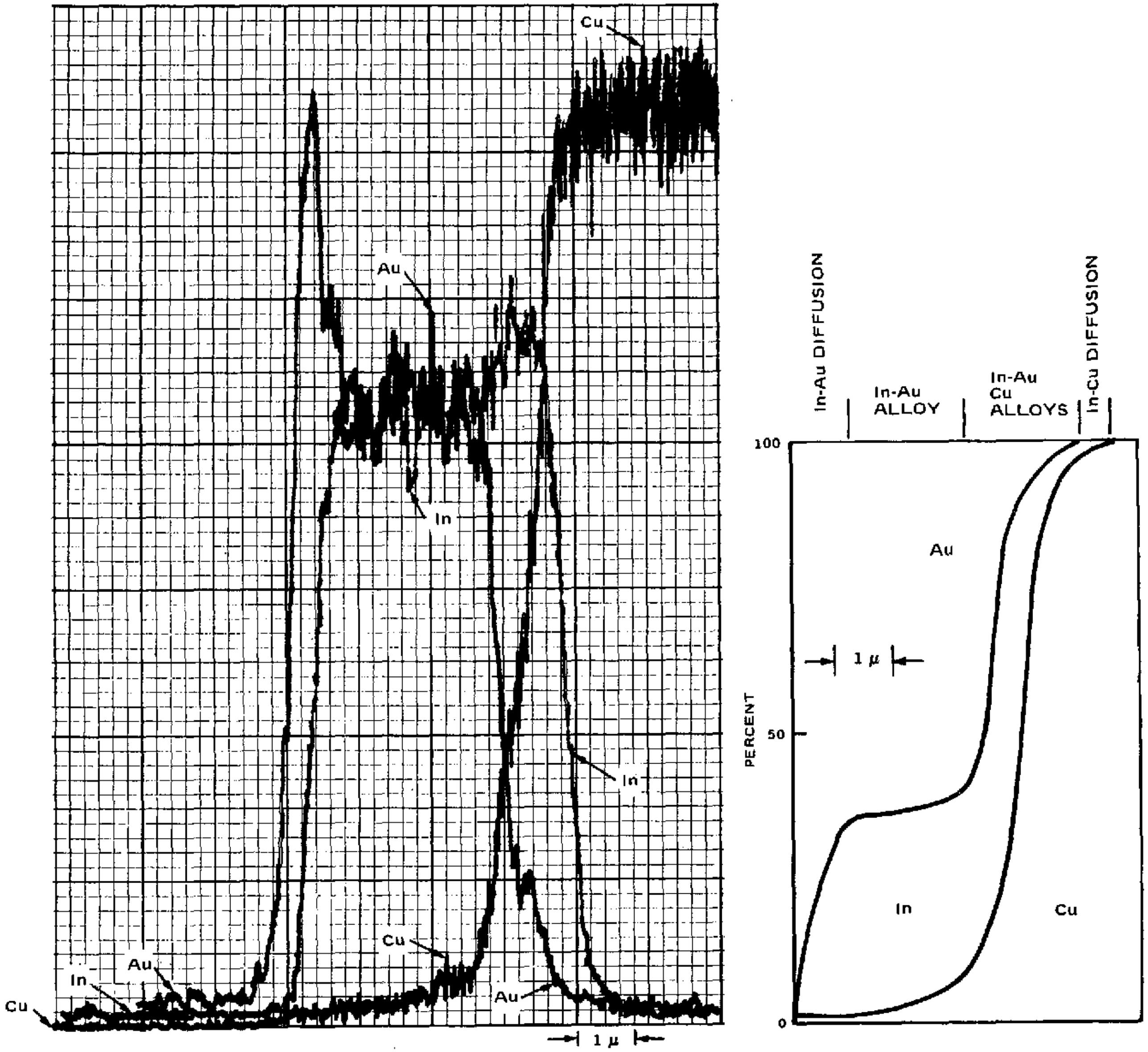


Figure 2-2B. Relative and Percentage Concentration of Elements in Indium-Bonded Flatpack Lead - Peg Tip Bonded

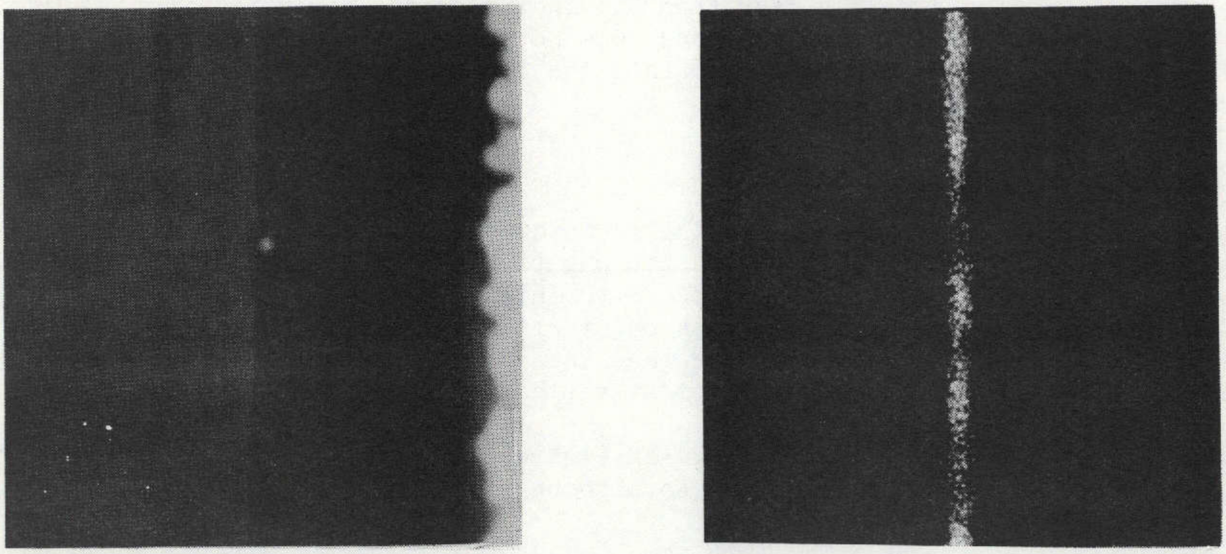
Tin Bonds

It was determined that the peg tip approach caused excessive board damage; therefore, the analysis of the tin bond was with parallel-gap bonding only. The line scans shown in Figure 2-3B differ from the indium sample shown in Figure 2-1B in that the extreme left side of the bond does not approach 100 percent gold. All gold and tin has alloyed or diffused into the copper providing a more complete three-element bond than with indium.

Summary of Initial Bond Analysis

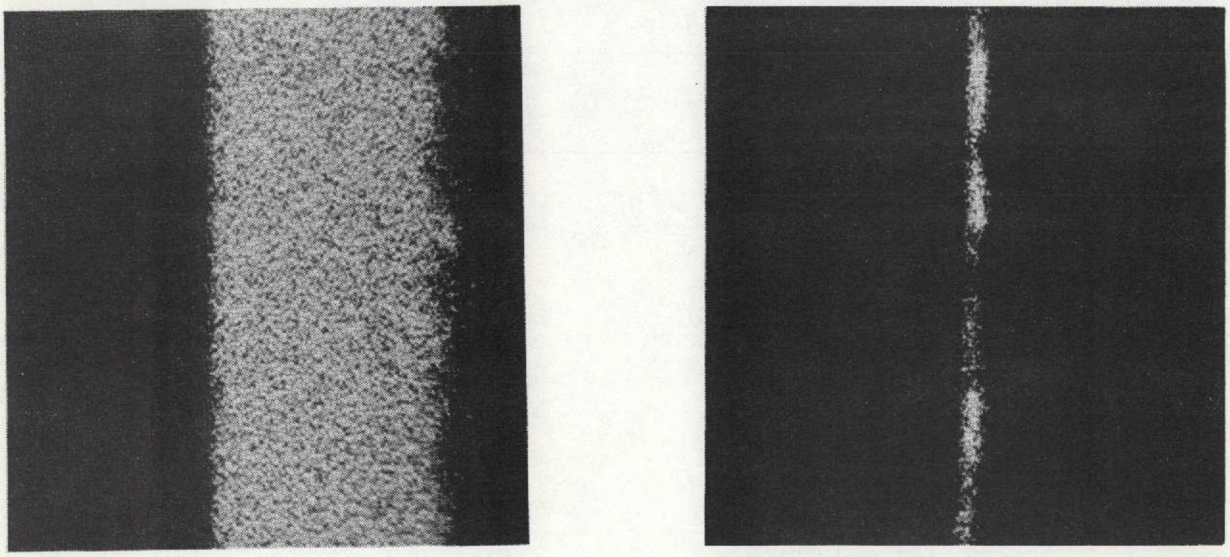
Comparison of the two types of bonding techniques shows more copper alloying with the parallel-gap technique than with the peg tip; thus the parallel-gap indicates a three-element bond while peg tip appears to involve two elements (Au and In). A slight amount of copper alloying does occur with the peg tip, but it is not appreciable. The tin bond is much narrower than the indium bond and involves complete alloying of the tin, gold, and copper at the bond interface.

The indium region appears quite large in Figure 2-1B and 2-2B, but the entire gold region is not in evidence (i.e., no Kovar boundary).



Positive-Absorbed Electrons
Showing Bond Interface

Bondline Showing
Distribution of Gold



Bondline Showing
Distribution of Copper

Bondline Showing
Distribution of Tin

Figure 2-3A. X-Ray Maps - Tin-Gold-Copper Bond - Parallel-Gap Bonded

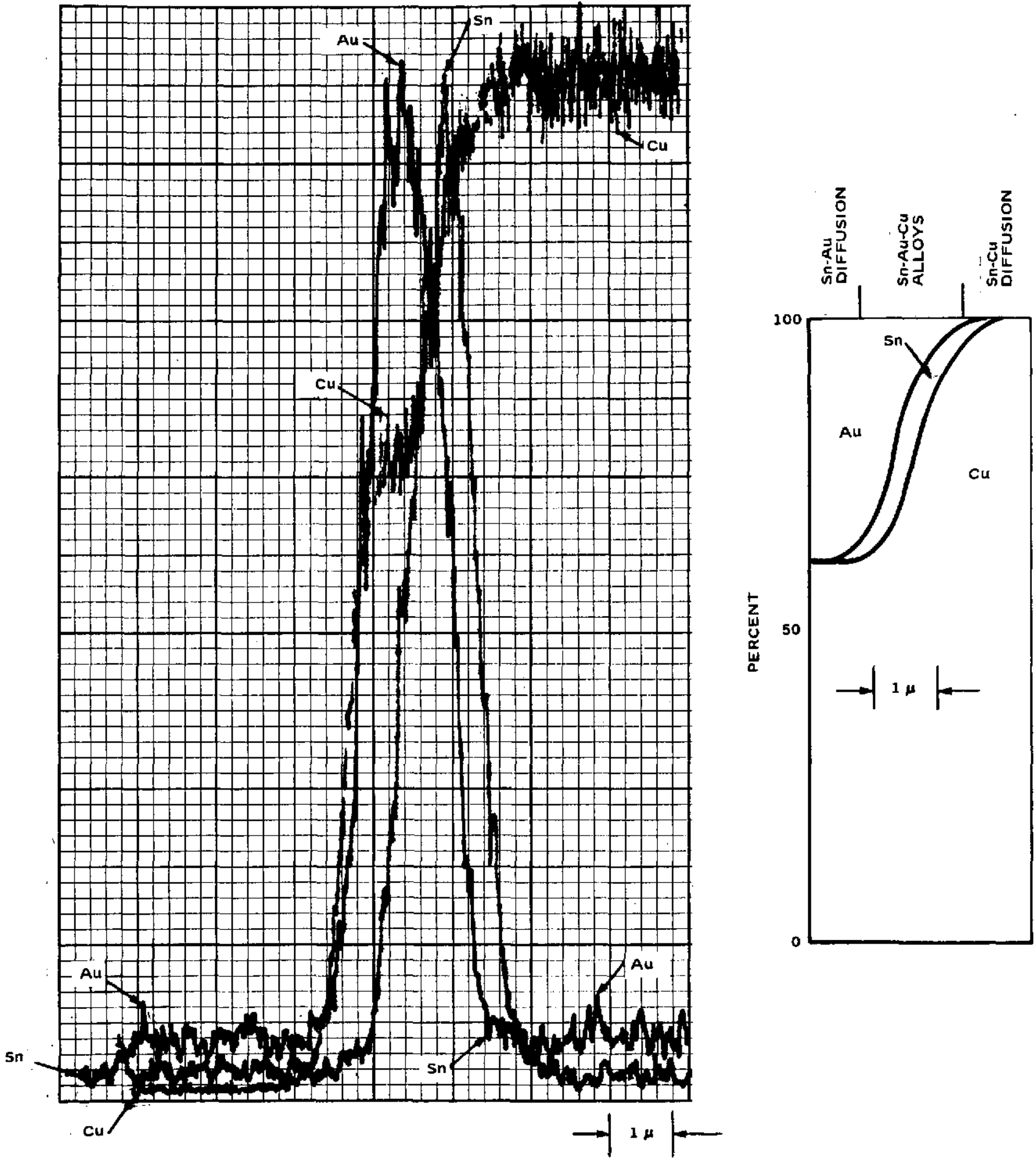


Figure 2-3B. Relative and Percentage Concentration of Elements in Tin-Bonded Flatpack Lead - Parallel-Gap Bonded

ANALYSIS OF AGED SPECIMENS

Bond tests on the tin boards after aging cast some doubt in the ability of tin to form stable bonds. For some reason the epoxy boards that were tin-plated degraded considerably while the boards with the indium bonds survived the 1000 hours of aging at 150°C in fair condition. The degradation of the copper to board bond was undoubtedly responsible for the low pull test values on the aged tin bonds. Line scans and element distribution graphs, however, were made and compared for the two different conditions, unaged and aged, for both tin and indium. The results are shown in Figures 2-4, 2-5, 2-6, and 2-7.

Two observations made from the scans are:

1. The bond lines appear to be wider on the aged samples than the unaged ones, and

2. The area designated In-Cu in Au, Figures 2-4 and 2-5, tends to show a constant ratio of In and Cu. This ratio is almost 50/50 Cu/In and thus tends to correspond to the η phase of the Cu/In diagram shown in Figure 2-8. The constant ratio did not appear in the tin specimens.

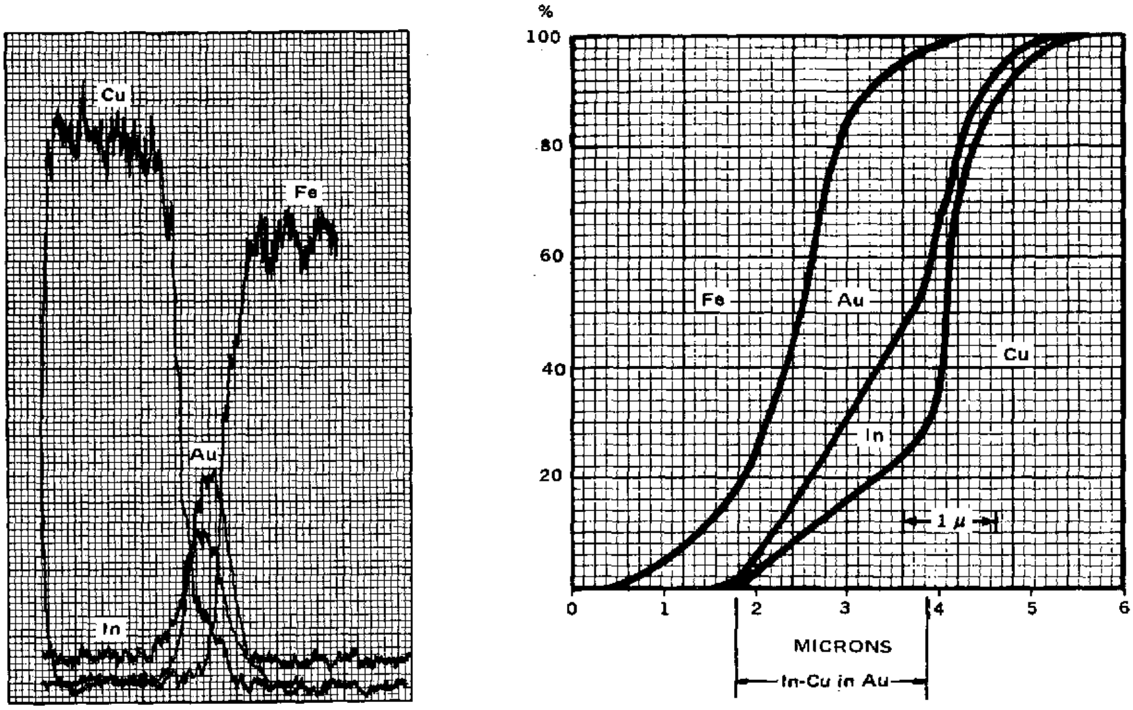


Figure 2-4. Line Scan and Element Distribution Graph of Indium Bond Unaged

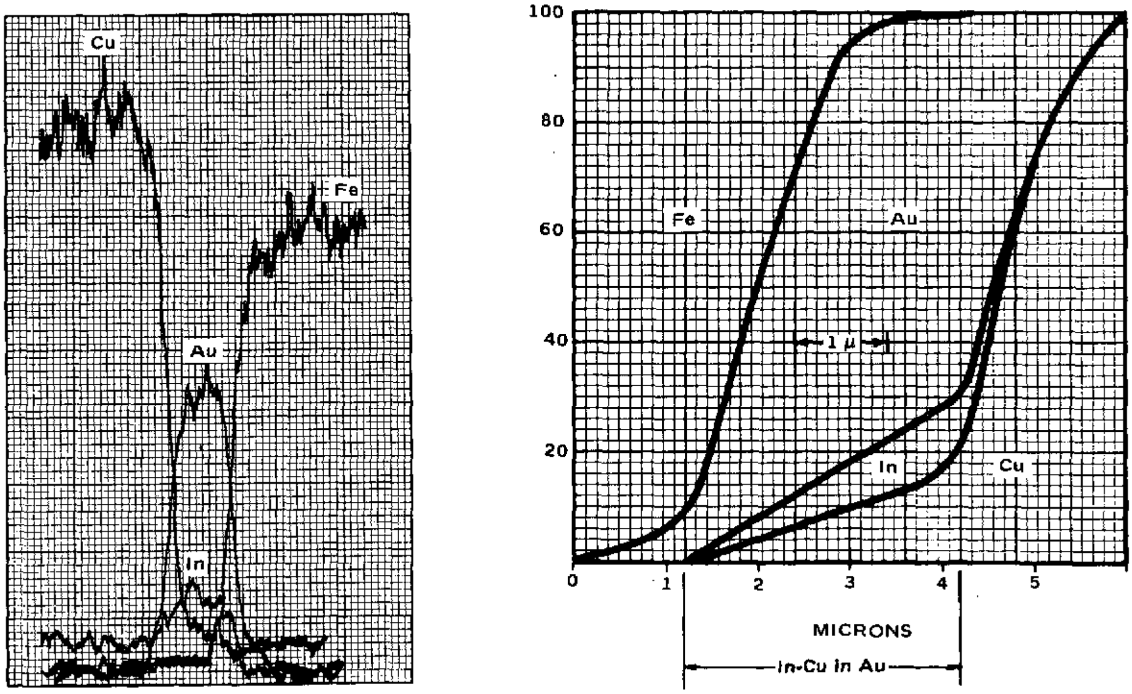


Figure 2-5. Line Scan and Element Distribution Graph of Indium Bond Aged 1000 Hours at 150°C

