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ELECTRICAL
CONNECTION
STUDY

BDX-613-204

September, 1970

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A prime contractor for the Atomic Energy Commission
Contract Number AT(29-1)-613 USAEC

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ABSTRACT

Uniform low-values of contact resistance between metal eyelets and thin aluminum coatings on a glass-reinforced epoxy or Mylar substrate were required for a special assembly. Nine joining methods which were investigated failed to produce the desired connection quality. Pulse-arc welding, however, appeared the most promising. Continued work will include further evaluation of ultrasonic bonding and laser welding. Infrared techniques will be investigated on a separate order to provide a suitable inspection method.

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Section 1

SUMMARY

Nine joining processes were examined for possible application in welding the eyelet assembly to a special PCB. Those processes were: brazing; conductive-adhesive bonding; diffusion bonding; miniature-spot resistance welding; electron beam welding; laser welding; parallel-gap welding; and ultrasonic welding.

The basic problem is to make a suitable electrical connection to thin (0.0005-inch) aluminum foil, or to plating on a substrate of glass-reinforced epoxy or Mylar. To date, none of the above-listed methods has produced the required low resistance connection quality.

Electrical resistance and potting/microsectioning techniques were investigated for use in testing and inspection. Neither of those techniques, however, have been fully reliable. Further investigations in this area will include infrared inspection techniques.

Some of the techniques which were not suitable for thin aluminum film applications will be re-evaluated for the new clip. Pulse-arc welding appears to be promising for that use. Ultrasonic bonding and laser welding will be further investigated also.

Section 2

DISCUSSION

INTENT

The original object of this study was to determine the feasibility of welding the eyelet assembly in place on the PCB. However, the scope of the work was expanded during the last quarter to include evaluation of electrical connections used on other types of printed circuits.

PROBLEM

Final inspection of some components requires electrical resistance measurements to be made on the assembly. For those measurements to be meaningful, the resistance through any internal connections must have both a low and uniform value. Use of thin (0.0005-inch) aluminum in these circuits has resulted in failure of conventional mechanical connections to meet the required electrical resistance parameters.

Preliminary study indicated that the present crimped-eyelet assembly used on the PCB (Figure 1), although structurally sound, produces an electrical connection of questionable quality. That conclusion is supported by the eyelet-to-PCB resistance data in Table 1. It is desirable to produce a joint which will provide a uniform, low value of contact resistance. None of the joining methods that have been investigated have produced the required joint quality.

BKC welding capabilities were reviewed and welding experiments were conducted in search for a solution to the eyelet joining problem. Much support was received from other Bendix departments, especially from Electrical Products Engineering, where a process of welding to plated aluminum was developed.

The investigation of test methods was co-ordinated with Advanced Quality Test Engineering, Department 445, and with the Bendix Materials Test Laboratory.

The basic problem is to form a uniform, low-resistance electrical connection between the eyelet and the 0.0005-inch foil or aluminum plating which constitutes the conductive surfaces of the glass-reinforced epoxy or Mylar PCB.

EYELET AND WASHER MATERIAL IS
1100-O OR 2011-T3 ALUMINUM
DEPENDING UPON APPLICATION.

Figure 1. Eyelet Assembly

For the aluminum plating, 0.030-inch-thick samples of glass-reinforced epoxy were flashed on both sides with 50 to 60 microinches of electroless copper to form a conductive coating on which 0.0005 inch of aluminum was electroplated. The plated aluminum has an uneven surface texture which is somewhat porous and is covered by an oxide layer. Adherence of the copper to the substrate is good, but the adherence of the aluminum to the copper flash can vary greatly from part to part. The maximum temperature the substrate can endure for an extended period is approximately 250°F. Above that point, blistering of the plating rapidly occurs at the aluminum-to-copper interface. The eyelets and washers were 1100 or 2011 aluminum, with a nominal thickness of 0.010 inch. The temper and thickness were varied as required for individual welding experiments. A second type of material was 0.0005-inch aluminum foil, laminated to 0.005-inch Mylar, with 0.005 aluminum on the reverse side. Maximum temperature endurance for the laminate material is about 300°F; above that temperature the Mylar begins to soften. Aluminum foil was also laminated to 0.020-inch glass-reinforced epoxy to simulate the assembly.

