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Solder Fused Interconnections in Multilayer Circuits

George Voida

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SOLDER FUSED INTERCONNECTIONS IN MULTILAYER CIRCUITS

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ABSTRACT

A new solder fusion process has been developed for production of multi-layer cables and multilayer printed wiring boards.

The multilayer process consists of three steps: (1) the photo-etching fabrication of the basic flexcircuit, (2) the lamination bonding of several flexcircuit layers together, and (3) solder fusion interjoining of the exposed lands to provide electrical continuity.

Solder fusion is the unique feature of the process.

In the solder fusion process the multilayer assembly is never in contact with highly reactive chemicals which, if entrapped, can lead to corrosion and dielectric breakdown of the assembly.

Accurate layer to layer registration can be accomplished with the solder fusion process.

A multilayer assembly produced by solder fusion can be shaped into three-dimensional configurations.

The repeatable electrical continuity of solder fused interconnections in multilayer assemblies has been confirmed by microhm resistance testing.

The solder fused multilayer assembly can be used very advantageously in highly sophisticated instruments and apparatus where portability, weight, bulk, environmental stability, and high reliability are critical requirements.

ACKNOWLEDGEMENT

I am gratefully indebted to R. T. Sylvester, 9573, and C. W. Jennings, 2153, for their critical review of the manuscript. Mr. Sylvester's suggestions have helped to effectively enhance the important features of the subject matter in this paper.

I am solely responsible for any errors or omissions that may occur in the document.

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INTRODUCTION

Flexible cables and harnesses are widely used in weapon, missile and satellite systems and for data processing equipment, in aircraft and automobiles, and other commercial applications. To enhance the usefulness of such flexible interconnecting assemblies in miniaturization of components and solid state packaging, the solder fusion process was developed to join several layers simultaneously together into a more compact interconnecting system.

This report describes the three separate steps used to produce the ultimate solder fused multilayer assembly:

1. Basic flexcircuits are fabricated with film type insulation materials and interconnected with small diameter plated through holes

2. The flexcircuits arranged in an orderly stack are next laminated into a layered structure bonded with film adhesive and

3. All of the flexcircuits in the stack are simultaneously solder fused together at adjacent cross-over points. Solder fusion is the salient step which makes this process unique.

The resulting multilayer assembly produced by this process is more reliable because it is not immersed in plating solutions during the interconnecting phase of the processing.

Optical examination and microhm resistance tests of the final multilayer assembly were used to confirm the mechanical integrity and the electrical continuity of the solder fused interconnections.

The multilayer assembly produced by the solder fusion process has the advantage of reduced weight, lower cost, high mechanical strength, outstanding electrical properties, exceptional thermal stability, and reproducible design.

The solder fusion process can be automated to produce multilayer assemblies by continuous roll-to-roll processing.

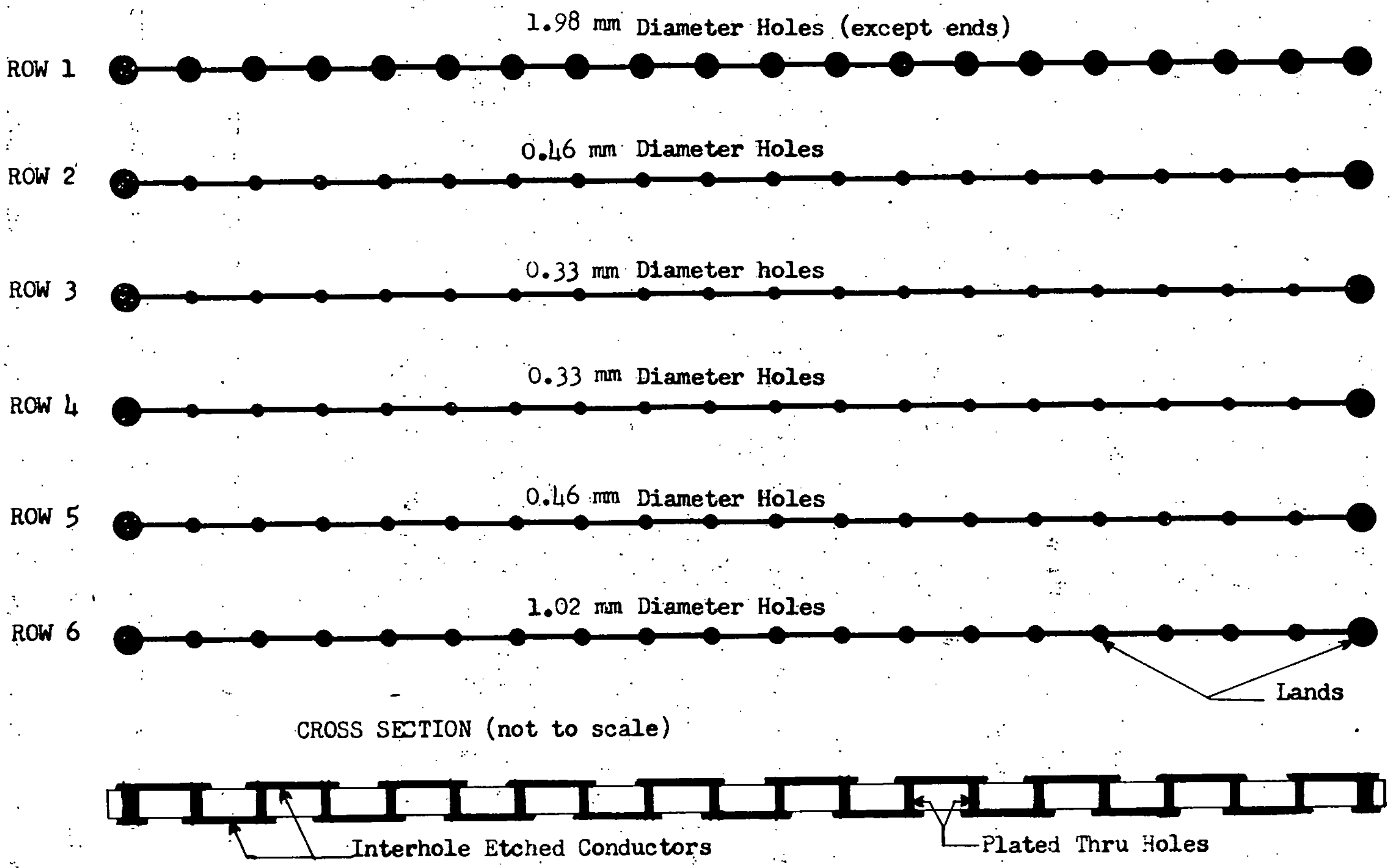
FABRICATION OF THE BASIC FLEXCIRCUITS

In the present design, the basic flexcircuit is fabricated from a thin composite of copper on dielectric film. Intra-connections between the conductors on the two sides of the flexcircuit consist of plated through holes. The conductors and the plated through holes were next overplated with tin-lead solder about 7.5 μm (0.0003 inch) in thickness to facilitate subsequent fusion of the contacting circuits. (The solder had been fused to minimize oxidation during storage and to enhance subsequent flow.) The conductors are produced by etching to the desired configuration. The resulting flexible cables are transparent and can be inspected visually or can be tested for continuity of the conductors and the through connections before proceeding with the rest of the processing.