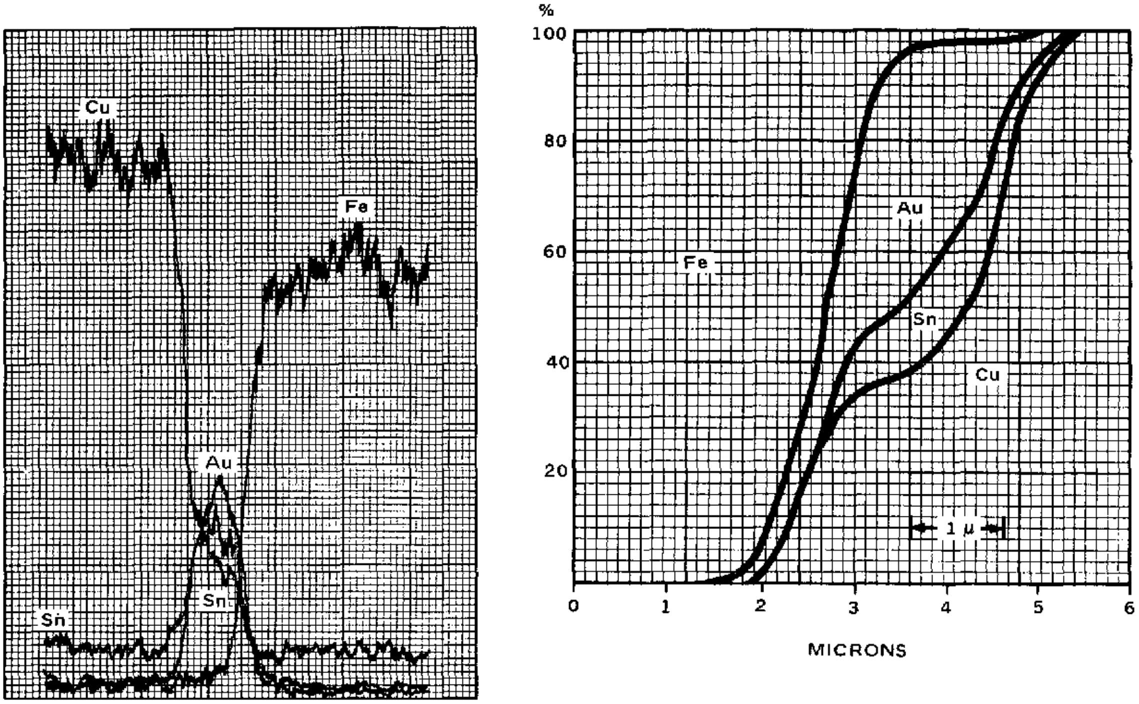


Figure 2-6. Line Scan and Element Distribution Graph of Tin Bond Unaged

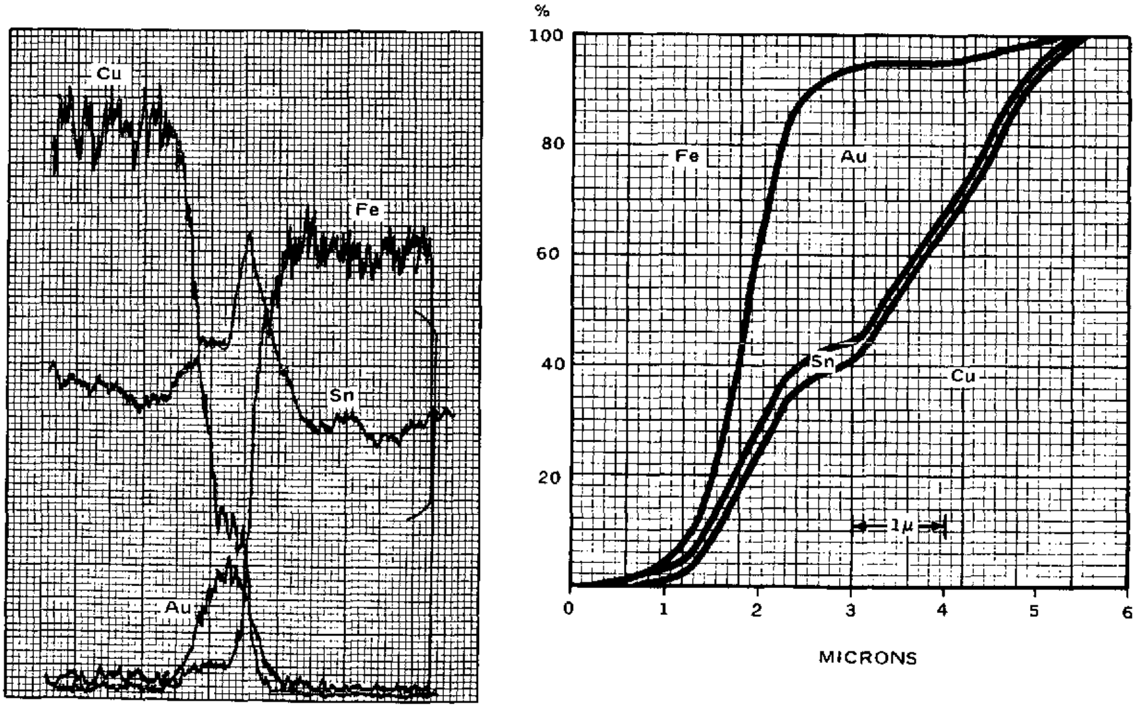


Figure 2-7. Line Scan and Element Distribution Graph of Tin Bond Aged 1000 Hours at 150°C

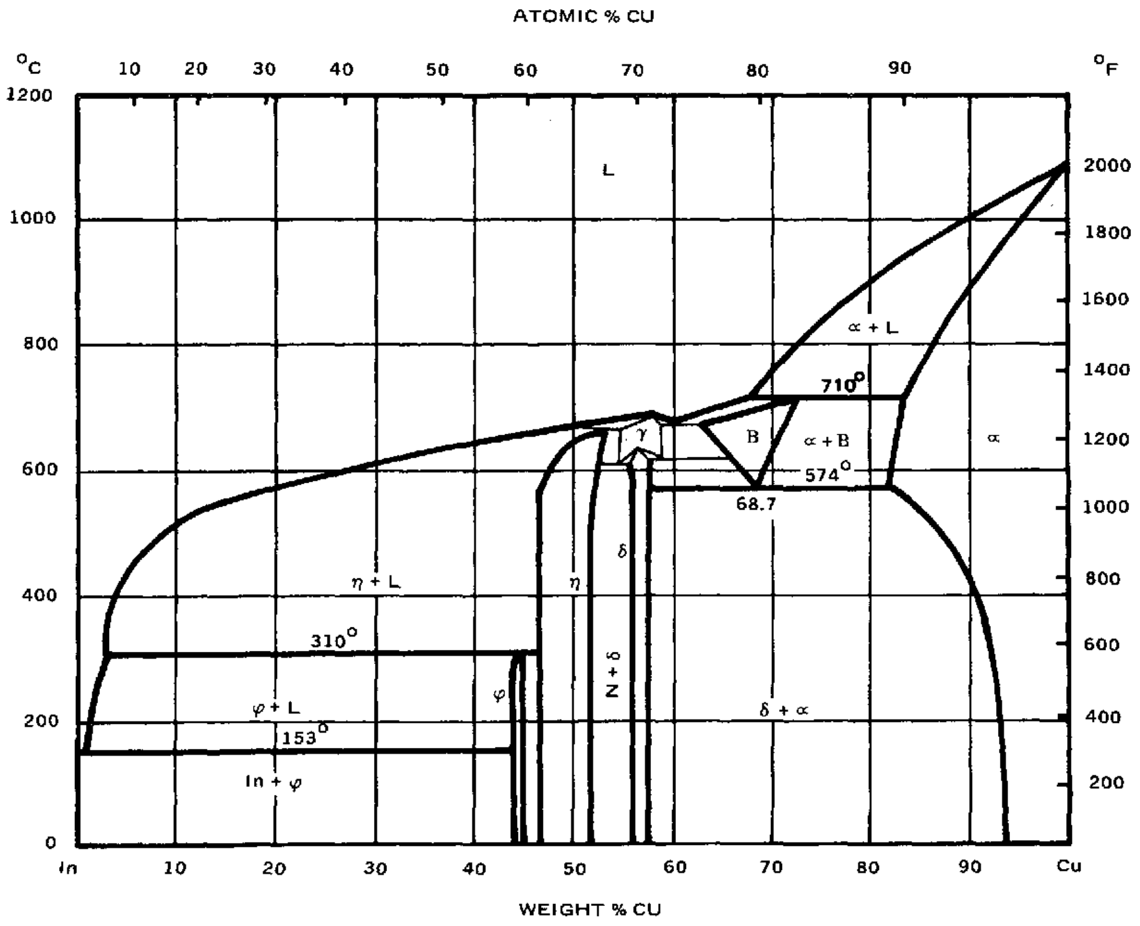


Figure 2-8. Copper/Indium Phase Diagram

ANALYSIS OF SEPARATED BONDS

All previous bondline analyses were made on bonds that were not pulled; therefore, it was not possible to relate the information gained to the relative strengths of the bonds. Also, an x-ray analysis represents a zone only 3 mils wide across a bondline that is 0.045 inch long and thus may not encompass the location of highest strength within a bond. For this reason it was decided to analyze specimens of pad to lead and pad to board separations in an attempt to detect any metallurgical differences in the two types of separation.

Pad to Board Separation

Pad to board separations with copper foil still intact were mounted and cross-sectioned. These were of primary interest since they represented the strongest type of bond. Line scans of leads pulled from indium and tin-plated boards are shown in Figures 2-9 and 2-10. The percentage distribution of elements across the bond were plotted from information taken from the scans and are shown on the right side of the figures. In both cases, all the elements are present completely across the bondline. The accompanying figures, 2-11 thru 2-16 for indium and 2-17 thru 2-22 for tin, indicate that metallurgically the bonds are basically due to alloying of gold, indium and copper, or, gold, tin and copper. The third metal (indium or tin) also acts to prevent oxidation of the copper prior to bonding and provides a lower melting interface to start the bond. As shown in the line scans and x-ray maps, the bond is practically all gold and in fact is approximately the width of the original gold-plating thickness on the Kovar lead material. Random measurements of the gold-plating thickness on the Kovar lead material were between 86 and 154 millionths of an inch. The bondline thicknesses shown in Figures 2-11, 2-17 and 2-18 are within this range.

Signs of bond separation or incomplete bonding can be seen in Figure 2-18 even though the bond separated in the pad to board mode. This is an indication of the cause of marginal bond performance experienced with tin.

The anlaysis of the pad to board separations agrees well with the data for unaged versus aged bonds. The indium shows the same indication of a possible n-phase (In-Cu) formation by the constant ratio portion of the element distribution curve. The tin shows a thinner bond area with formation of tin-gold alloy in the bond and little copper diffusion or alloying.

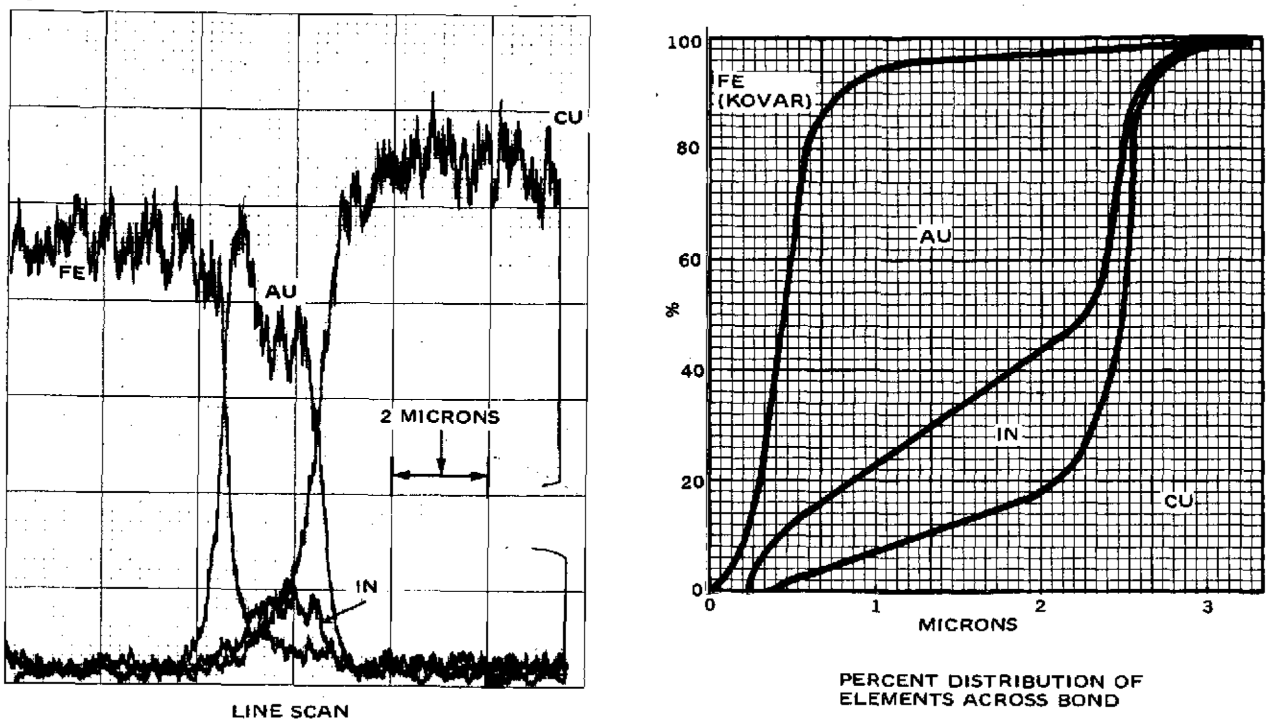


Figure 2-9. X-Ray Analysis of Pad to Board Separation - Indium-Plated Board Specimen