Table 1. Eyelet Resistance

Assembly No.	Eyelet Resistance (Ohms x 10 ⁻³)		
	Machine Set Crimped	Conductive Adhesive Bonded	Laser Welded
1	2.7	40.8	11.1
2	1.8	16.7	2.8
3	1.8	14.5	2.7
4	5.5	3.2	699.0
5	4.3	5.3	57.8
6	2.5	25.1	26.4
7	25.2	16.2	7.6
8	3.8	8.2	24.0
9	3.8	21.4	3.9
10	3.5	20.7	4.3
11	3.9		40.6
12	4.2		14.1
13	3.4		2.9
14	2.9		2.2
15	4.5		3.1
16	3.3		3.1
17	4.0		Open
18	2.3		3.6
19	112.6		7.1
20	2.4		Open
21	2.8		6.5
22	3.9		6.2
23	1.8		3.3
24	2.2		78.0
25	1.7		4.6
26	1.4		890.0
27	4.9		1.8
28	4.1		2.2
29	5.2		
30	2.5		
31	13.5	*Resistances greater than 1 ohm were considered open for this application	
32	54.1		
33	3.9		
34	1.8		
35	3.0		
36	2.9		
37	5.7		
38	7.7		

Section 3

PROCESSES

BRAZING

Brazing is a process of joining aluminum with a filler material whose melting point is below that of the joint materials. Zinc was selected as the brazing material for the eyelet assembly, primarily because of its low melting temperature (790°F for zinc, 1220°F for aluminum). A 0.002-inch zinc preform was placed between the eyelet and aluminum plating, with current being supplied from the power source of a miniature spot welder. The small cross-sectional area of the plating would not carry enough current to melt the zinc preform without melting the plating. Figure 2 shows a typical result of a brazing attempt where the aluminum path was melted away between the point of electrode contact and the eyelet. The zinc preform was not melted. Power was 1kVA, with a 1-second duration. Although this process is not acceptable using zinc as the filler material, it might be applicable if a lower-melting-point filler could be used, preferably plated onto the materials to be joined. Investigation of this process will be continued and extended to the aluminum/Mylar laminate.

CONDUCTIVE-ADHESIVE BONDING

The conductive adhesive considered for this application was powdered gold or silver in a matrix of epoxy. Because there are many particle-to-particle contact resistances in series for the powdered metal, the bulk resistivity for such an adhesive is necessarily much higher than the resistivity of a pure metal. A typical value for the resistivity of a silver/epoxy adhesive is 0.05 ohm/cm, while the resistivity of pure silver is 2×10^{-6} ohm/cm and pure aluminum is 4×10^{-6} ohm/cm. A joint designed with a layer of conductive adhesive should have the resistance of the adhesive to the contact resistance between the eyelet and plating creating an over-all resistance which would be significantly higher than the joint resistance for a crimped eyelet alone. Actual resistance values (Table 1) did not substantiate this proposal, which is probably due to direct contact between the eyelet and aluminum plating in some areas. Variation of contact resistance within a group of conductive adhesive bonded eyelets was about the same as the variation found in a group of crimped eyelets. Photomicrographs (Figure 3) indicate that the adhesive layer ranges from 0.001 to 0.003-inch thick. Continued investigation will include chemical removal of oxide from the aluminum in an inert atmosphere to produce bonds with a more consistent contact resistance.

Figure 2. Brazing

Figure 3. Conductive-Adhesive Bonding

DIFFUSION BONDING

Diffusion bonding is a process where two oxide-free metals are brought into intimate contact for a time (usually a period of days at low temperature) sufficient for self diffusion to occur. Variations of this process are known as thermocompression bonding, yield-point bonding, and cold welding. Although self-diffusion of aluminum does not appear feasible, various bonding aids which diffuse more rapidly, along with process variations (heat, pressure, current) which may assist diffusion, will be investigated during FY71.