The flexcircuits were fabricated from commercial copper-Kapton*-copper (35 μm - 25 μm - 35 μm) (1.4 mil - 1 mil - 1.4 mil) laminate bonded with a nylon epoxy adhesive. The flexcircuits were produced by the panel plating process in a production facility.

The test panels consisted of 165 mm x 240 mm ($6\frac{1}{2}$ x $9\frac{1}{2}$ inches) sheets. Each panel contained 120 plated through holes arranged in six rows with 20 interconnects per row. (See Figure 1). The diameter of the through connections were 0.33, 0.46, 1.02, and 1.98 mm (0.013, 0.018, 0.040, and 0.078 inch, respectively). The holes were drilled by numerically controlled drill. Drilling was performed at a speed of 25,000 rpm at a feed rate of 510 millimeter/minute (20 inches/minute). The holes

*Trademark - DuPont Co., Inc., Wilmington, DE, 19898.



FLEXCIRCUIT TEST PANEL CM-PS 75202

Figure 1

CM-PS75202
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SH 2 OF 2

were drilled while each flexible panel was individually supported between phenolic backup boards. After the hole and panel surfaces were sensitized and plated with electroless copper, the panels were electroplated at a current density of 0.03 A/cm^2 ($30\ A/ft^2$) for a period of time sufficient to build up the desired 25 μm (0.001 inch) thickness of copper in the holes. The cross section of the PTH's 0.33 mm and 0.46 mm in diameter are shown in Figures 2 and 3, respectively.

The standard electroless copper plating process was modified as outlined below by pretreating the drilled hole with Shipley 1160 sensitizer:

Immerse part in Shipley 1160 Conditioner at 71 to 74°C for 4 to 5 minutes;

Immerse part in a 240 g/l (2.0 lb/gal) solution of ammonium persulfate for 1 to 3 minutes;

Immerse part in a 10-percent solution of sulfuric acid for 1 to 3 minutes;

Immerse part in a 25-percent solution of hydrochloric acid for 1 to 3 minutes

Immerse part in a 70-percent solution of Catalyst 9F for 1 to 3 minutes;

Immerse part in a 164 g/l (22 oz/gal) solution of Accelerator 19 for 6 to 60 minutes; and

Immerse part in a 10-percent solution of Cuposit at 44°C for 20 to 30 minutes (the Cuposit consists of 90 g/l (12 oz/gal) Shipley 328A, 90 g/l (12 oz/gal) Shipley 328D and 15.6 g/l (1.98 oz/gal) Shipley 328C.

All operations except the hydrochloric acid immersion were followed by a thorough water rinse.

EVALUATION OF PLATED THROUGH HOLES IN FLEXCIRCUITS

The results of tests conducted with these flexcircuits after a series of environmental exposures are described in Reference 1.

The exposure included flexure over 6.35 mm (0.250 inch) diameter mandrel to simulate installation in next assembly; 150°C aging for 100 hours; temperature