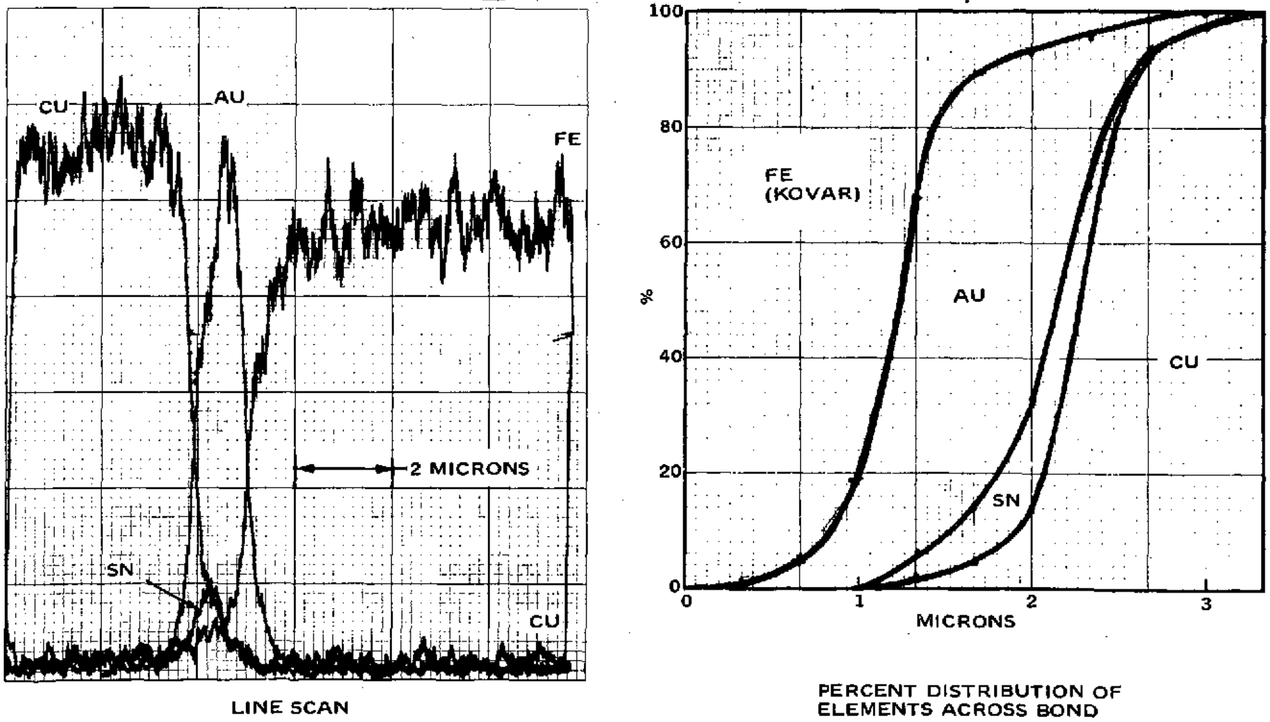


Figure 2-10. X-Ray Analysis of Pad to Board Separation - Tin-Plated Board Specimen

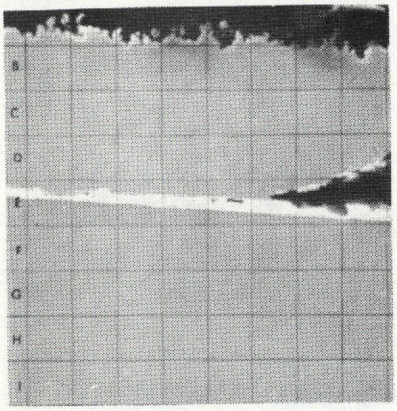


Figure 2-11. SEM Photograph of Indium Bond Resulting in Pad to Board Separation (570X)

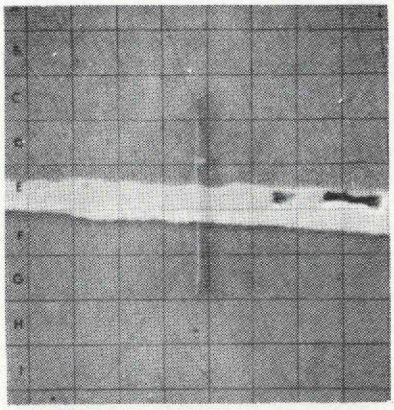


Figure 2-12. SEM Photograph of Indium Bond Resulting in Pad to Board Separation (1140X)

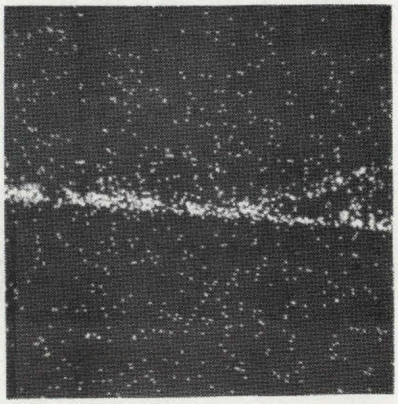


Figure 2-13. X-Ray Map Showing Distribution of Gold in Diffusion Bond Resulting in Pad to Board Separation (Indium Bond) (570X)

Figure 2-14. X-Ray Map Showing Distribution of Indium (Arrow) in Diffusion Bond Resulting in Pad to Board Separation (570X)

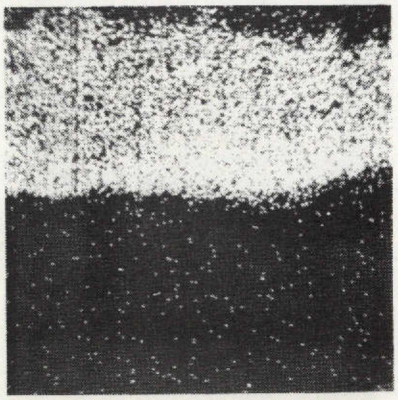


Figure 2-15. X-Ray Map Showing Distribution of Copper in Diffusion Bond Resulting in Pad to Board Separation (Indium Bond) (570X)

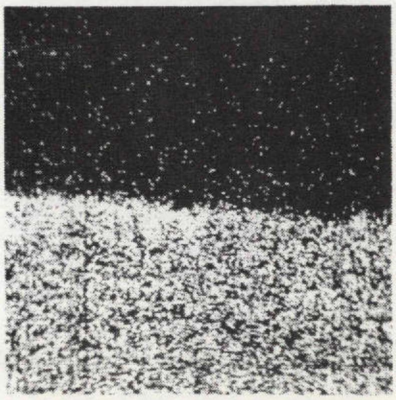


Figure 2-16. X-Ray Map Showing Distribution of Kovar in Diffusion Bond Resulting in Pad to Board Separation (Indium Bond) (570X)

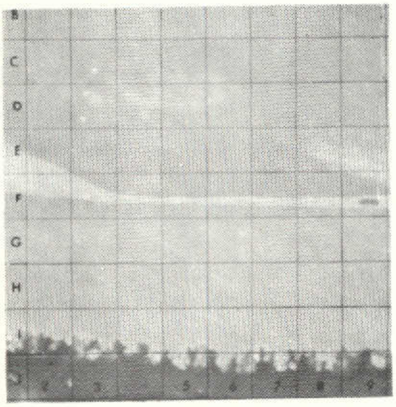


Figure 2-17. SEM Photograph of Tin Bond Resulting in Pad to Board Separation (570X)

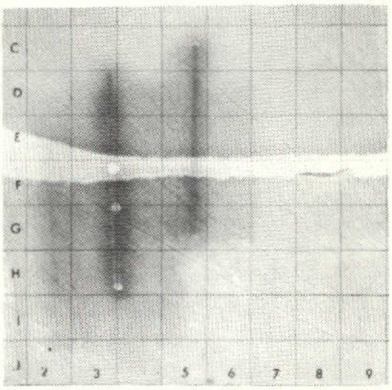


Figure 2-18. SEM Photograph of Tin Bond Resulting in Pad to Board Separation (1140X)

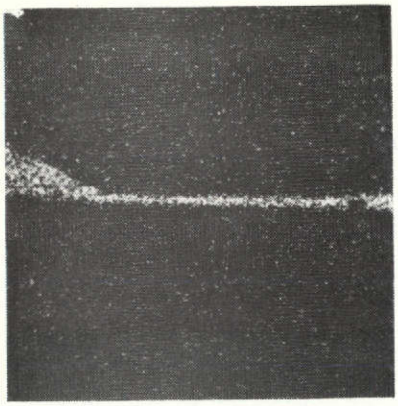


Figure 2-19. X-Ray Map of Gold Distribution in Tin Bond Resulting in Pad to Board Separation

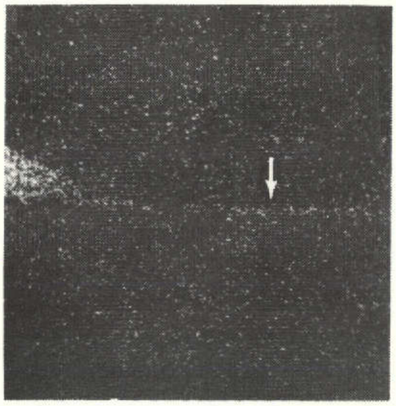


Figure 2-20. X-Ray Map of Tin Distribution in Bond Resulting in Pad to Board Separation

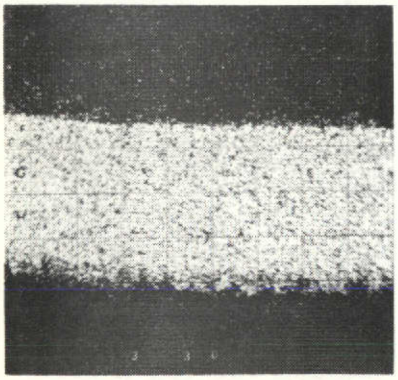


Figure 2-21. X-Ray Map of Copper Distribution in Tin Bond Resulting in Pad to Board Separation

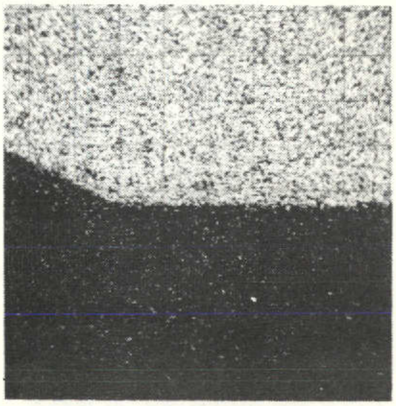


Figure 2-22. X-Ray Map of Kovar Distribution in Tin Bond Resulting in Pad to Board Separation

Pad to Lead Separation

As a comparison to previous analyses and for purposes of identifying a cause for such separations, further x-ray analysis was conducted on samples that separated in the pad to lead mode. Specimens consisted of the remaining pieces of bonds after tensile testing. In all cases, the board material was tin-plated copper and the lead material was gold-plated Kovar. No specimens of indium were examined since this type of separation with indium was too rare to be of interest. It occurred quite frequently with tin, however, and was of interest in obtaining insight into the nature of the bond. Samples of the failures were examined by analysis directly on the failure surface rather than in cross-section as conducted on previous analyses. Both the Kovar side and copper side of separated bonds were examined.

Examination of Leads

Examination of the leads showed dark areas opposite the side on which the electrodes made contact, indicating high pressure points where bonding was probably the strongest. Figure 2-23A is the x-ray spectrum of the elements present. Typical areas are in zones F-4 and D-5 of Figure 2-23B. The relative amounts of the elements are registered in "x-ray counts." Two areas were of interest on this sample: that immediately under the electrode (D-5), and that away from the electrodes (F-5). Table 2-1 gives the comparative analysis for these areas and they are represented in Figure 2-23A as bars (D-5) and dots (F-5).

TABLE 2-1. X-RAY COUNTS ON KOVAR LEADS - PAD TO LEAD SEPARATION

Element	X-Ray Counts - Figures 2-23A & B	
	Zone D-5	Zone F-5
Aluminum	0	0
Silicon	318	2350
Gold	5194	36285
Chlorine	0	210
Tin	702	1706
Iron	37245	2201
Cobalt	11544	541
Nickel	12398	687

The results show a significant difference in the amount of gold and tin between the two areas indicating that gold is dissolved in the tin and the two materials are squeezed out of the area directly under the electrodes. As an aid for comparison to the analysis, Figure 2-24, the spectrum for Kovar, is included. The high concentration of Kovar for zone D-5 (Figure 2-23A and Table 2-1) indicates the depletion of

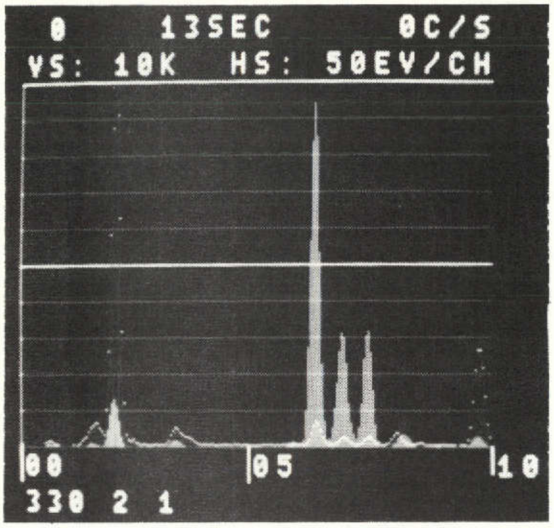


Figure 2-23A. X-Ray Spectrum of Gold-Plated Lead Resulting in Pad to Lead Separation

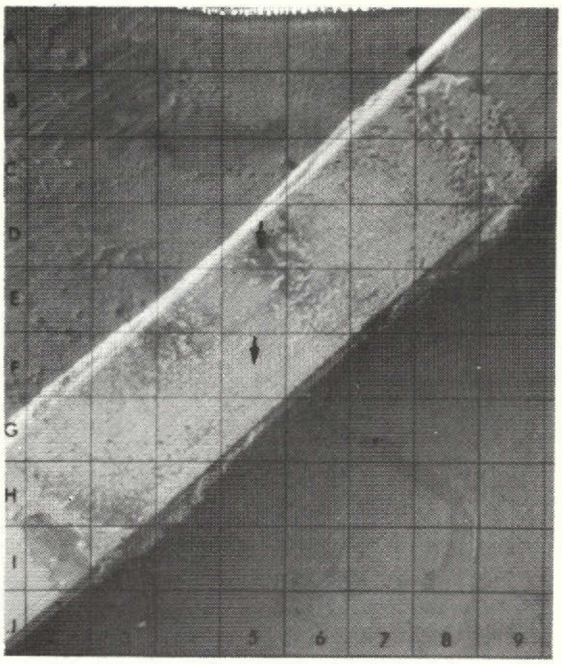


Figure 2-23B. SEM Photograph of Gold-Plated Lead Resulting in Pad to Lead Separation
(Arrows show locations of analyses)

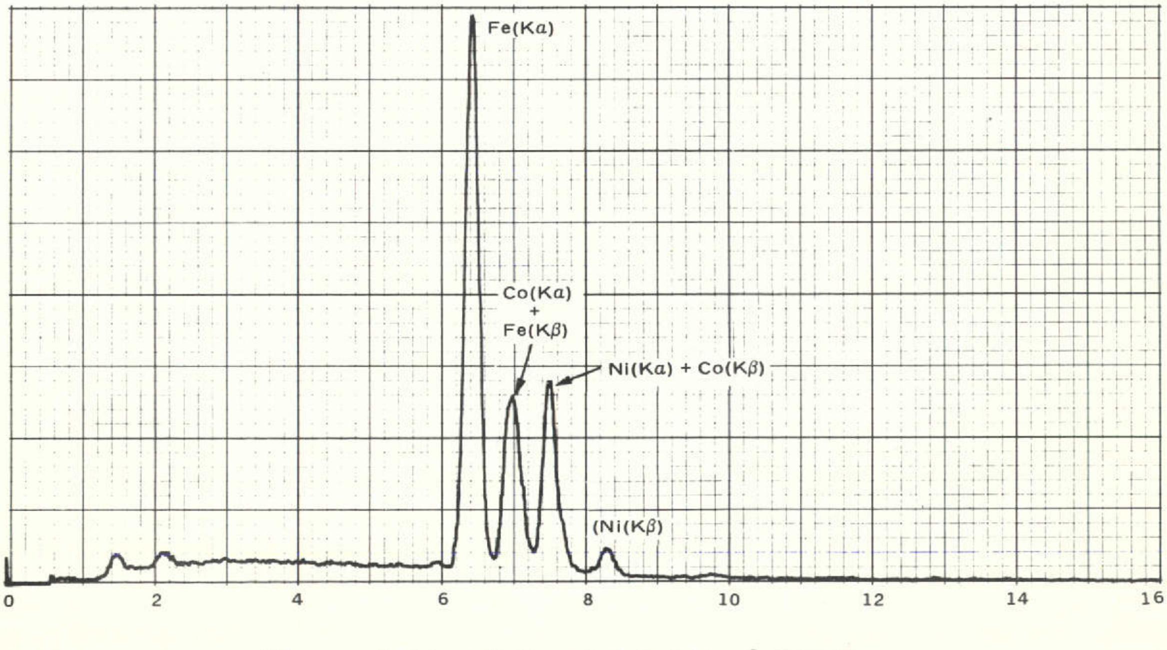


Figure 2-24. X-Ray Spectrum of Kovar

gold and tin in the electrode area. To aid in comparison of all spectra present, Figure 2-25 covering elements of interest, is included. The presence of silicon and chlorine is probably due to contamination.

Examination of Copper Foil Impressions

Typical impressions in tin-plated copper foil are shown in Figures 2-26 thru 2-30 which represent the following:

Figure 2-26 - Total pad to lead separation (sample #1)

Figure 2-27 - Borderline pad to lead separation (sample #2)

Figure 2-28 - Total pad to lead separation (sample #3)

Figure 2-29 - Borderline pad to lead separation (sample #4)

Figure 2-30 - Pad to board separation

X-ray counts for the various elements, from the figure locations noted, are tabulated in Table 2-2. Since each analysis was confined to a specified region, these regions are shown by means of grid coordinates in Table 2-2 and by means of coordinates and arrows in the appropriate figure. The x-ray analysis represents an area approximately 5 mils square within the square in the vicinity designated by the arrow.

It should be noted that analyses from Figure 2-30 (pad to board) was taken adjacent to the strongest part of the bond where copper was torn. In all cases, except data from Figure 2-29, the gold content for the P/B separation was lower while tin was higher. Also, considerably more copper was in evidence. Since the Figure 2-29 data was from a borderline type of separation, it might be grouped with that from Figure 2-30. It appears that the higher strength bonds (P/B separations) are the result of more interaction with copper in the formation of the bond. The remaining tin/gold ratios (Figures 2-27, 2-28 and 2-29) are considerably different and copper does not enter the reaction as much. In the later samples, the formation of brittle gold-tin intermetallics is a possible contribution to lower strength bonds resulting in P/L separations.

Due to the foregoing analyses, further board impressions were examined using a known low and a high strength bond that had separated in a pad to lead mode.

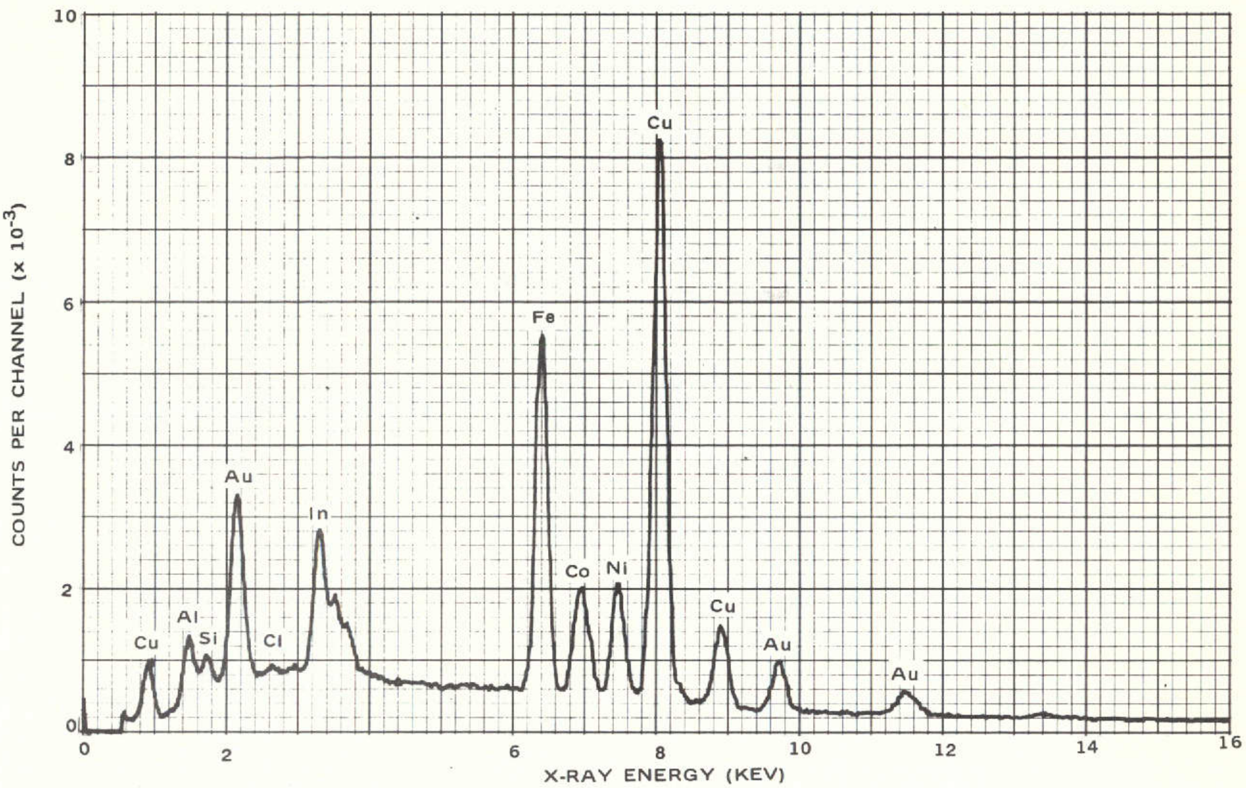


Figure 2-25. Typical X-Ray Spectrum of Elements of Interest

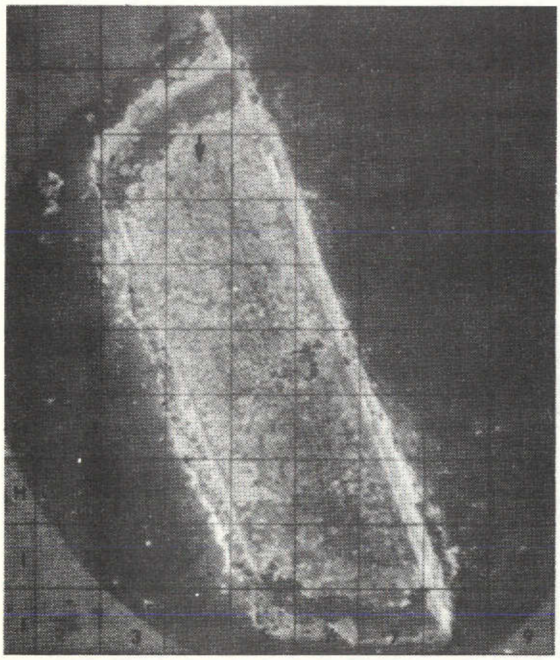


Figure 2-26. SEM View of Tin-Plated Bondline of Total Pad to Lead Separation (Sample #1)

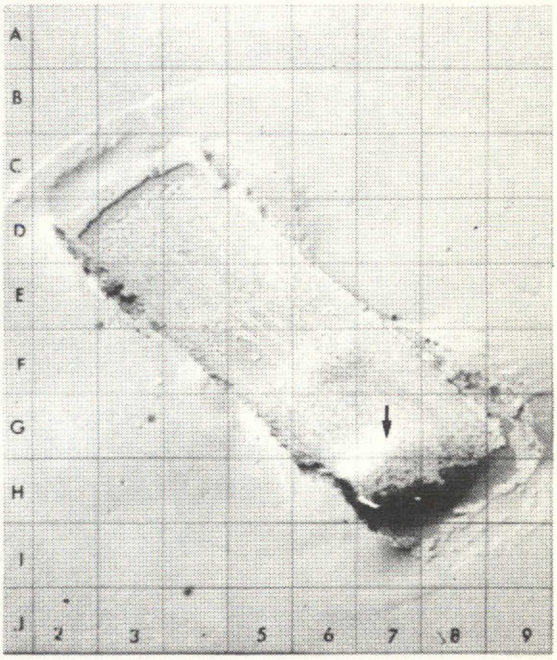


Figure 2-27. SEM View of Tin-Plated Bondline of Borderline Pad to Lead Separation (Sample #2)

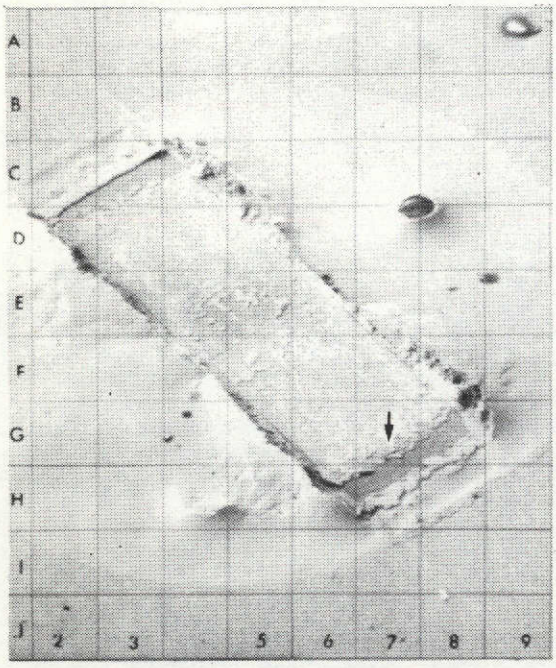


Figure 2-28. SEM View of Tin-Plated Bondline of Pad to Lead Separation (Sample #3)

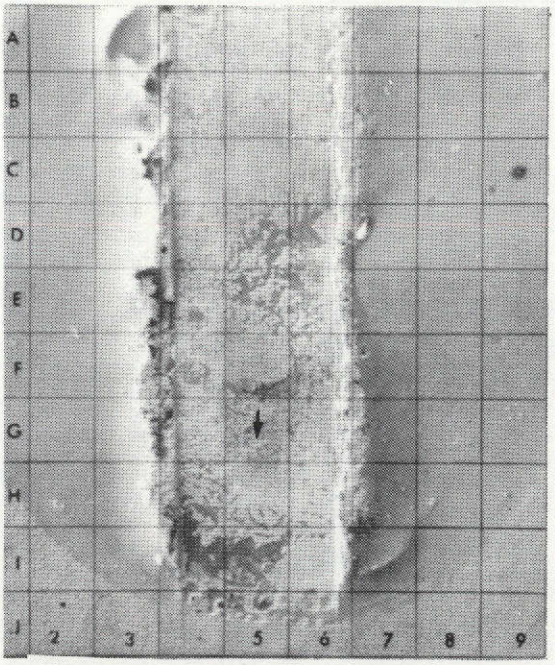


Figure 2-29. SEM View of Tin-Plated Bondline of Pad to Lead Separation (Sample #4)

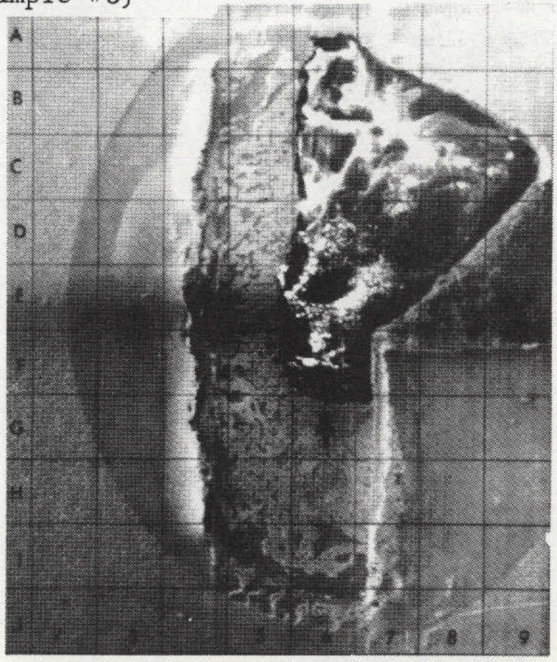


Figure 2-30. SEM View of Tin-Plated Bondline of Pad to Board Separation

TABLE 2-2. X-RAY COUNTS IN BONDLINES OF PULLED SPECIMENS - TIN-PLATED BOARDS

Type of Separation	P/L		Borderline		P/B
Figure	2-26	2-28	2-27	2-29	2-30
Region	C-4	G-7	G-7	G-5	G-6
Element					
Aluminum	-	2233	647	1573	2148
Silicon	2285	1976	1831	1366	1734
Gold	35323	35508	34834	20798	26248
Chlorine	3463	2689	1822	25	123
Tin	4223	3512	5061	5302	5109
Iron*	705	700	1047	556	484
Copper	32132	25739	26671	37178	36580

*Representing Kovar

Shown in Figures 2-31A, B, C and D are the separated surface and x-ray displays for tin, copper and gold from the selected low strength bond while Figures 2-32A, B, C and D represent the same for the higher strength bond. General appearance of the bonds are similar as indicated by the A photos. Comparison of element distribution indicates more gold and less copper in the weaker bond (Figure 2-31). Both bonds show some copper-tin alloying has occurred adjacent to the pad. Higher magnification analyses of the same bonds resulted in the SEM photographs and x-ray displays shown in Figures 2-33A thru D and 2-34A thru D. Comparison of these sets of figures reveals more copper present in the high strength bond (Figure 2-34) and less tin in the low strength bond (Figure 2-33). Note that in Figure 2-34, the counting time for copper was reduced 0.25 times indicating a considerable amount of copper present to achieve the display. Also, the counting time for tin was doubled to obtain the display shown in Figure 2-33, an indication of less tin.

Careful examination of the series of displays in Figure 2-33 shows that the apparent bond areas are made up of primarily gold-tin. As an example, the formation shown in 4D and 4G of 2-33A corresponds to the indication for tin and gold in 2-33B and 2-33C, respectively, while the same area shows no copper indication in 2-33D.

In summary, the stronger bond appears to contain more gold, less tin, and more copper than the weaker bond. Also, the weaker bond generally exhibits more gold-tin alloying, thus the possibility of gold-tin intermetallics. The above agrees well with the data shown in Table 2-2 comparing P/B and P/L types of separation.

Figure 2-31A. SEM Photograph of Selected Low Strength Bondline (50X)

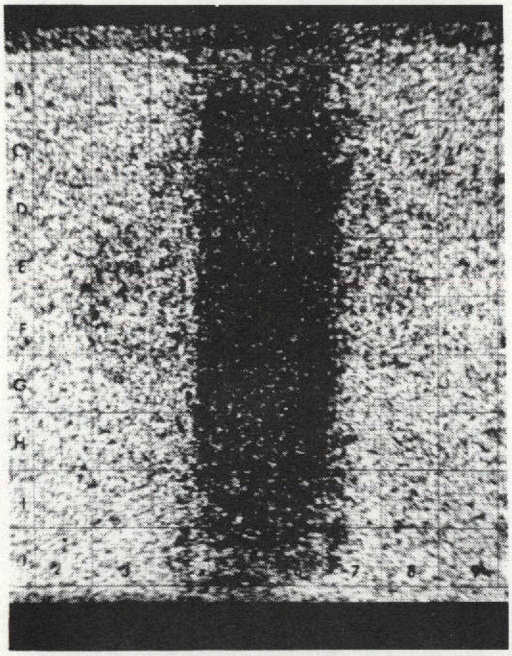


Figure 2-31B. X-Ray Map of Tin in Selected Low Strength Bondline (50X)

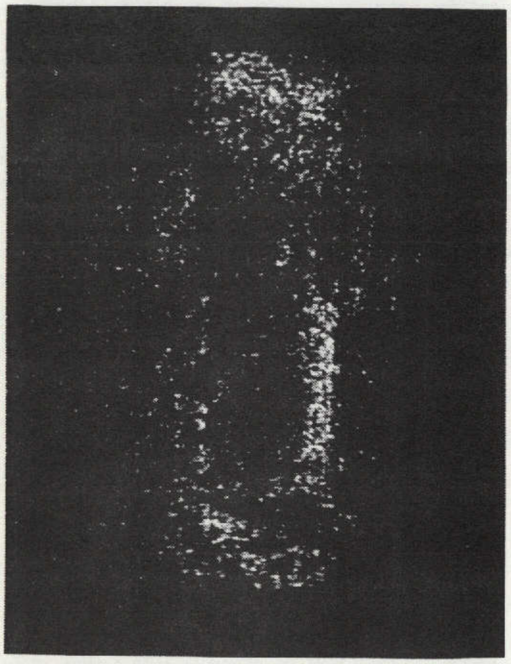


Figure 2-31C. X-Ray Map of Gold in Selected Low Strength Bondline (50X)

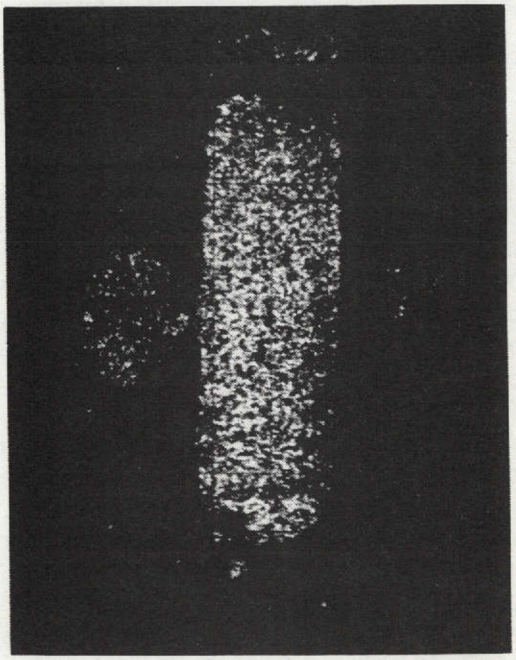


Figure 2-31D. X-Ray Map of Copper in Selected Low Strength Bondline (50X)

Figure 2-32A. SEM Photograph of Selected High Strength Bondline (50X)

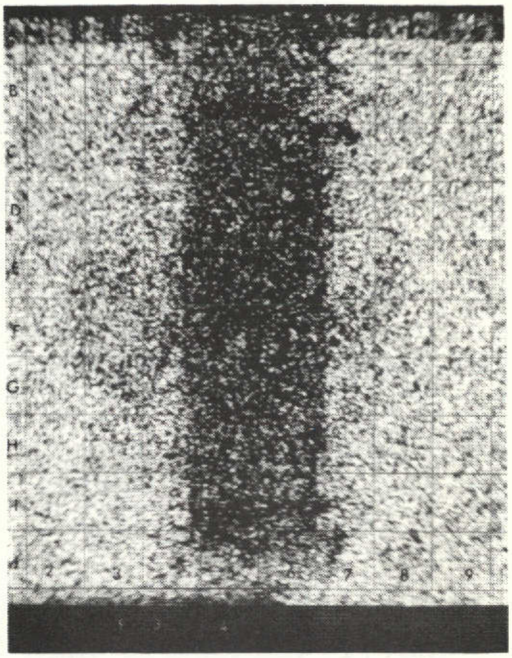


Figure 2-32B. X-Ray Map of Tin in Selected High Strength Bondline (50X)

Figure 2-32C. X-Ray Map of Gold in Selected High Strength Bondline (50X)