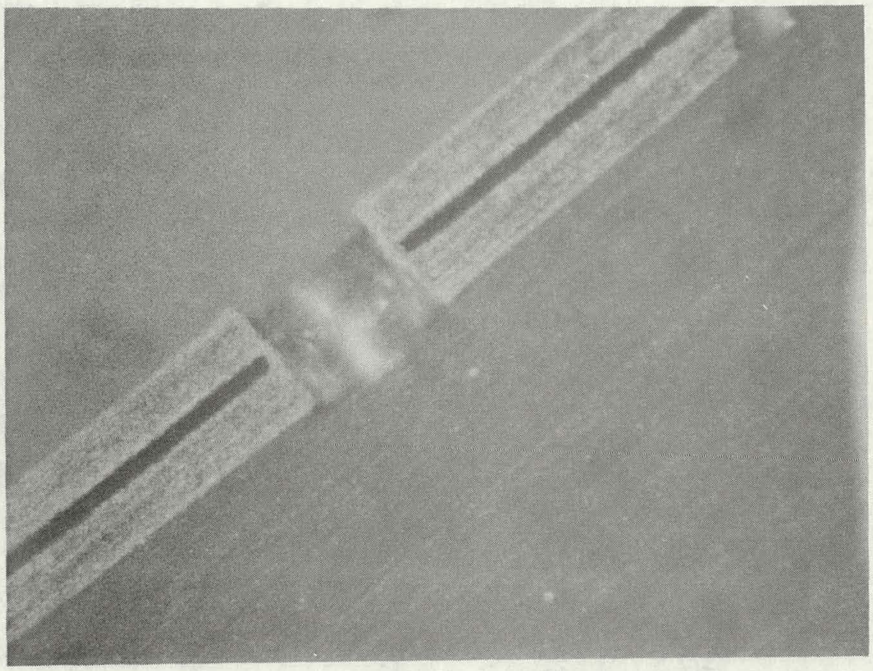


Figure 2. PTH 0.33 mm in Diameter. 70X

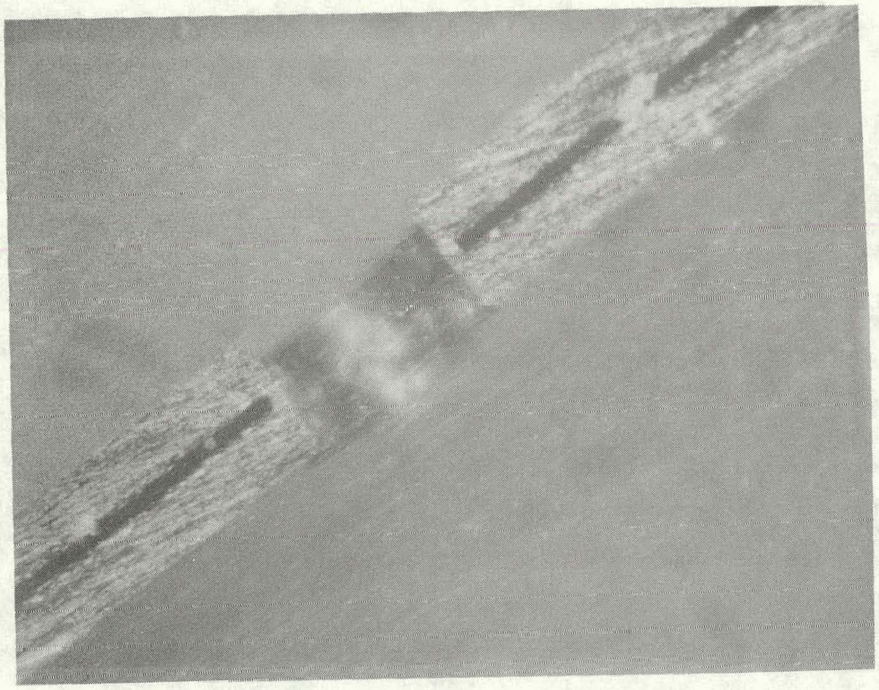


Figure 3. PTH 0.46 mm in Diameter. 70X

shock from -55 to 150°C to determine effects of thermal stresses; MIL-STD 202 humidity testing to determine incidence of galvanic activity; and vibration and mechanical shock and altitude testing to determine survival capability in weapon applications. The 0.33 mm plated through holes (PTH) carried currents of 20 amperes without exhibiting any deleterious effects. Wire leads were soldered and unsoldered a total of 10 times in the 0.33 mm PTH's with no adverse effects.

Typical microhm resistance values of 0.33 and 0.46 mm diameter PTH's in the flexcircuits are presented in Figures 4 and 5. These values did not change upon exposure of the flexcircuits to the conditions mentioned above.

LAMINATION AND SOLDER FUSION OF MULTILAYER ASSEMBLIES

Because of their exceptional environmental stability described above, several layers of the flexcircuits were adhesively bonded together to produce either multilayer flexible cables (Figure 6) or multilayer printed wiring boards[2] (Figure 7). By this process, it was possible to fabricate reliable and economical multilayer assemblies as shall be described later.

After the two-sided flexible circuits are fabricated with the required interconnecting pattern by the photo-etching-plating process described in the preceeding section, they can be inspected visually and tested electrically for conformance with the drawing requirements. Alignment holes can be provided on the artwork and during processing these can be located precisely to achieve the desired layer to layer registration.

The initial multilayer assembly was built in stages. First, two layers were bonded together then the third layer was bonded to the two-layer core, then the fourth layer was bonded to the three-layer core, and so on. Nylon epoxy film adhesive #1044 from American Cyanamid Co. was sandwiched between the aligned

FIGURE 4

COMPARISON OF CROSS SECTION THICKNESS OF PTH's WITH MICROHM RESISTANCE MEASUREMENTS (TEST PANEL #41-ROW3)

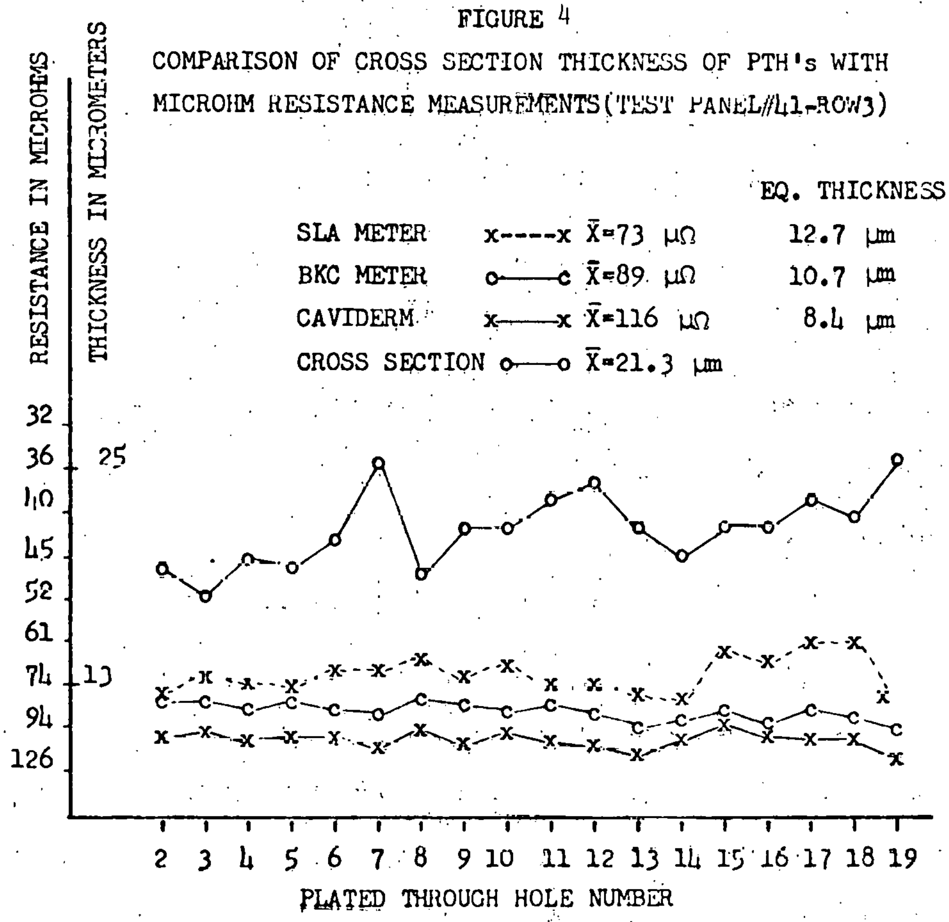


FIGURE 5

COMPARISON OF CROSS SECTION THICKNESS OF PTH's WITH MICROHM RESISTANCE MEASUREMENTS(TEST PANEL#41-ROW2)