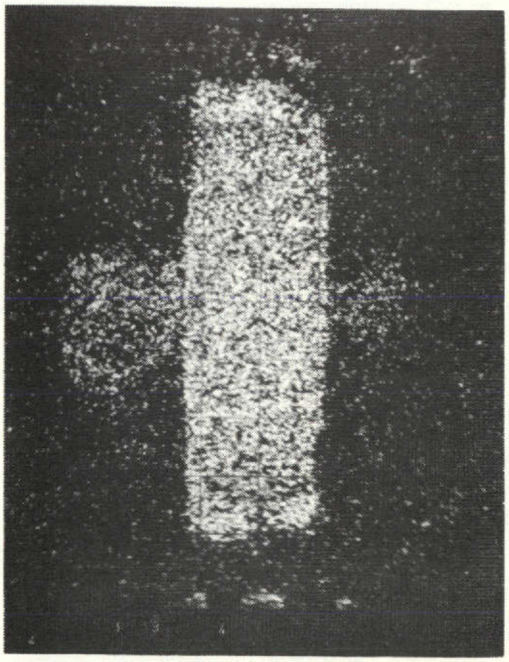


Figure 2-32D. X-Ray Map of Copper in Selected High Strength Bondline (50X)

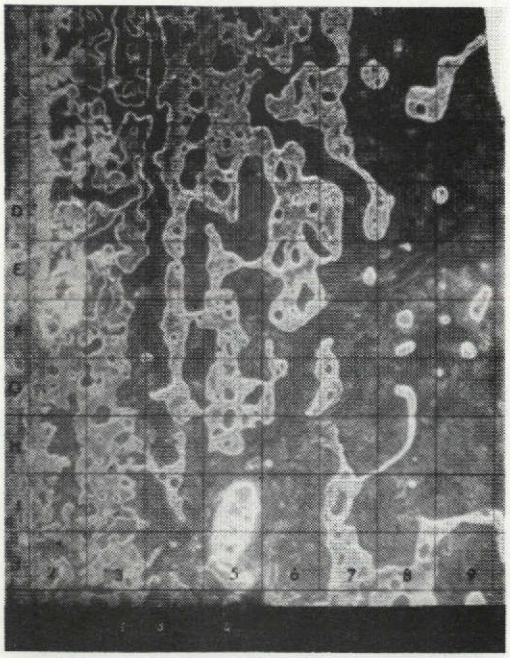


Figure 2-33A. SEM Photograph of Selected Low Strength Bondline (200X)

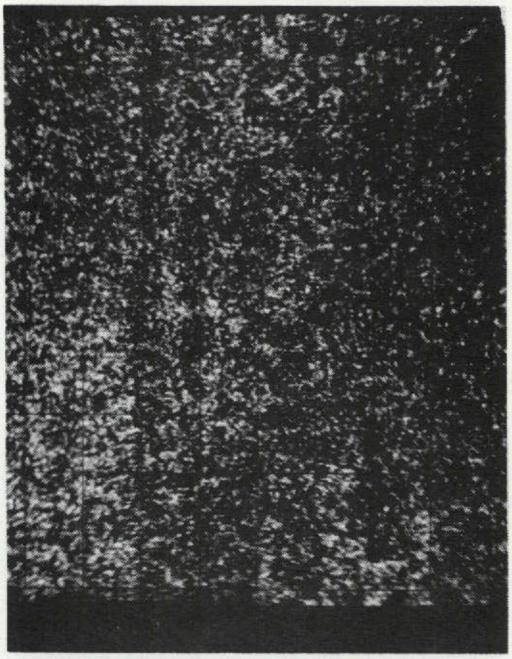


Figure 2-33B. X-Ray Map of Tin in Selected Low Strength Bondline (200X)

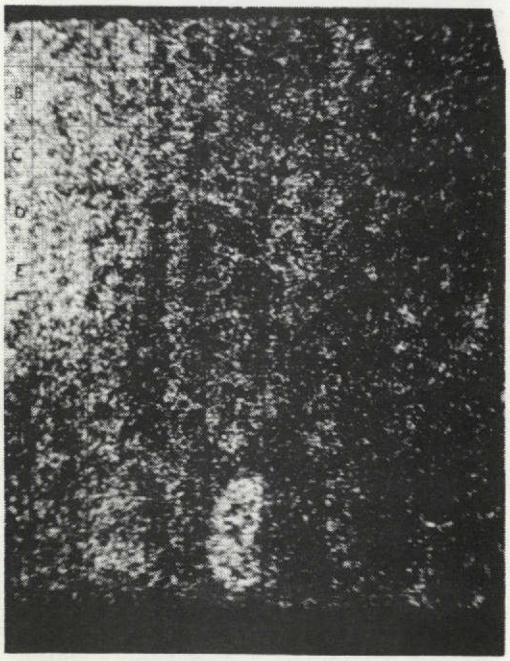


Figure 2-33C. X-Ray Map of Gold in Selected Low Strength Bondline (200X)

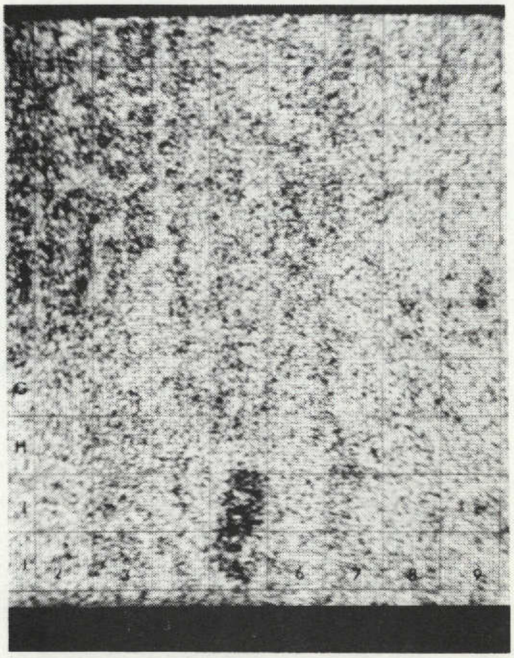


Figure 2-33D. X-Ray Map of Copper in Selected Low Strength Bondline (200X)

Figure 2-34A. SEM Photograph of Selected High Strength Bondline (200X)

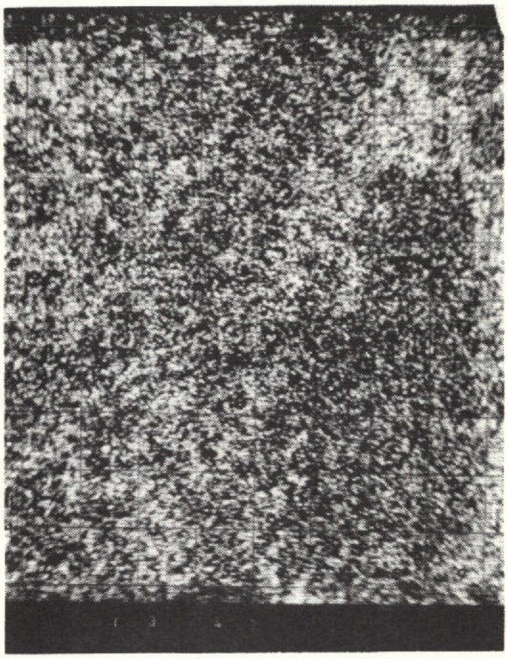


Figure 2-34B. X-Ray Map of Tin in Selected High Strength Bondline (200X)

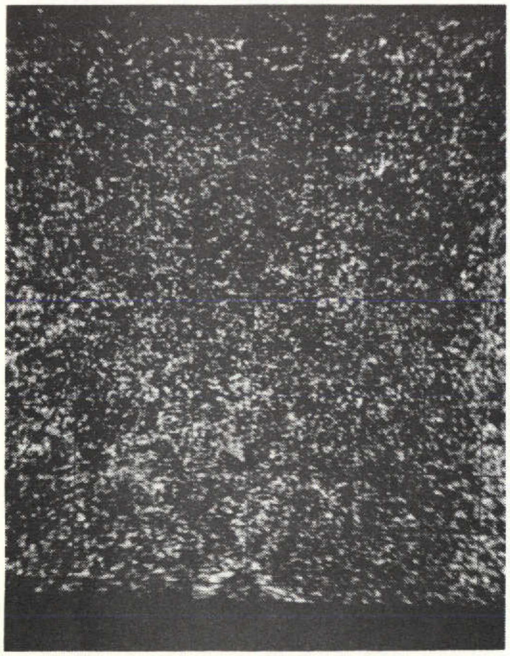


Figure 2-34C. X-Ray Map of Gold in Selected High Strength Bondline (200X)

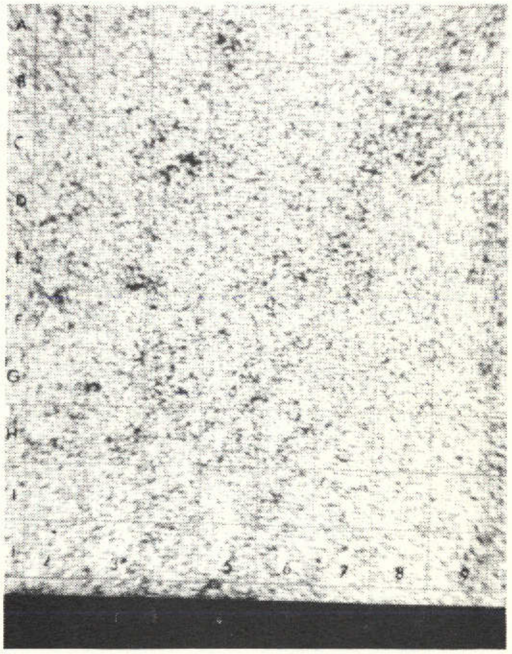


Figure 2-34D. X-Ray Map of Copper in Selected High Strength Bondline (200X)

ANALYSIS OF BONDS WITH TIN-PLATED LEADS

Although an in-depth study of bonds made between tin-plated leads and indium and tin-plated boards was outside the statement of work for this contract, since there is a trend toward tin-plated flatpack leads in the industry, it was considered important to include some work on these systems. Good bond strength results were obtained with indium boards but not with tin boards in this application (see tables 1-27 and 1-28). For this reason only the indium-tin bonds were examined using x-ray analysis.

The results of two bonds are shown in the line scans and element distribution curves of Figures 2-35 and 2-36. Both curves show a heavy indium/tin area with little if any copper diffusion. Due to the difficulty in separating indium from tin indications on the x-ray analyzer, that area is shown only as an alloy with no attempt to separate by elemental analysis. Using a computer analysis of the x-ray data and with pure tin and indium standards it was determined that the approximate alloy composition in the joint was 60 indium/40 tin.

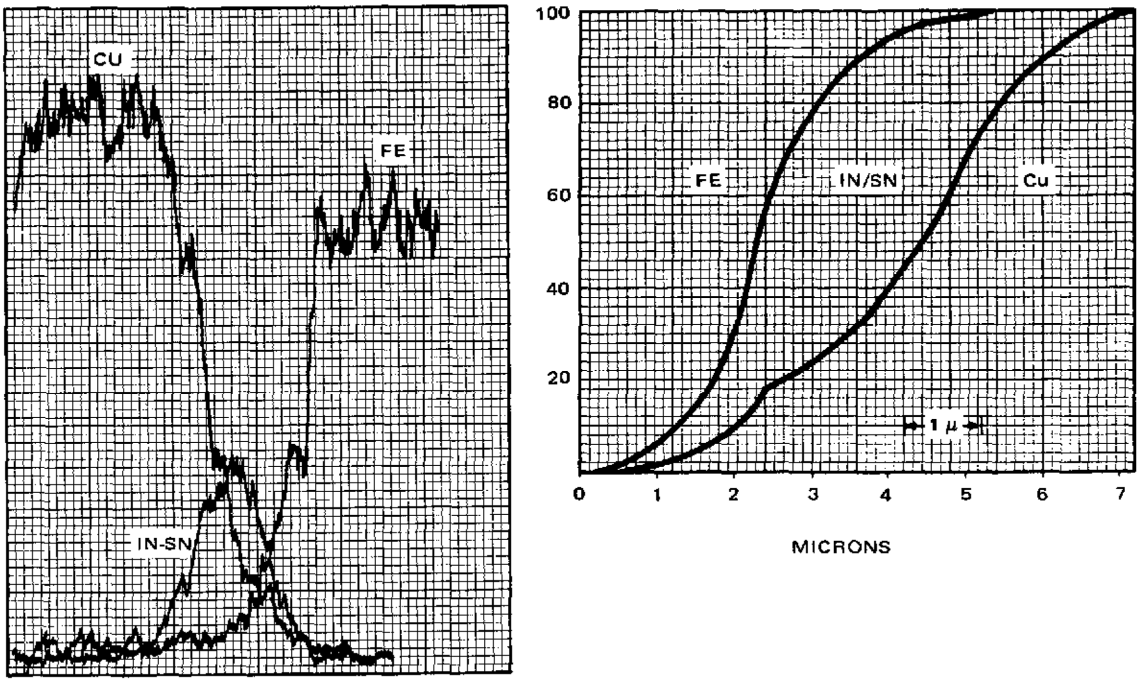


Figure 2-35. Line Scan and Element Distribution Graph of Tin-Plated Kovar to Indium-Plated Copper (Sample 1)

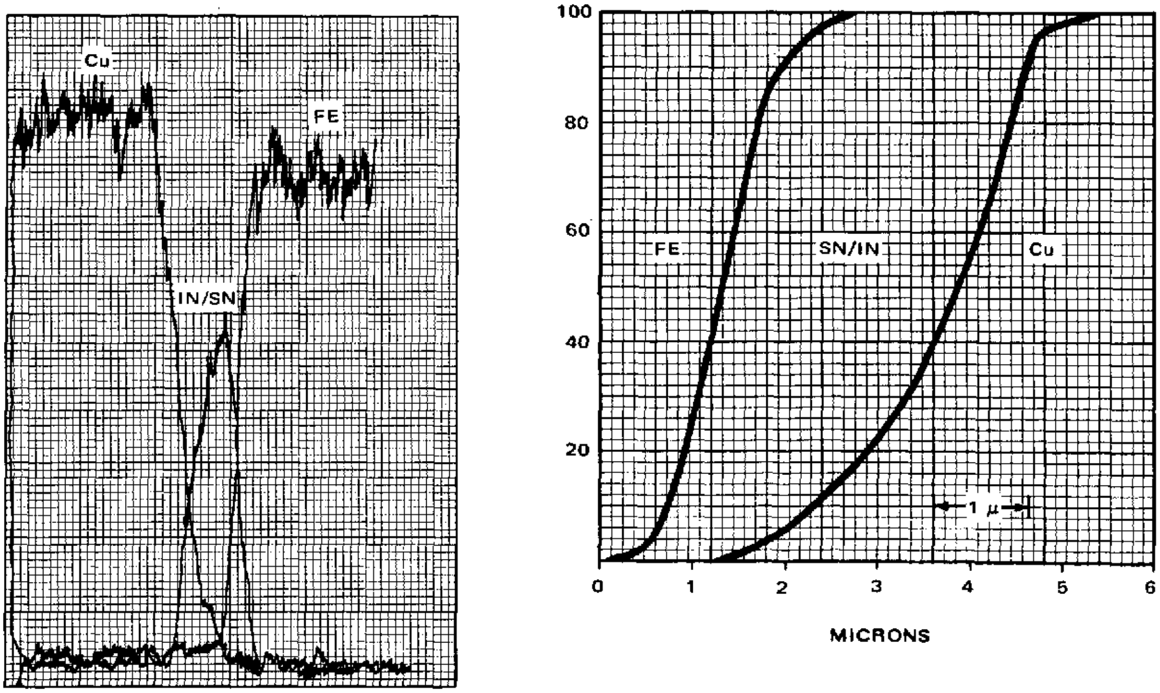


Figure 2-36. Line Scan and Element Distribution Graph of Tin-Plated Kovar to Indium-Plated Copper (Sample 2)

SUMMARY OF METALLURGICAL ANALYSIS

The initial bond analysis showed relative differences between peg tip bonds made by means of a resistance heated bar and bonds made with a parallel-gap tip. The parallel-gap bond resulted in a three-element bond; i.e., gold, indium or tin and copper, while the peg tip bond resulted in a two-element alloy involving gold and tin or indium with only a minor amount of copper alloying. The parallel-gap tin bond was narrower than the indium bond and involved complete alloying of the available tin and gold. The indium bond approached 100 percent gold at the Kovar interface; however, the tin-Kovar interface was mostly copper with less than 50 percent gold. This line scan for tin, however, does not appear to be completely representative of tin bonds since it was observed later that frequently very little alloying with copper occurs. In fact this appeared to be the main difference between indium and tin.

In the analysis of the aged specimens no differences that could be attributed to the effects of aging could be discerned. This corresponds with the fact that there were basically no differences in bond strengths on aged specimens.

The analysis of separated bonds revealed that indium bonds result in more copper alloying than tin with a possible n-phase formation. This explains why a relatively high percentage of tin bonds below one pound separated in the copper to Kovar mode.

The foregoing analysis supports the selection of indium as the optimum material for use in application of the diffusion bonding technique to printed circuit joining. The separation mode is consistent with indium while that for tin varied between copper to circuit board and Kovar to copper. The latter may be attributable to formation of brittle phases.

SECTION 3

MULTIPLE LEAD DEVELOPMENT

MULTIPLE LEAD BONDING DEVELOPMENT

This portion of the contract was directed toward selecting the proper equipment and modifying or redesigning tooling to accomplish simultaneous diffusion bonding of all fourteen flatpack leads. This work was carried out in several parts.

First a determination of the bonding process was required with respect to methods of making the bond. It was important to determine whether diffusion bonds could be made using a resistance heated tip or whether it was necessary to use a parallel-gap bonder. A resistance heated bar 0.035 x 0.100 inch, known as a peg tip, was selected for initial bonding tests. The rationale for this was: First, the processing closely resembles existing reflow soldering techniques and equipment; second, the results generated would be applicable to multiple lead bonding since the tip is a variation of a multiple lead reflow soldering bar currently in production use. The tip could be used to bond two flatpack leads at a time or a single lead at a time depending on orientation. Both methods were tried. Better results were obtained with the single lead because of the larger bonding area. Bond strengths and details on the peg tip bonding are recorded in Section 1. Bonds made using the MCW 550 D.C. power supply were erratic and generally low in strength. It was felt that better results might be achieved with an alternating current power supply, the HAC-1. This power supply had a time control for 1 to 9.9 seconds and an amplitude control from 1 to 100 percent for each of five different ranges. The amplitude control is the percentage of output for each given range setting. The Hughes ERL 35-100 peg tip (0.036" x 0.100") was used with a thermocouple attached. Tip temperature was monitored by means of a strip chart recorder. The results are given in Table 1-5 in Section 1. The results were generally lower than those achieved with the D.C. power supply since an effort was made to achieve an adequate bond strength at as low a temperature as possible to prevent board damage. Board damage generally occurred at settings required to obtain bond strengths of over 0.5 pound. Because the results were not encouraging, further work with the peg tip was discontinued. It was apparent that high strength bonds could only be made at relatively high power settings using short periods of time to prevent circuit board damage. Consequently, bonding had to be accomplished by means of parallel-gap electrodes and a short current pulse.

Following the attempt to use a resistance heated tip, a determination of equipment capabilities and requirements was made for multiple lead parallel-gap bonding. The current required to make a single bond was measured. This current appeared to be about 150 amps but varied slightly depending on the individual resistance of the lead. The capability of the Hughes MCW 550 constant voltage power supply is 675 to 800 amps which would handle a maximum of four bonds, assuming power was applied simultaneously and the resistance of the tip did not appreciably restrict the current flow. Accordingly, a power supply having five times the output of the existing supply would be required to do all fourteen leads.

During this part of the contract a brief literature search for past work on multiple lead welding was conducted. A description of a multiple tip under development by Texas Instruments was reported in Reference 5. The design provided for five individual sets of electrodes with cantilever spring action for equalization of contact resistances. The welding energy was to be distributed to each of the five leads according to the requirement of each lead. The report claims that this type of multiple electrode should greatly reduce the sensitivity of the welding cycle because selective distribution of the power occurs at all five leads. A second approach to multiple lead parallel-gap bonding was reported in Reference 6. This design is used for bonding beam lead devices and consists of two independent rectangular tips, one inside and concentric with the other. The tips are conically ground to make contact with one lead at a time. Sequential bonding of leads is accomplished by rotating the tip with a wobble bonding mechanism. The weld pulse duration is set to maximum and remains on during the entire bonding cycle.

A design similar to the one described in Reference 5 was proposed by W. Hill of Hughes Industrial Products Division. It is shown in Figure 3-1 and consists of multiple sets of cantilevered electrodes for spring action compliancy. Electrodes of the same polarity are made from a single piece of beryllium copper. The design assumes an equal resistance and current split for each lead. A tip with this basic design was made and is shown in Figure 3-2. Since the maximum output of the power supply was 675 to 800 amps the device was limited to three tips.

Multiple Lead Schedules With Three Lead Tip

Work on establishing a schedule with the multiple lead tip began with a board consisting of pads only, plated with 0.4 mil tin. Bond tests shown in Table 3-1 were made at room temperature. Results are recorded for each of the three separate tips: left, center, and right. Schedules were also established for double and single lead bonds using the same three-lead tip. These results are recorded in Tables 3-2 and 3-3. The purpose of this initial work was (1) to generally determine the consistency and integrity of the resulting bonds and (2) to see if it were necessary to change machine settings for single and double lead bonds. Some combination of single and double lead bonds would be necessary for flatpacks, either 3 and 2 lead bonds for 10 lead packages or 3, 3 and 1 for 14 lead packages. Similar bonding was done with an indium-plated board; however, results were less consistent. These results are given in Table 3-4.

Electrical resistance measurements were made to determine any appreciable difference in the three sets of electrodes. Each electrode was measured independently by means of a digital voltmeter. The sum of the individual resistances for the positive and negative sides are given below. These measurements do not include the contact resistance with the Kovar lead.

Left	3.6 milliohms
Center	3.7 milliohms
Right	3.9 milliohms

Since the resistances are close, the lack of consistent repeatability was probably due to variable contact resistance of the tips on the leads. Slight differences in spring action or alignment was probably the major cause of inconsistency.

The three-lead tip appeared to be practical; however, further work would be required to improve its repeatability and consistency. It was felt that designs should be considered that would not limit the number of bonds by the capacity of the power supply. Building larger power supplies to accommodate larger tips is not feasible. The next portion of the contract involved analyzing the feasibility of other possible designs.

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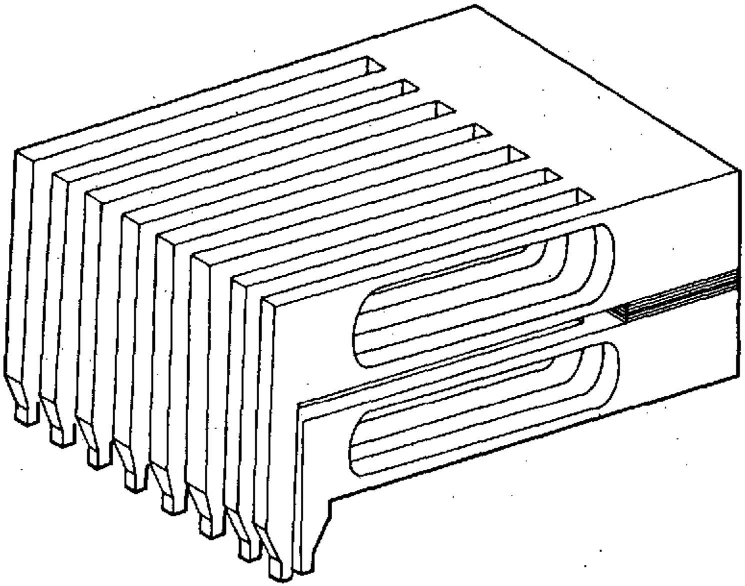

Figure 3-1. Multiple-Lead Parallel-Gap Compliant Tip Concept

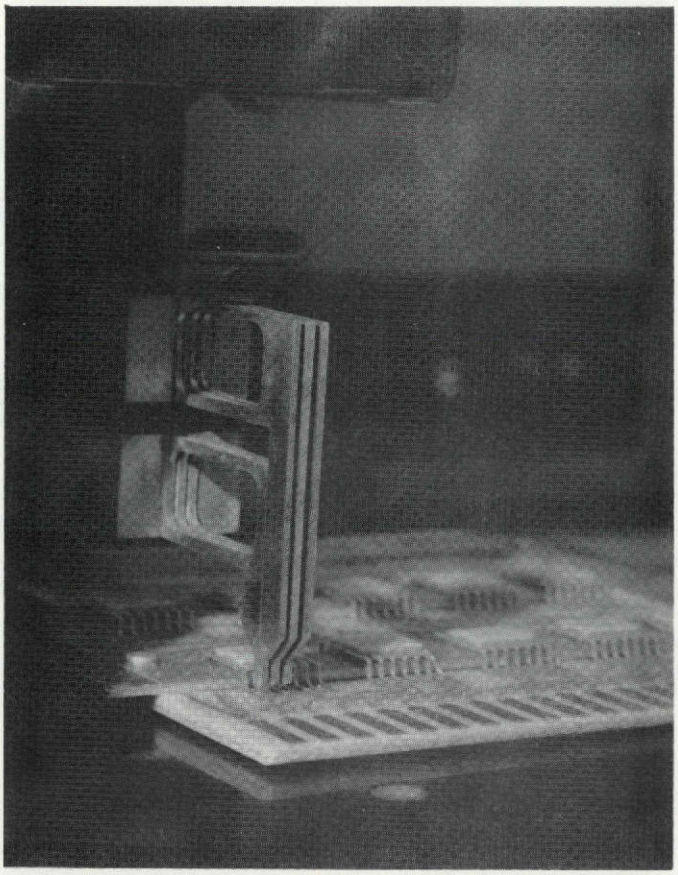

Figure 3-2. Multiple-Lead Parallel-Gap Bonding of Flatpack Leads

Three leads at a time can be bonded with the experimental head shown above. Individual electrodes are made of beryllium copper for individual spring action compliancy.

C2

C2

TABLE 3-1. MULTIPLE LEAD BONDS-THREE LEADS AT A TIME
0.4 MIL TIN

Force (Lbs)	Voltage	Time Ms	Bond Strength			Type of Separation*	
			Left	Center	Right	P/L	P/B
6	0.64	5	1.35	1.21	0.98	LCR	
6	0.64	6	1.81	1.64	2.31	LCR	
6	0.63	6	1.07	3.03	0.56	LCR	
6	0.62	5	0.43	0.42	0.45	LCR	
6	0.63	5	0.62	0.74	0.52	LCR	
9	0.63	6	0.46	1.01	1.2	LCR	
9	0.64	6	0	2.89	1.59	CR	
9	0.64	6	0.76	2.4	1.01	LCR	
9	0.64	6	0.61	1.68	1.56	L	CR
9	0.64	6	0.96	2.42	1.09	LCR	
9	0.64	6	0.88	2.38	0.52	LR	C
9	0.64	6	0.5	0.68	0.67	LCR	
9	0.64	6	1.21	2.84	0.93	LCR	
6	0.64	6	1.91	2.6	2.01		LCR
6	0.64	6	1.63	1.78	2.15		LCR
6	0.64	6	2.5	0.71	0.67		LCR
6	0.64	6	1.11	1.92	1.81		LCR
6	0.63	6	1.43	1.76	1.67		LCR
6	0.64	6	0.95	1.8	1.86	L	CR
6	0.64	6	1.4	1.59	2.17	L	CR
6	0.64	6	1.7	2.23	2.83	L	CR
6	0.64	6	2.3	2.62	2.3		LCR
6	0.64	6	2.64	2.13	1.71		LCR
6	0.64	6	1.3	2.18	2.19	L	CR
6	0.64	6	0.76	2.43	2.03	L	CR
6	0.64	6	1.91	2.19	2.01		LCR
6	0.64	6	2.1	1.7	0.87	R	LC
6	0.64	6	1.78	1.33	1.56	CR	L
6	0.64	6	0.72	0.51	1.0	LC	R
6	0.64	6	1.54	2.4	2.78	L	CR

*P/L = Pad to Lead; P/B = Pad to Board; L, C, and R designation refers to left, center and right electrode

TABLE 3-2. MULTIPLE LEAD BONDS-TWO LEADS AT A TIME
0.4 MIL TIN

Force (Lbs)	Voltage	Time Ms	Bond Strength (Lbs)		Type of Separation*	
			Left	Right	P/L	P/B
6	0.5	5	1.18	0.85	CR	
6	0.5	5	0.5	0.5	CR	
6	0.5	5	0.45	0.35	CR	
6	0.5	5	0.68	0.66	CR	
6	0.5	5	0.76	0.5	CR	
6	0.5	6	0.72	0.63	CR	
6	0.5	6	0.58	0.49	CR	
6	0.5	6	0.54	0.57	CR	
6	0.5	6	0.53	0.44	CR	
6	0.5	6	0.42	0.45	CR	
6	0.5	6	0.4	0.46	CR	
6	0.6	6	0.91	0.58	CR	
6	0.6	6	0.49	0.99	CR	
6	0.6	6	0.65	0.54	CR	
6	0.6	6	0.45	0.54	CR	
6	0.64	6	1.81	2.32		CR
6	0.64	6	2.42	1.56		CR
6	0.64	6	1.58	1.56		CR
6	0.64	6	1.34	2.13		CR
6	0.64	6	1.53	2.07		CR
6	0.64	6	1.2	1.81		CR
6	0.64	6	1.36	0.138		CR
6	0.64	6	0.75	1.74	C	R
6	0.64	6	1.11	1.58	C	R
6	0.64	6	1.13	1.54		CR
6	0.64	6	1.63	1.42		CR
6	0.64	6	0.64	2.1	C	R
6	0.64	6	2.12	3.8	R	C
6	0.64	6	0.58	2.68	C	R
6	0.64	6	2.17	1.42	R	C
6	0.64	6	1.18	1.83	CR	
6	0.66	6	1.55	1.96		CR
6	0.66	6	2.41	2.65		CR
6	0.66	6	1.09	0.62	R	C
6	0.67	7	1.42	0.99	R	C
6	0.67	7	1.45	1.63		CR
6	0.67	7	1.83	1.23		CR

*P/L = Pad to Lead; P/B = Pad to Board; L and R designation refers to left and right electrode

TABLE 3-3. MULTIPLE LEAD BONDS-ONE LEAD AT A TIME
0.4 MIL TIN

Force (Lbs)	Voltage	Time Ms	Bond Strength (Lbs)	Type of Separation*	
				P/L	P/B
6	0.5	5	0.45	X	
6	0.5	5	0.44	X	
6	0.5	5	0.39	X	
6	0.5	5	0.25	X	
6	0.5	5	0.39	X	
6	0.5	5	0.45	X	
6	0.5	5	0.26	X	
6	0.64	6	2.23	X	
6	0.64	6	1.5	X	
6	0.64	6	1.53		X
6	0.64	6	1.19	X	
6	0.64	6	1.38	X	
6	0.64	6	1.1	X	
6	0.64	6	1.88		X
6	0.64	6	1.46		X
6	0.64	6	1.98		X
6	0.64	6	1.21	X	
6	0.64	6	1.11	X	
6	0.64	6	2.23		X
6	0.64	6	0.88	X	

*P/L = Pad to Lead; P/B = Pad to Board

TABLE 3-4. MULTIPLE LEAD BONDS
0.4 MIL INDIUM

Force (Lbs)	Voltage	Time Ms	Bond Strength (Lbs)			Type of Separation*	
			Left	Center	Right	P/L	P/B
6	0.67	3	0.25	0.42	0.2	LCR	
6	0.66	4	0.5	0.75	0.8	LCR	
6	0.65	5	0.6	1.62	1.67	L	CR
6	0.61	6	0.4	0.3	0.5	LCR	
6	0.57	11	0.34	0.57	0.71	LCR	
6	0.56	12	0.44	0.8	1.16	LC	R
6	0.55	13	0.1	0.54	0.58		
6	0.55	14	0.5	1.82	1.32	L	CR
6	0.55	14	0.4	1.27	1.74	L	CR
6	0.55	14	0	0.95	1.48		CR

*P/L = Pad to Lead; P/B = Pad to Board; L, C, and R designation refers to left, center and right electrode

Consideration of Different Multiple Lead Designs

Three basically different multiple lead bonding systems were considered. Briefly they are described as follows:

1. Multiplexing. A set of electrodes would be provided for each lead. Power would be indexed to each set of electrodes in sequence either by electrical multiplexing or mechanical switching.

2. Parallel-gap wobble bonding. Power would be applied to a parallel-gap wobble bonding tip by pulses synchronized with the contact of the tip on each lead. This design would be basically similar to the one described in Reference 6.

3. Double rocker tip bonding. This tip consists of two sets of electrodes that span seven leads and are radiused to prevent contact with more than one lead at a time.

Each of these systems are described in more detail below, along with the potential problems and equipment modification required. The choice that was selected for trial was based on the approach that was considered the most feasible and would involve the least modification to the existing system.

Multiplexing

The system would consist of a multiple lead tip with fourteen individual sets of electrodes. The multiple lead tip would require:

1. Fourteen individual sets of electrodes with electrical isolation between each set.
2. Terminals and wires for fifteen electrical connections capable of handling 250 amperes at 0.6 volt for 5 milliseconds.
3. Power operated pressure control. The amount of pressure applied to a single lead is from 3 to 5 pounds. The equivalent pressure for a fourteen lead device is 40 to 70 pounds which would be difficult to apply manually.

Electronic multiplexing would require fourteen separate channels that sequentially trigger and direct the circuit that controls the voltage and duration of the pulse. A block diagram of this design is shown in Figure 3-3. The multiplexer requires fourteen separate parallel-power transistor switches used to carry the output current. The present switch in the MCW 550 power supply consists of seven power transistors in parallel. The switches would be gated electronically by the multiplexing circuit.

An option to using the electronic multiplexer and associated power switches is to use a mechanical stepping switch that sequentially triggers a bank of fourteen separate power relays which direct current to the electrodes at a preset interval. A block diagram of this design is shown in Figure 3-4.

Parallel-Gap Wobble Bonding

Parallel-gap wobble bonding involves a single tip consisting of two rectangular tubes, one inside the other, separated by an insulator. The tip would be conically ground to permit contact with a single lead at a time when a wobble motion is applied. The simplest control on the electrical pulse is to set the pulse control circuit for the maximum duration or the time for one complete rotation of the wobble tip, whichever is least. A rotary motion of the tip, however, would result in a non-uniform dwell time on each lead due to the geometrical arrangement of the leads. A rectangular wobble motion would result in equal dwell time on each lead but would be a more complex mechanism. The block diagram for the single pulse design is shown in Figure 3-5. Most likely the single pulse design would result in excessive power inputs to each lead since the duration of the schedule is 5 milliseconds. If it is necessary to control the duration of each pulse and synchronize it with the dwell time on each lead, it would require an encoder and counter as shown in the block diagram in Figure 3-6. This does not seem like a difficult requirement to satisfy since the required pulse duration is so much shorter than the probable dwell time on each lead.