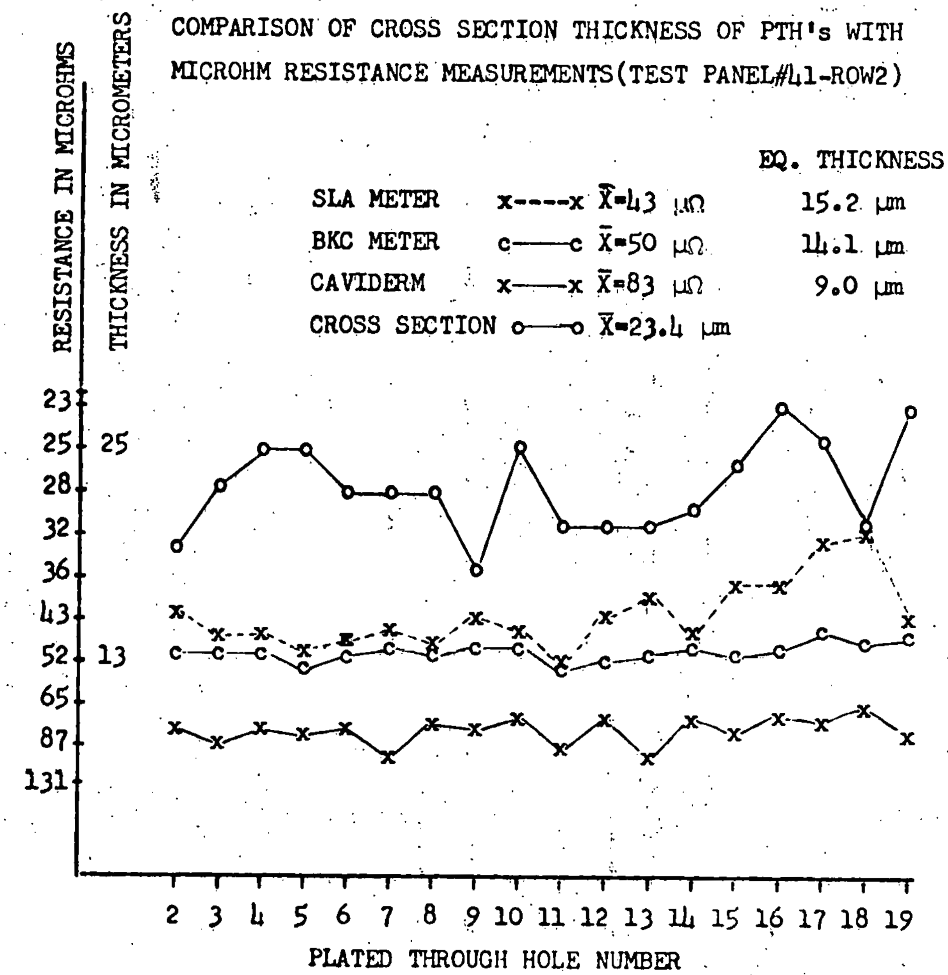
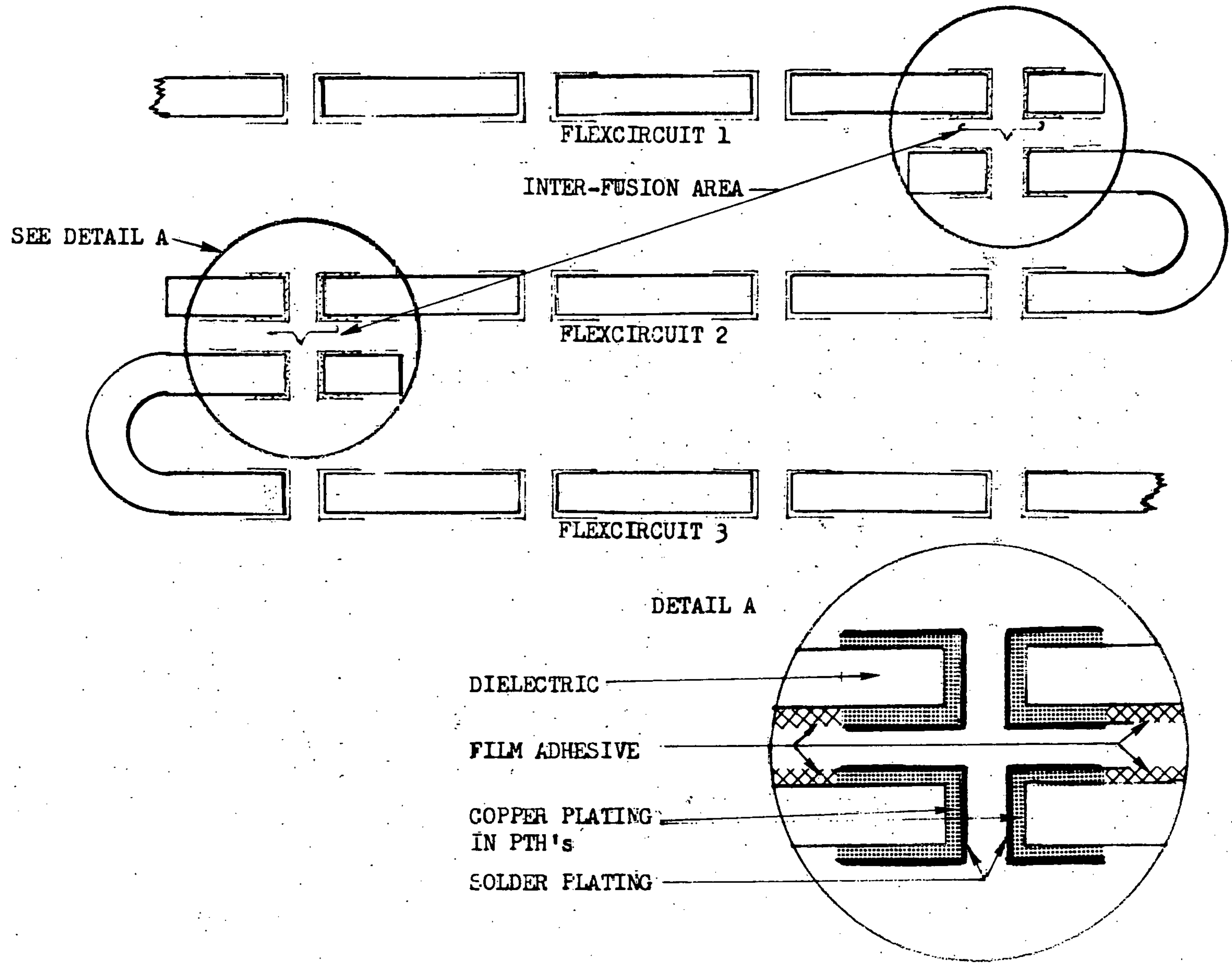


FIGURE 6

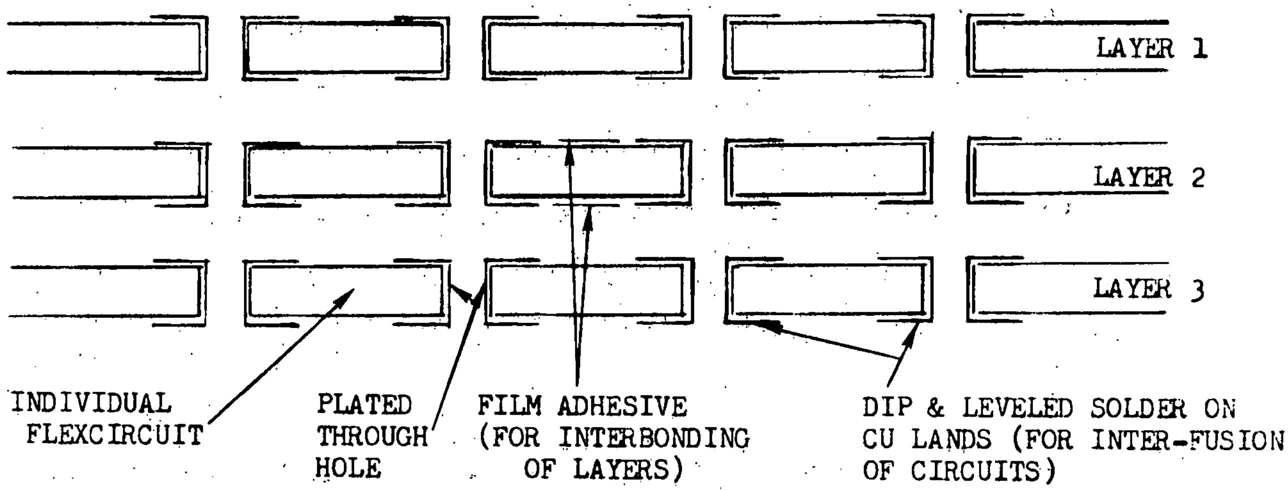
SOLDER FUSED INTERCONNECTIONS BETWEEN FLEXCIRCUITS