Double Rocker Tip Bonding

Rocker tip bonding consists of two sets of electrodes, each designed to span seven leads and radiused to make contact with one lead at a time with a rocking motion. This design, like the wobble tip, would probably require pulsing the current rather than setting the pulse control circuit for the full duration of the cycle. This function could be provided by a reflective object sensor which could be incorporated to trigger the power supply as the tip makes contact with each lead.

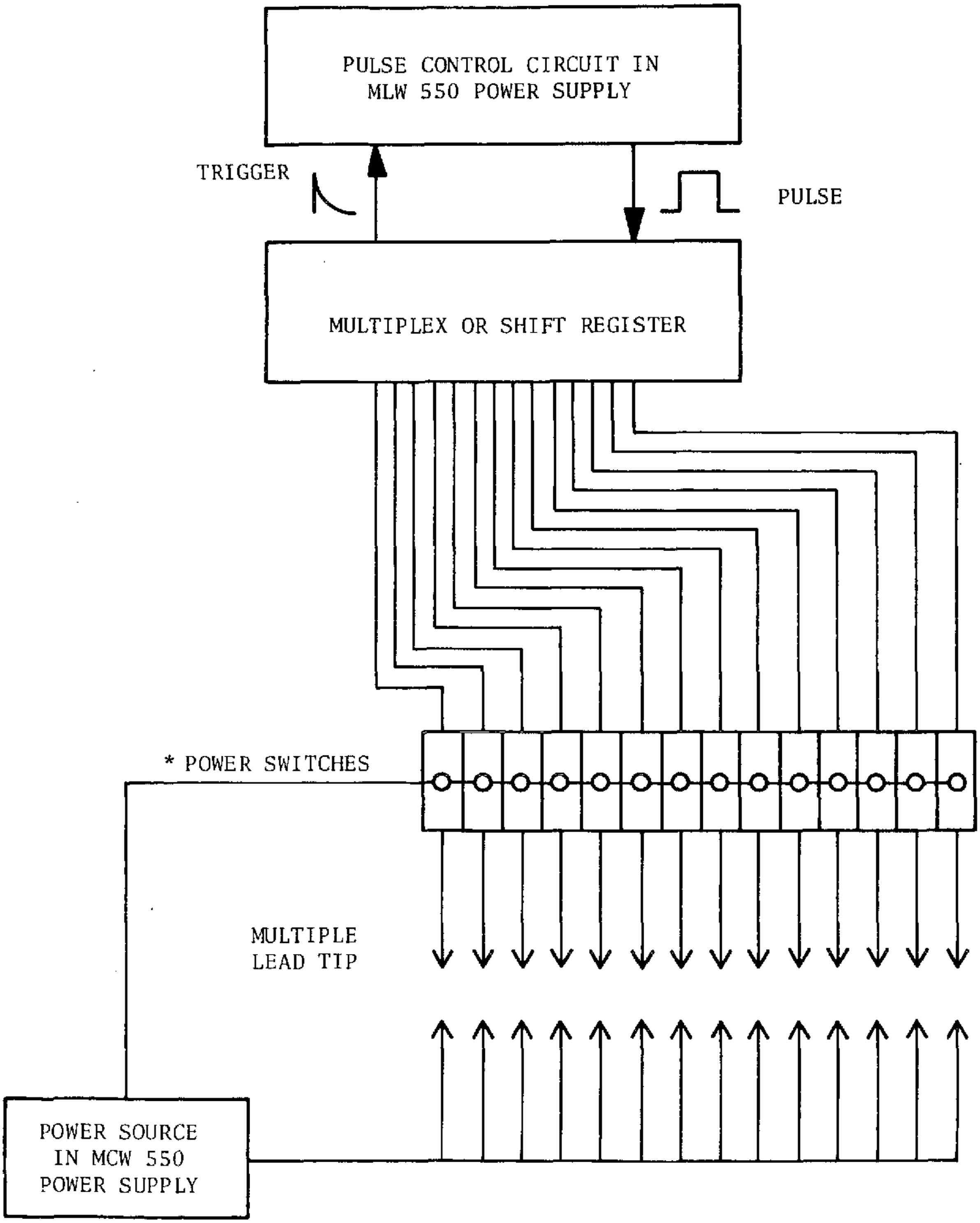

Figure 3-3. Block Diagram of Electronic Multiplexing for 14 Lead Multiple Tip

*Each power switch represents a set of power transistors in parallel.

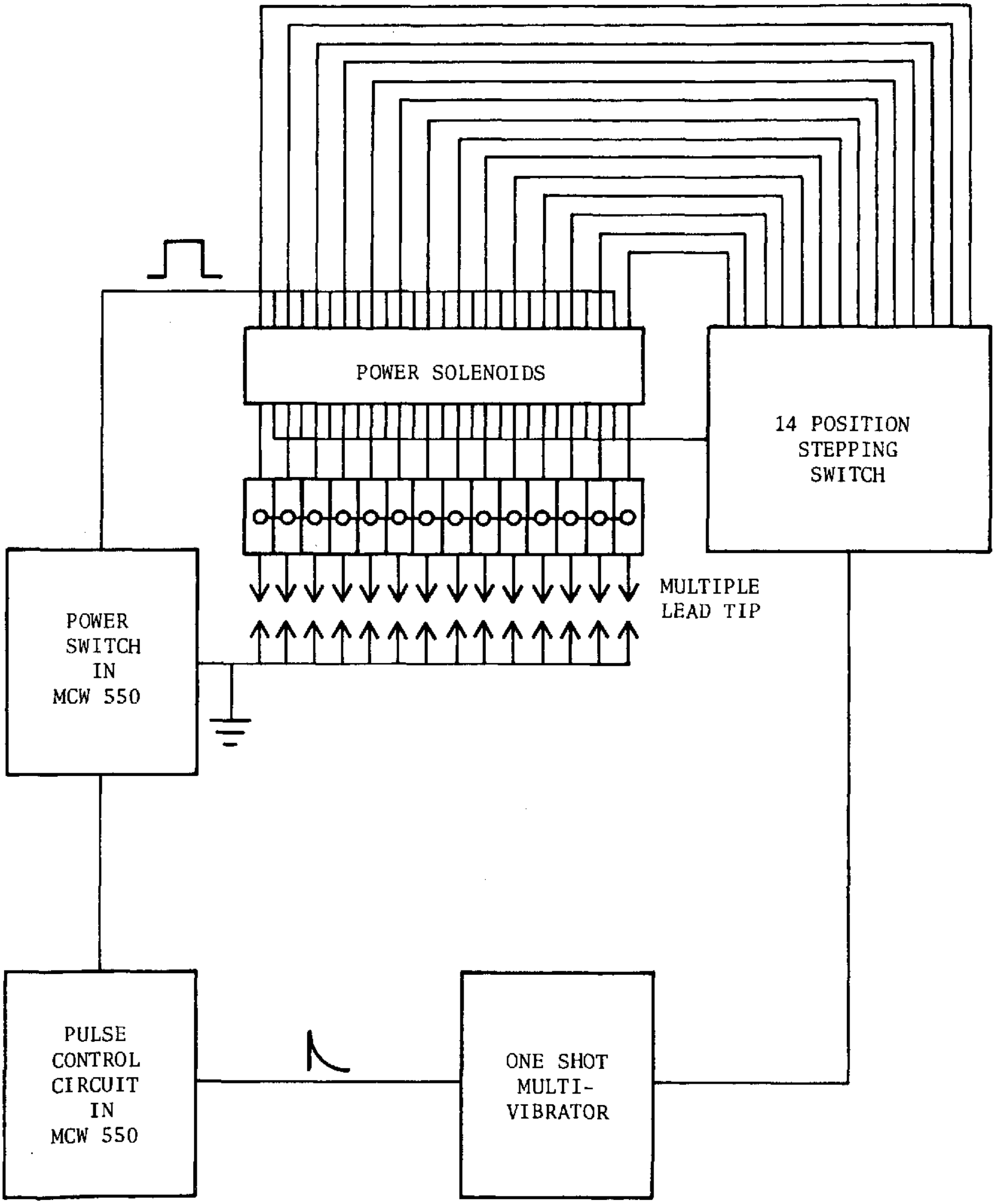

Figure 3-4. Block Diagram of Mechanical Switching for 14 Lead Multiple Tip

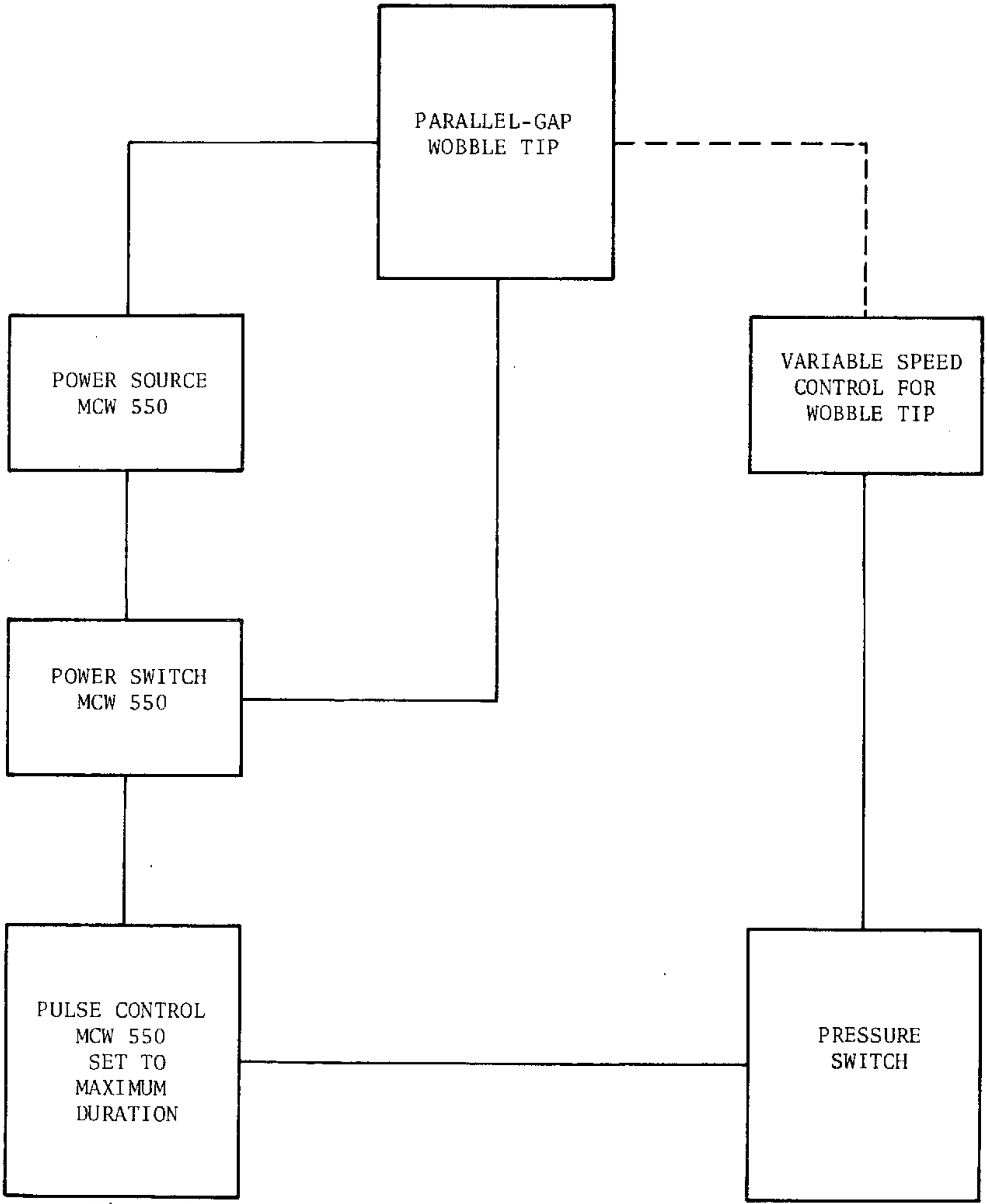

Figure 3-5. Block Diagram for Parallel-Gap Wobble Bonding Tip Using a Single Pulse for all Fourteen Leads

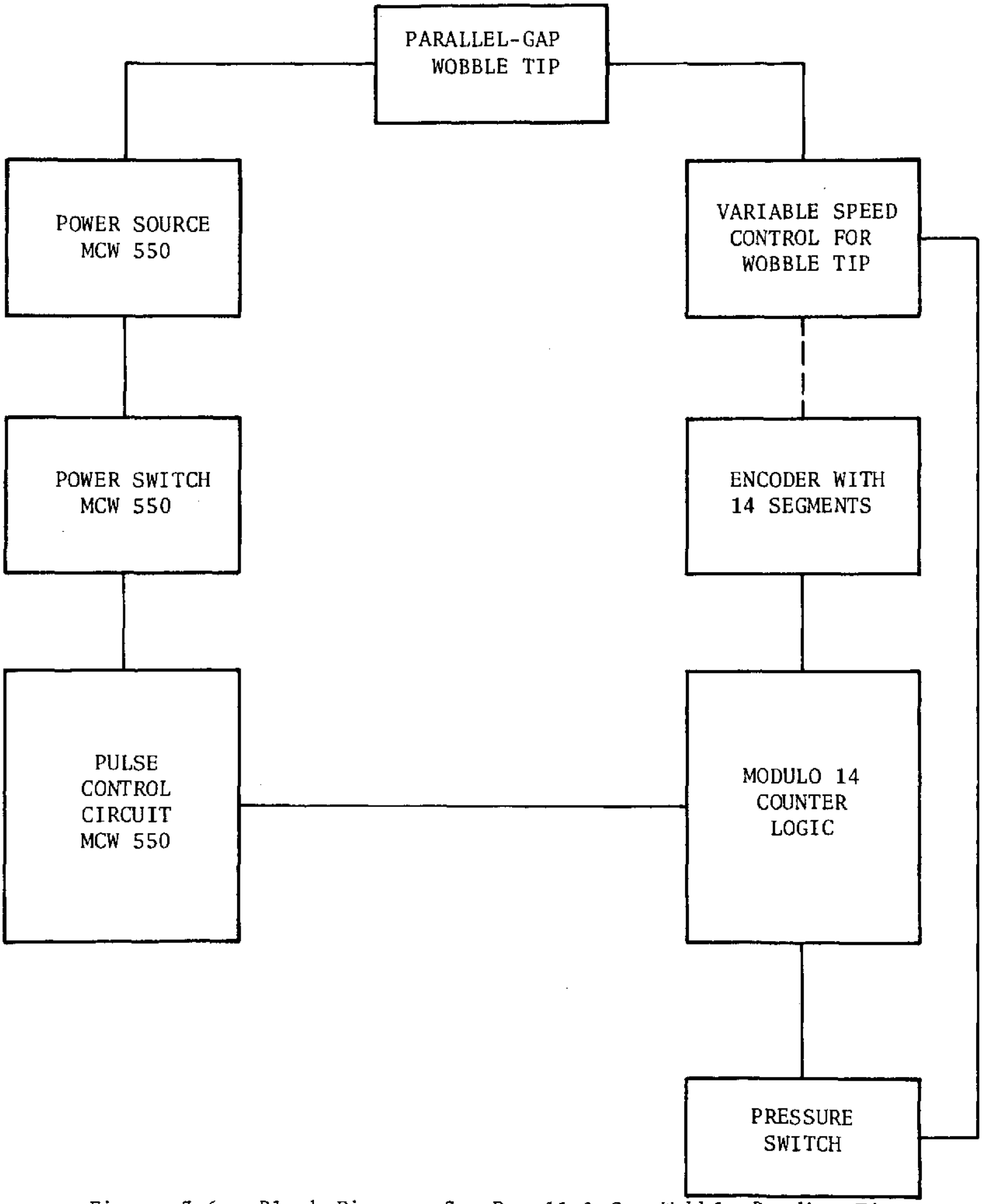

Figure 3-6. Block Diagram for Parallel-Gap Wobble Bonding Tip Using a Single Pulse for Each Lead

The designs shown in Figure 3-3 and 3-4, which involve electronic and mechanical switching, would be expensive, require considerable bulky hardware and would involve a complicated multiple lead tip that would be expensive to replace. The wobble tip and double rocker tip designs shown in Figures 3-5, 3-6, and 3-7 appear to be simpler and more practical. The mechanism for the double rocker tip could be relatively simple in that the circuit board could be free to move and would provide a linear drive that would roll the tip from one lead to another. A mechanism for a wobble tip of sufficient size was not available and would have been too expensive to design and fabricate. It was felt that the rocker tip would be fairly simple and easy to fabricate.

Rocker Tip Design - The design for the rocker tip for multiple lead bonding is shown in Figures 3-7 and 3-8. It basically consists of two sets of independent electrodes, one inside the other. Individual compliancy for each tip is provided to ensure positive contact of all four tips throughout the bonding cycle. The compliancy for the outer electrodes is maintained by spring action of rubber inserts pressing downward against the two ends of the axle on which the tip is mounted. Compliancy for the inner electrodes is provided by a rubber gasket bonded to the top side of the piece from which the electrodes are made. Electrical power connections are made by means of flexible cables. At this point it was difficult to conceive of electrical connections that did not interfere with the rocker motion of the tip assembly. A second problem was selecting the elastomeric materials that would provide the proper difference in spring action between the inner and outer electrodes. Insulation with low coefficient of friction was used between the inner and outer electrodes to ensure free movement between the two.

The rocker tip is supported by a holder that mounts to the VTA 66 welding head. An additional fixture was required to support the circuit board and move it laterally while in contact with the tip. This was an ordinary sliding drawer mechanism mounted horizontally with an attachment for the board. It was expected that the lateral motion of the rocker tip, as it comes in contact with the leads, may tend to misalign them with respect to the pads. This does not appear to be a serious problem in actual practice.

Rocker Tip Operation - The rocker tip installed in the machine is shown in Figure 3-8. The actual tip in operation is shown in Figures 3-9 and 3-10. The circuit board is mounted on a sliding track and brings the leads in contact with the tip as it moves in a transverse direction. Some multiple lead bonds were made by using low voltage and long duration settings, but since the unit was hand-operated it was difficult to achieve uniformity and close control.

The bond settings used were too high, were overpowered, and there was some board damage because of the resulting long duration of the pulse. It was apparent that a triggering circuit is required to control the time of the bond cycle individually for each set of leads. Also, the power did not seem to be evenly split between the leads on the two sides of the package, probably a result of improper alignment or differences in contact resistance. The fact that the inner electrode is floating and mounted in a resilient support provides a slight offset between the two electrodes that occurs mostly at the extreme ends of the package. This acts to hold the adjacent set of unbonded leads away from the outside set of electrodes thus preventing shorting.

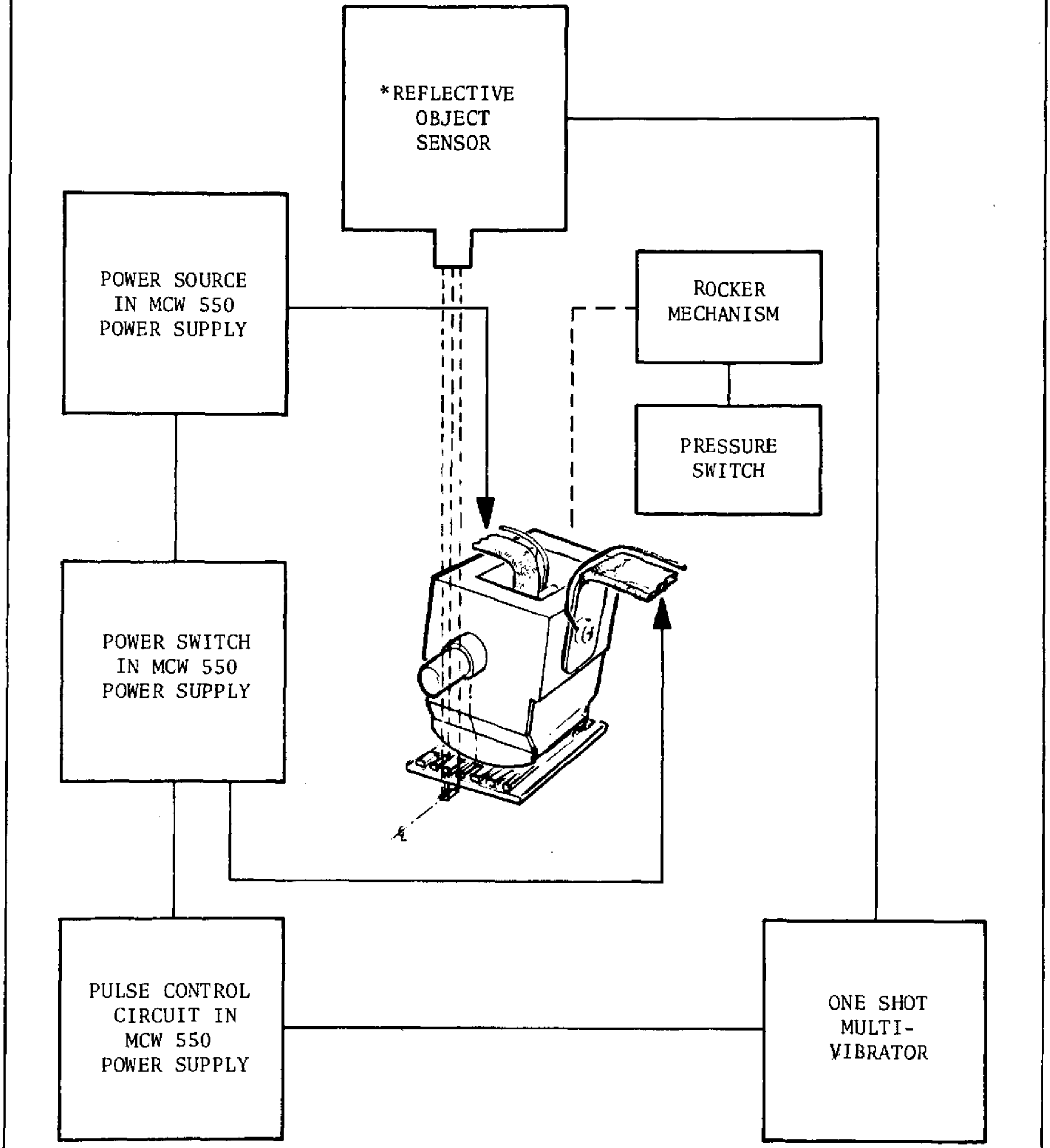

Figure 3-7. Block Diagram of a Double Rocker Tip

*Reflective object sensor would cause power supply to fire as tip makes contact with each lead.

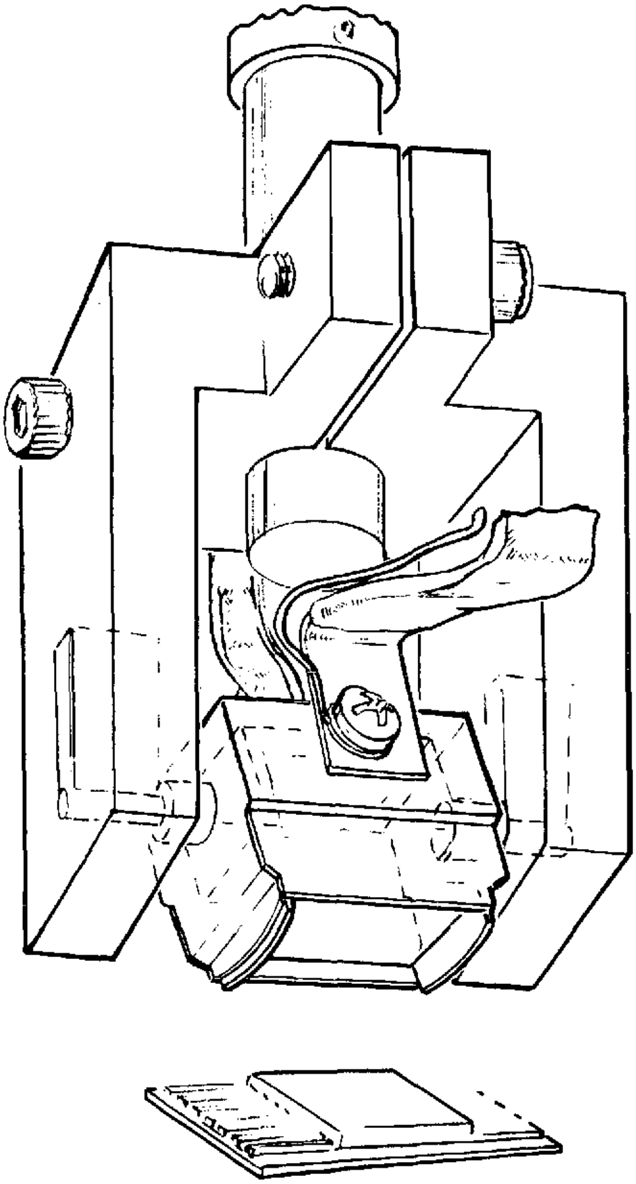

Figure 3-8. Rocker Tip Assembly Installed in Machine and in Position for Bonding. (Tip is driven by linear motion of circuit board.)

Tip is driven by linear motion of circuit board.

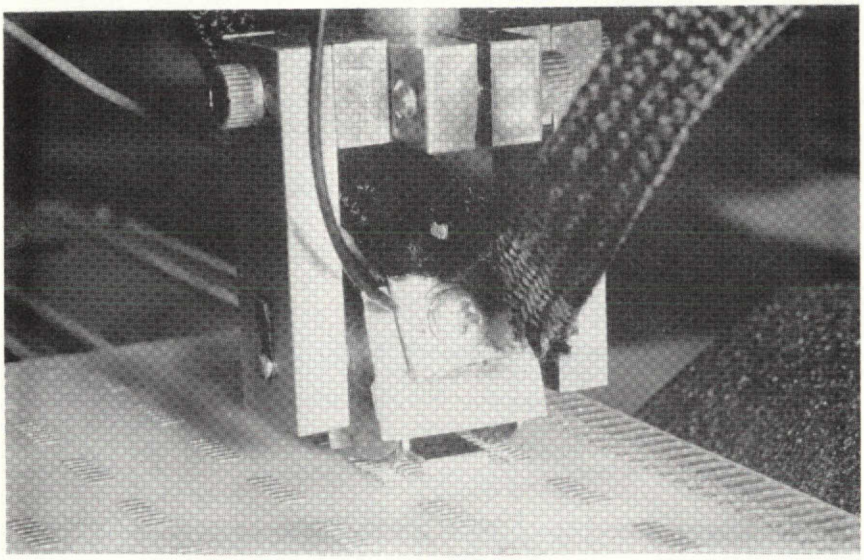

Figure 3-9. Rocker Tip Bonder Oblique View
(Circuit board is mounted on a sliding track in line with bonder.)

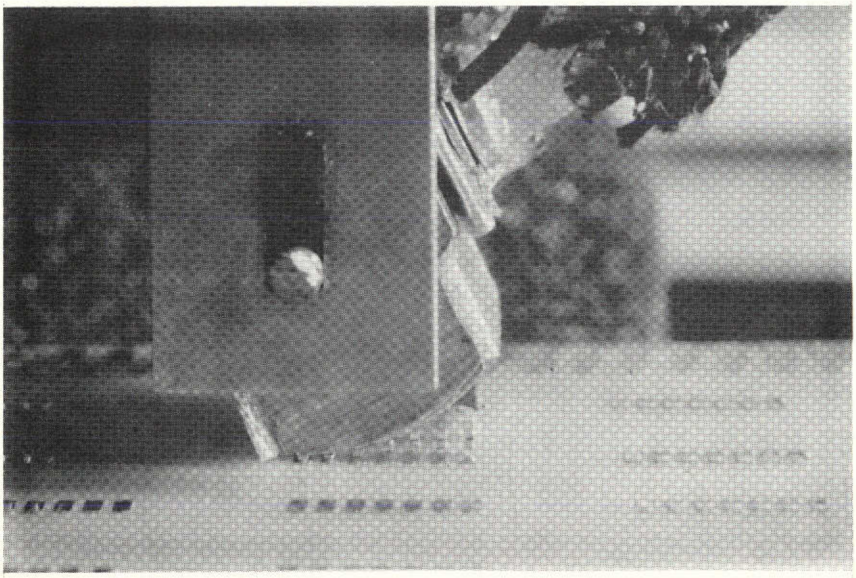

Figure 3-10. Rocker Tip Side View
(Slight offset of electrodes prevents shorting by adjacent unbonded leads.)

Single Lead Bonds With Rocker Tip - Single lead bonds with the rocker tip were made to determine its general bonding characteristics.

This was accomplished by insulating one side of the tip from the circuit board and making contact with one set of electrodes. One lead was bonded at a time. A higher voltage setting was required (0.82 v, 5 ms) than was required for a single lead tip, probably to overcome higher resistance in the tip. The bonds were made with gold-plated leads on an indium-plated board. The bond area seemed smaller possibly due to the radius on the tips; however, consistently high bond strengths were obtained and are reported in Table 3-5. If the mechanical and electrical modifications to the tip were made that would trigger a pulse to each lead as the tip makes contact, it appears that this approach would be feasible.

TABLE 3-5. SINGLE LEAD BONDS WITH MULTIPLE LEAD ROCKER TIP
INDIUM-GOLD

Schedule: 0.82 - 5.0 ms; 5 pounds pressure

No.	Bond Strength	Type of Separation*		No.	Bond Strength	Type of Separation*	
		P/L	P/B			P/L	P/B
1	1.6		X	19	2.68		X
2	1.6		X	20	2.56		X
3	1.78		X	21	2.38		X
4	1.14		X	22	1.85		X
5	2.5		X	23	2.11		X
6	2.43		X	24	2.33		X
7	1.53		X	25	2.13		X
8	2.22		X	26	1.76		X
9	1.89		X	27	1.0		X
10	1.96		X	28	2.6		X
11	2.41		X	29	2.69		X
12	1.68		X	30	2.61		X
13	2.39		X	31	1.86		X
14	2.08		X	32	2.09		X
15	2.48		X	33	2.35		X
16	2.68		X	34	3.3		X
17	1.5		X	35	1.43		X
18	2.38		X				

*P/L = Pad to Lead; P/B = Pad to Board

Future Rocker Tip Development - Further development required to achieve a rocker tip design capable of being used as a production tool would involve the following:

1. A means of providing power input that did not restrict or interfere with the mechanical movement. Two possibilities are a lighter weight flexible cable and using the axle mount as a conductor.
2. An electronic circuit using some type of encoder to trigger the power supply at the appropriate time according to a preselected setting.
3. A spring-loaded mechanism to return the tip to a starting position.
4. A mechanical drive to move the circuit board with respect to the tip at a controlled rate.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Diffusion-bonded joints between gold-plated Kovar leads and indium-plated copper circuit pads offer some unique advantages for electronic circuit packaging. Test results show that consistent high strength bonds stronger than the copper circuit foil are achieved by parallel-gap bonding at relatively low power settings. The bonds are basically formed by the alloying of the gold, indium, and copper at the bond interface. The lower melting indium acts to prevent oxidation prior to bonding and provides a lower melting interface to start the bond. Other low melting metals such as tin can also be used; however, tin does not offer the case of bonding that results in consistent failure of the copper foil during pull testing. Higher power settings were required with tin to get the same quality of bond but resulted in thermal damage to the circuit board. Preliminary work with tin-plated Kovar leads gave encouraging results with indium but poor results with tin-plated boards. The trend in the industry is changing from gold-plated Kovar leads to tin-plated lead devices. This situation presents a problem for circuit cards designed for welding because tin-plated leads cannot be welded to gold-plated copper circuitry. Special masking of the boards and tinning of the pads is required to permit soldering and welding to the same board. The use of indium plating offers promise of bonding both types of plated lead devices to the same board by the same process. Another advantage of indium is that it can be reflowed (fused) after plating at the same temperature as tin-lead plate, 420°F (possibly lower). Tin, on the other hand, would require an extremely high temperature to reflow, approximately 550°F. Experience shows that indium reflows easily with good wetting while tin plate tends to dewet and solidify unevenly.

Indium, however, has at least two disadvantages. First the metal is fairly expensive at $4.95 an ounce. As a result, the plating solutions are relatively high in cost. Some typical prices are as follows:

Cyanide Plating Solution	$51.75 gallon (8 oz. In/gal)
Fluoborate Plating Solution	$108.90 gallon (12 oz. In/gal)
Sulfamate Plating Solution	$35.60 gallon (4 oz. In/gal)

Although the cyanide bath is the most inexpensive - $6 per ounce per gallon versus $9 per troy ounce per gallon for the fluoborate and sulfamate baths - it is highly alkaline and is not compatible with organic photo resists. In practice, this probably does not present much of a problem because the use of indium should probably be restricted to the printed circuit pads, which would require a variation in processing procedures. A second disadvantage of using indium is that it does not act as a resist to the etchants normally used for circuit board processing. It would have to be protected with an organic resist. Consequently, additional processing steps would be required.

Some of the advantages of diffusion bonding with indium are identical with those of welding over soldering, specifically:

1. Weight saving due to the fact that solder in the quantities required for soldering is heavier than the amounts of gold required for welding. Soldering requires pretinning of leads and solder fillet formation which can add additional weight.

2. The production flexibility of wave-soldering components to boards after mounting of flatpacks. When discrete components and flatpacks are mounted to the same board it is convenient to mount flatpacks first because soldered leads in plated-through holes disrupt the flat surface desirable for flatpack lead bonding.

3. Elimination of the necessity to pretin gold-plated leads. The process is time-consuming, involves close control and results in additional expense and delay.

4. A bond capable of higher temperature strength than solder.

These advantages, however, do not have real significance until a more rapid means of bonding on a production basis is available. The initial work done in this program indicates that multiple-lead bonding with a parallel-gap tool is possible, but requires additional development and refinement. All the technology is available to accomplish the task; however, it needs to be adapted to this application.

As with any new technique, more work is needed to further investigate some new areas discovered in the course of this program and to accumulate additional in-depth data on diffusion bonding. The areas considered most important and recommended for further work are the following:

1. Modification and refinement of the rocker tip to include:

    a. Circuitry to meter and synchronize the power individually for each lead or set of leads according to a preselected voltage and time cycle,

    b. Redesign of electrical power connections to minimize drag.

2. Obtain more extensive data on tin-plated - indium-bonded leads concerning elevated temperature stength and metallurgical nature of bonding mechanisms.

3. Determine printed circuit board processing changes required to fabricate boards with indium-plated circuitry and/or indium-plated pads in conjunction with solder-plated or gold-plated circuitry.

4. Investigate the features of fused indium plating. Fused indium may have better resistance to printed circuit board etchants, thus enabling it to be used as a resist.

5. Investigate repair techniques for removing and replacing diffusion-bonded devices.

6. Investigate the use of indium for sealing of microelectronic packages.

7. Investigate the application of diffusion bonding to beam lead devices.

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