NOTE: INTER-FUSION THROUGH ROWS OF PTH's AT EDGE OR END OF JOINED FLEXCIRCUITS.

FIGURE 7

CONSTRUCTION OF SOLDER FUSED MULTILAYER PRINTED WIRING BOARD
(CROSS SECTION)



NOTE: ANY NUMBER OF FLEXCIRCUITS COULD BE STACKED TOGETHER. ADHESIVE APPLIED ONLY TO INTERMOST LAYERS OF STACK AS SHOWN. ADHESIVE KEPT OFF LAND AREAS TO ENSURE METAL TO METAL CONTACT. INTER-FUSION PROVIDES POSITIVE CONTINUITY BETWEEN LAYER VIA THE PTH's.

flexcircuits. The adhesive was 0.076 mm (0.003 inch) in thickness and was prepunched at the adjacent land areas where intercontinuity and fusion were required. During lamination, silicone rubber pads were used on the top and bottom of the assembly to distribute the pressure uniformly over the flexcircuits being bonded. The bottom pad was 3.2 mm (0.125 inch) in thickness and had a Shore A durometer of 50; the upper pad was composed to sponge 1.6 mm (0.062 inch) in thickness. The adhesive was cured at 150°C for 20 minutes at a pressure of 0.85 MPa (125 psi). At the completion of the core, the specimen was immediately removed from the press. The additional flexcircuits were successively bonded in the above manner until the required number of layers was assembled. After each lamination, the assembly was examined at 10X magnification to determine the physical condition of the PTH's. When the adhesive in the final layer was cured, the assembly was subjected to a temperature of 200°C (with pressure maintained at 0.85 MPa) for two minutes to fuse the solder of the adjacent lands together. Thus metal bonding was developed between all of the PTH's in a given stack. Microhm resistance measurements were made on all holes using a MICROHM METER D143* to determine the consistency of land-to-land continuity. Four and six layer assemblies were fabricated by the successive bonding procedures. The microhm test results are summarized in the next section.

In order to expedite fabrication of the multilayer assembly, an attempt was made to simultaneously bond all of the layers together in a single operation. This attempt was successful. No detectable misalignment or damage to the PTH's occurred during the lamination as was confirmed by the subsequent microhm test results. A significant cost saving is achieved by the simultaneous bonding of all layers in the stack.

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*MICROHM PRODUCTS INC., ALB., NEW MEX.

EVALUATION OF SOLDER FUSED INTERCONNECTIONS

The resistance of the PTH's in the single layer flexcircuits averaged about 50 microhms for the 0.46 mm holes and about 100 microhms for the 0.33 mm ones. The microhm measurements of the 1.02 and 1.98 mm holes were not obtained because the meter probes shorted due to the extreme thinness of the specimen.

Since the solder fusion process is a new method for providing PTH's in multilayer assemblies as opposed to the conventional process in which the holes are plated after lamination, microhm resistance measurements were made to ascertain the quality of the holes.

Microhm readings were obtained after each successive layer was bonded to the inner core. No attempt was made during these experiments to fuse the adjacent lands together after each successive lamination. Fusion was accomplished only after the whole stack was bonded.

The resistance readings of the interconnects in Panel #5 at the different laminating stages are presented in Table 1. The microhm values confirmed that there was electrical continuity between all the interconnects in the four layers. The readings appeared unusually high. Solder fusion of the land areas of this panel did not lower the resistance of the PTH's in the stack. Apparently the misaligned adhesive partially covered the lands and prevented intimate metallic contact between the layers. The fusion temperature appeared to spread the adhesive even more extensively between the lands and to impede metallic continuity even more.

In fabrication of Panel #6 the separate layers of the flexcircuits and the adhesive were superimposed more precisely over each other. Slight processing changes were also made. At the inception of the bonding, a contact pressure was applied for $1\frac{1}{2}$ minutes after press loading of the assembly. The low pressure was

TABLE 1

MICROHM RESISTANCE READINGS OF PTH's IN PANEL #5
(AFTER SUCCESSIVE LAYERS BONDED)

(2-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	351	193	182	188	189
2	0.46 mm	331	364	419	429	470
3	0.33 mm	475	466	454	451	477
4	0.33 mm	334	448	419	457	476
5	0.46 mm	305	324	328	314	327
6	1.02 mm	234	218	209	223	224

(3-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	627	267	272	316	242
2	0.46 mm	574	607	644	657	578
3	0.33 mm	765	689	708	706	707
4	0.33 mm	628	657	653	657	685
5	0.46 mm	463	503	512	597	515
6	1.02 mm	393	293	297	328	331

(4-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	928	483	484	457	429
2	0.46 mm	748	827	855	877	887
3	0.33 mm	1170	930	882	896	994
4	0.33 mm	762	822	849	869	974
5	0.46 mm	602	642	659	731	740
6	1.02 mm	458	526	466	655	552

*

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	378	499	447	423	395
2	0.46 mm	1450	832	868	904	811
3	0.33 mm	1550	1500	1011	1035	1081
4	0.33 mm	1230	1248	1061	977	969
5	0.46 mm	1134	908	772	768	766
6	1.02 mm	525	534	551	926	592

* 2 minutes at 200-210°C and 0.85 MPa (125 psi) to fuse lands to each other

to allow the escape of entrapped or absorbed volatiles from between the polyimide layers so as to ensure interbonding of the circuits over the entire areas where adhesive was present. The cure temperature was raised to 160°C.

The microhm resistance readings of the holes in Panel #6 after each of the laminating stages are reported in Table 2. The values on each of the holes of the different sizes increased uniformly in resistance from layer to layer until the sixth flexcircuit was added. The results are presented in Table 3. The unusual rise in resistance of holes in Rows #3, #4, and #5 may be attributed to the misalignment of the last adhesive layer which may have partially overlapped the land areas. With sophisticated production punching dies and locating fixtures, this condition can be corrected by more precise location of the holes in the adhesive and more precise alignment of the flexcircuit layers with respect to each other.

Panel #7 consisted of four flexcircuit layers all of which were bonded simultaneously. The basic steps of the process were similar to those used in the fabrication of Panel #6. Inspection of the laminated assembly at 30X confirmed that no damage had occurred to the PTH's and no detectable layer misalignment resulted from the single stage bonding.

The microhm test results of the PTH's in Panel #7 are reported in Table 4. These results show the excellent agreement of values in Rows 3 and 4 (0.33 mm PTH's) and Rows 2 and 5 (0.46 mm PTH's). The data confirm the feasibility of indexing and bonding of a stack of circuits simultaneously. On the basis of these results, it is indicated that the single stage laminating process is adaptable for the mass production of multilayer cables and multilayer printed wiring boards.

Samples of Panels #6 and #7 were plastic-mounted and cross-sectioned to determine the interlayer alignment and the interfusion of the solder plating between the adjacent circuits. Figure 8 shows the almost perfect alignment of the six layers.

TABLE 2

MICROHM RESISTANCE LEADINGS OF PTH's IN PANEL #6
(AFTER SUCCESSIVE LAYERS BONDED)

(2-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	161	172	161	164	165
2	0.46 mm	244	264	263	258	270
3	0.33 mm	299	363	353	362	368
4	0.33 mm	275	363	366	357	363
5	0.46 mm	226	227	240	232	244
6	1.02 mm	142	146	147	146	148

(3-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	218	198	169	170	168
2	0.46 mm	364	415	407	392	405
3	0.33 mm	488	503	557	566	530
4	0.33 mm	465	506	519	571	523
5	0.46 mm	376	361	427	362	403
6	1.02 mm	305	251	239	267	256

(4-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	306	261	246	240	264
2	0.46 mm	523	516	541	550	557
3	0.33 mm	696	717	721	709	732
4	0.33 mm	692	713	725	725	694
5	0.46 mm	504	497	498	536	528
6	1.02 mm	393	374	351	356	378

(5-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	465	380	340	370	387
2	0.46 mm	681	666	665	679	729
3	0.33 mm	803	1020	859	869	907
4	0.33 mm	873	862	846	859	888
5	0.46 mm	629	569	643	617	684
6	1.02 mm	437	356	363	379	528

(6-LAYERS)

Row No.	PTH Size	Column No. 1	2	3	4	5
1	1.98 mm	571	482	473	449	488
2	0.46 mm	786	823	799	881	869
3	0.33 mm	992	1363	1123	1169	1127
4	0.33 mm	963	1482	1077	1147	1118
5	0.46 mm	836	858	908	977	948
6	1.02 mm	648	539	486	437	499

TABLE 3

AVERAGE MICROHM READINGS OF PTH's IN PANEL #6

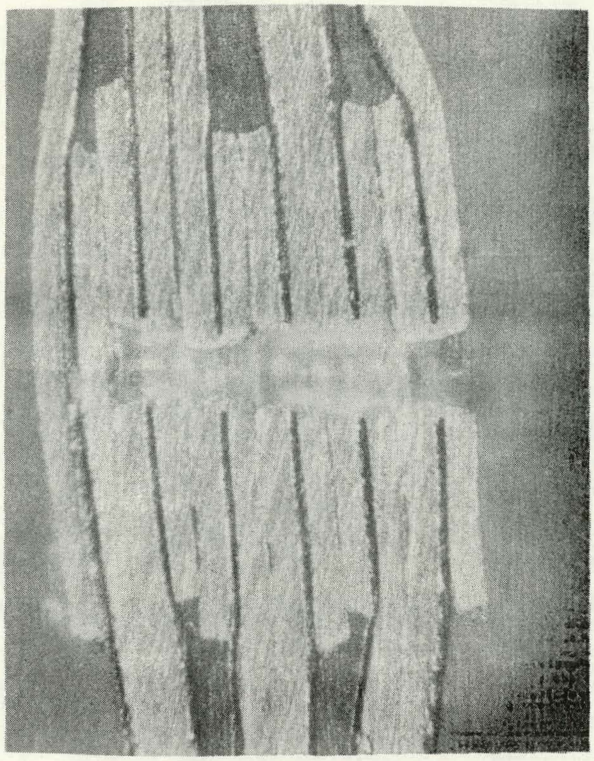
Row No.	1		2		3		4		5		6	
PTH Diameter	1.98 mm		0.46 mm		0.33 mm		0.33 mm		0.46 mm		1.02 mm	
No. of Layers	Microhm	Diff.	Microhm	Diff.	Microhm	Diff.	Microhm	Diff.	Microhm	Diff.	Microhm	Diff.
2	165	--	260	--	350	--	345	--	234	--	146	--
3	185	20	397	137	530	180	515	170	385	151	364	118
4	263	78	537	140	715	185	710	195	523	138	370	6
5	388	125	684	147	892	177	866	156	629	106	413	43
6	493	105	832	148	1154	262	1157	291	905	276	521	108

Each Value An Average of 5 Readings

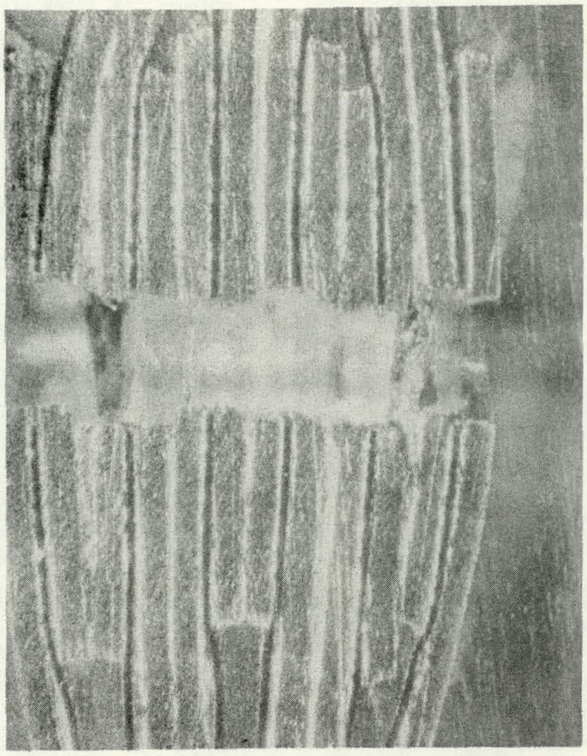
TABLE 4

MICROHM READINGS OF PTH's IN PANEL #7

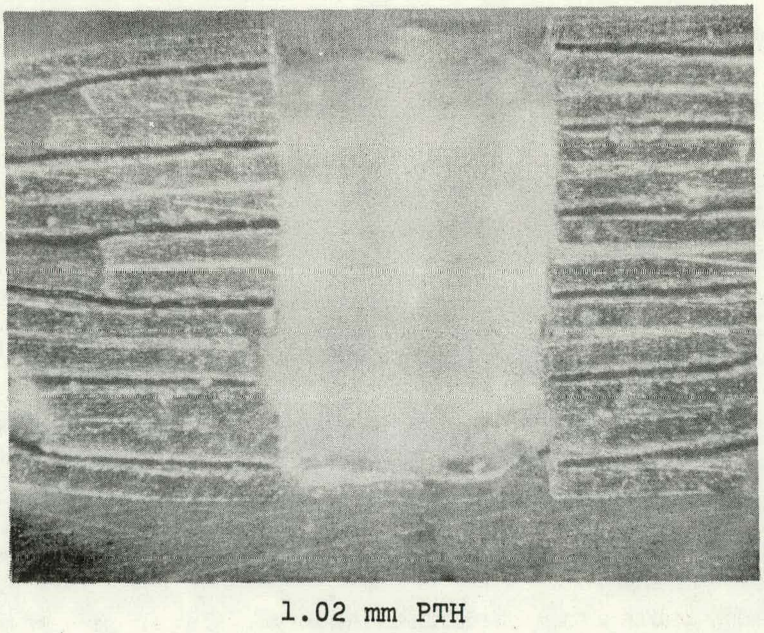
Row No.	Column / PTH Diameter	1	2	3	4	5	Average
1	1.98 mm	238	192	181	173	197	196
2	0.46 mm	496	523	547	540	483	518
3	0.33 mm	627	648	648	672	641	647
4	0.33 mm	602	620	651	639	606	624
5	0.46 mm	481	492	492	512	493	494
6	1.02 mm	278	273	253	278	299	276



0.33 mm PTH
40X



0.46 mm PTH
40X



1.02 mm PTH

Figure 8. Six Layer Assembly. Multi-Stage Lamination

This is evident from the appearance of the different size holes. Even the 0.33 mm holes were perfectly matched. In all three holes, fusion of the solder between the contacting circuit surfaces appeared to form continuous bridges.

Figure 9 shows the holes in Panel #7 in cross section. The layers were perfectly matched. Excellent solder fusion was evident in the 0.33 mm hole. However, there was evidence of only partial fusion at the circuit interfaces of the 0.46 and 1.02 mm holes. No suitable explanation can be offered for this condition.

It may be possible to provide more positive solder fusion by using infrared heating, a solder leveling technique, the vapor condensation heating*, or a suitable modification of these techniques.

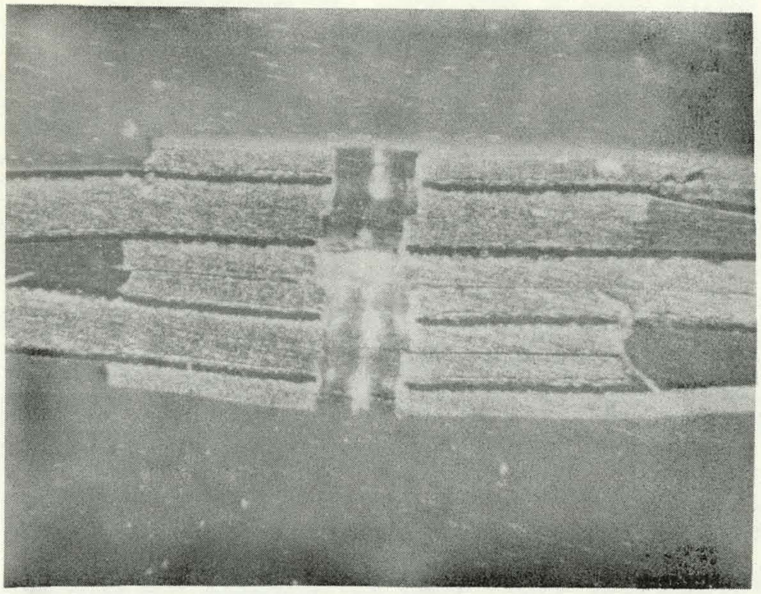
ADVANTAGES OF THE SOLDER FUSED ASSEMBLY

The basic solder fusion process described in this report is considered very valuable to the flexible cable and the printed wiring industries because of the uniqueness of the method for interjoining of multilayer assemblies.

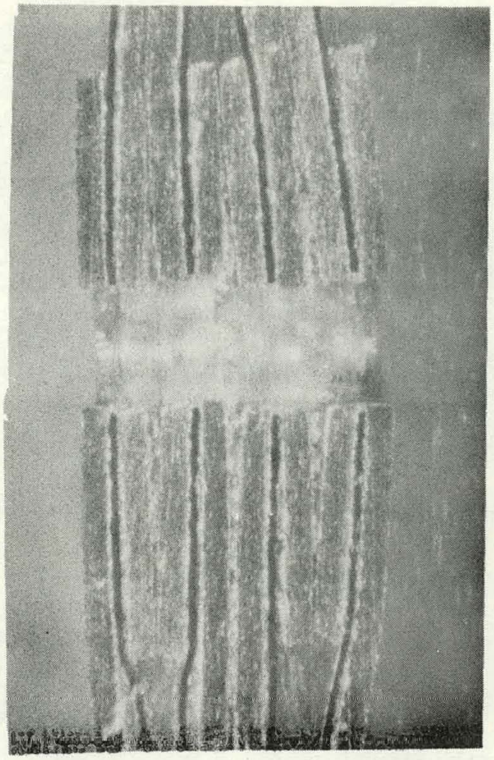
Specific advantages of this process are listed as follows:

- The process is adaptable for automated production.
- Double-sided flexcircuits with plated through connections can be produced by a roll-to-roll process.
- The basic flexcircuit can be inspected visually and electrically to screen out rejects before proceeding with the lamination/fusion process.
- Multilayer flexible cables and harnesses and multilayer printed wiring boards made by the process are reliable and economical.

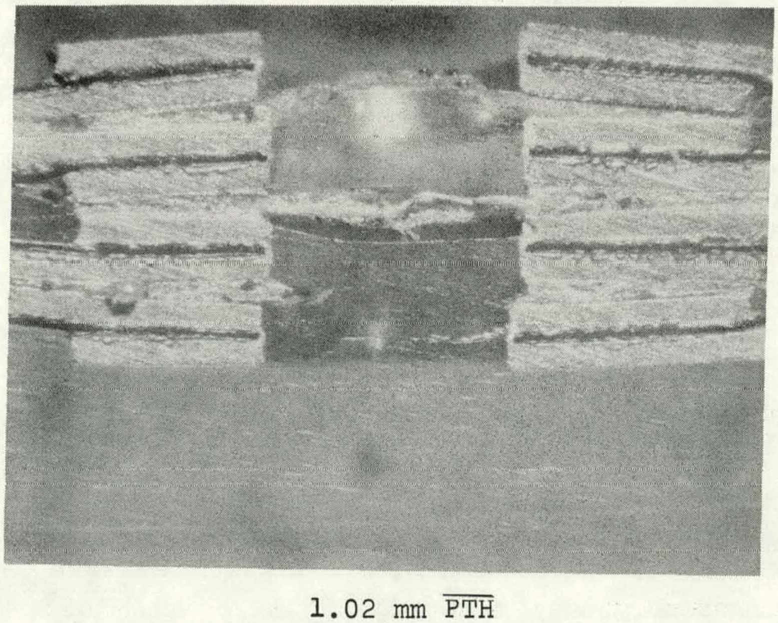
*"Fluorinert" - Trademark - Commercial Chemicals Division, 3M, St. Paul, MN, 55101.



0.33 mm PTH



0.46 mm PTH
40X



1.02 mm PTH
40X

Figure 9. Four Layer Assembly, Single Stage Lamination

- The plated through layers are interjoined by a solder fusion process and the finished assembly at no time is exposed to electrolyte solutions which could subsequently result in corrosion and dielectric breakdown of the assembly.
- The multilayer assemblies can have built-in mechanical flexibility.
- The multilayer assemblies can be constructed with variety of flexible dielectric substrates.
- The solder fused multilayer assemblies could be shaped into three-dimensional configurations.
- The solder fused multilayer assemblies are sufficiently rugged to support mounted components or can be adapted for attachment of miniaturized packages.
- Use of the solder fusion process to bond the multilayer sections together provides good layer-to-layer registration.
- Application of the multilayer assembly can provide a reliable transition between flex and rigid circuits.

OTHER SOLDER FUSED INTERCONNECTING CONCEPTS

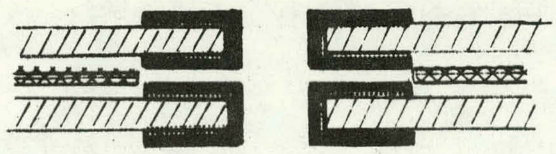
The solder fusion process described in this report is only one of many similar approaches that could be used to interjoin several layers of circuits together electrically.

As a matter of fact the plated through connections could be eliminated altogether in a multilayer assembly.

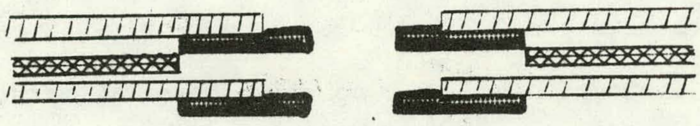
In Figure 10 are illustrated several different variations of the solder fusion concept. In Figure 10b, for example, are shown single-sided flexcircuits that could be produced with the desired etched conductors. The insulation on the

FIGURE 10

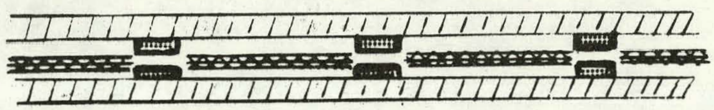
DIFFERENT SOLDER FUSED INTERCONNECTING SCHEMES
(CROSS SECTION)



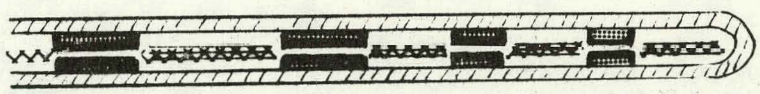
a. SOLDER FUSION JOINING OF PTH



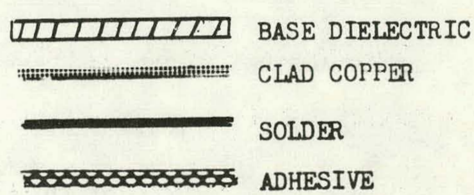
b. COUNTERBORE INSULATION-SOLDER FUSION OF LANDS



c. SOLDER FUSION AT CROSS-OVER OF CONDUCTORS



d. FOLD-OVER CIRCUIT-SOLDER FUSION OF LANDS
AND CONDUCTORS



back-side of the conductors could be removed by counter-boring, lazer stripping, chemical dissolution, or other suitable means. The conductors could then be drilled or punched to provide lead holes of a desired size. The exposed copper conductors could next be solder coated on both sides at these "window" areas so that upon lamination the adjacent circuits could be interjoined by solder fusion as described above. In this scheme, the etched circuitry (except for the land areas) could be completely sealed by the coverlay insulation.

In another scheme shown in Figure 10c, the required two-sided circuitry is again produced by photo-etching. The adhesive/coverlay insulation is punched out at the desired cross-over areas and is bonded to the flexcircuit. The exposed cross-over areas are next solder coated. Upon lamination the circuits are solder fused together at the contacting points and completely sealed within the insulation.

Another extention of the solder fusion process is shown in Figure 10d. In this case the conductors on the two sides of the flexcircuit are interjoined by folding the circuit over on itself and solder fusing the conductors through the matched windows.

Combinations of these interconnecting schemes or similar circuitry arrangements can be interjoined by the solder fusion technique. The variations of such schemes are as prolific as the imagination of the designer utilizing them.

APPLICATION OF THE FLEXIBLE MULTILAYER CABLE

The solder fused multilayer assembly can be used very advantageously in highly sophisticated instruments and apparatus where portability, weight, bulk, environmental stability, and high reliability are critical requirements.

CONCLUSION

A new solder fusion process has been developed for production of multilayer cables and multilayer printed wiring boards.

The multilayer process consists of three steps: (1) the photo-etching fabrication of the basic flexcircuit, (2) the lamination bonding of several flexcircuit layers together, and (3) solder fusion interjoining of the exposed lands to provide electrical continuity.

Solder fusion is the unique feature of the process.

The solder fusion lap joint is very reliable and can withstand severe environmental exposures.

In the solder fusion process the multilayer assembly is never in contact with highly reactive chemicals which, if entrapped, can lead to corrosion and dielectric breakdown of the assembly.

Accurate layer-to-layer registration can be accomplished with the solder fusion process.

The solder fusion process can provide reliable transitions between flexible and rigid circuits.

A multilayer assembly produced by solder fusion can be shaped into three-dimensional configurations.

The repeatable electrical continuity of solder fused interconnections in multilayer assemblies has been confirmed by microhm resistance testing.

The solder fused multilayer assembly can be used very advantageously in highly sophisticated instruments and apparatus where portability, weight, bulk, environmental stability, and high reliability are critical requirements.

REFERENCES

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2. Sandia Laboratories Engineer's Notebook Type A, No. A-3933, pp. 132-5, 138-9, 142-3, 144-8.

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