MINIATURE-SPOT RESISTANCE WELDING

In this process, the two materials to be welded are pressed together with the electrical resistance at the interface producing the welding heat when current is applied. It is normally not applied to work pieces of this foil thickness because of the excessive heat generated.

This process, although it did produce some welds, failed in several respects. The process was not consistent. In most instances, the electrical discharge exploded a portion of the eyelet or aluminum plating. It was theorized that this was due to the relatively high resistance of the oxide layer at the joint interface. When the voltage broke down the oxide layer, the arc produced consumed a portion of the eyelet or plating. Removal of the oxide layer by wire brushing or solution etching did not entirely alleviate the problem, since the oxide re-formed when the surface was exposed to air. Because the cross-sectional area of the aluminum plating is extremely small, the current necessary to effect a weld either melted the plating or heated it until it blistered and became detached from the substrate. No additional investigation of this process is planned.

ELECTRON BEAM WELDING

With this process, heat for welding is produced by a focused beam of electrons which melts the surfaces of the two work pieces to be joined. It is normally used to weld exposed edges or seams. The workpieces must be contained in a high vacuum.

Electron beam welding could possibly be used to form a bond between the crimped eyelet roll-over and the washer without much difficulty other than fixturing the part in the welder. This process could not be used to weld the washer or eyelet flange to the aluminum plating because of the necessity for first melting through the relatively thick (0.010 inch) aluminum and stopping the penetration in the aluminum plating (0.0005 inch). Electron beam welders do not ordinarily possess capability for such precision, since

power supplied is affected by factors such as line voltage variations, length of warm-up, and room temperature. In addition, heat generated in this process probably would destroy the bond between the aluminum plating and substrate. The same limitations apply to the aluminum/Mylar laminate. Although the process will not be applied to thin aluminum films, it will be considered for joining the eyelet roll-over to the washer of the shell assembly and to the spring clip of the assembly shown in Figure 4.

Figure 4. Assembly

LASER WELDING

Welding with a laser is similar to electron beam welding, except that the heat is produced by a focused beam of coherent light. The laser beam produces a hole in the material by virtue of the localized heating by the light beam, and welding occurs around the edges of the hole. Initial development work on the laser process was performed by two companies: one company used a ruby laser; the other company used a YAG laser.

The problems encountered were similar to those encountered in electron beam welding: an inability to control the laser power to stop penetration in the region of the 0.0005 aluminum plating, and difficulty in keeping the surface of the part in proper relation to the focal point of the laser. The photomicrographs in Figure 5 show a laser weld which failed to penetrate the eyelet flange (A) and another which passed through the aluminum plating and into the substrate with no apparent welding. Failure to weld was confirmed by the contact resistance of the laser-welded eyelet assemblies listed in Table 1, which was generally as high as that of the unwelded assembly.

A. Shallow Weld Penetration

B. Excessive Weld Penetration

Figure 5. Laser-Weld Samples

PARALLEL-GAP WELDING

In this process the electrodes are placed side by side on the conductor lead to be welded, as shown in Figure 6. If the material is of low resistance it must be plated with a high-resistance, lower melting metal such as nickel or zinc. The welding current density will be greater than can be transmitted by the conductor lead alone, forcing current to flow through the high resistance metal plating which melts and forms the weld. This process, because it is a hot-weld technique, could only be used on a high-temperature substrate.

Figure 6. Typical Parallel-Gap Welding Application

PRESSURE WELDING

Pressure welding is a bonding technique which uses deformation of the metal to create a scrubbing action at the interface. Typical lap joint applications for aluminum require a 50 to 75 percent decrease in the cross-sectional area and typical pressures in excess of 150,000 psi. Elevated temperatures can be used to decrease the pressure required for welding. Because the compressive strength of epoxy glass laminates is usually less than 40,000 psi and much deformation of the metal is required, this process could not be applied to welding eyelets. Similarly, the Mylar in aluminum/Mylar laminates could not withstand pressure welding.

Future investigation of this process will be limited to application of pressure in diffusion bonding investigations.

ULTRASONIC WELDING

Under certain conditions, this process can be used to bond an eyelet to 0.0005-inch plated aluminum. The equipment used to develop test specimens was a Model W-750-AW lateral drive ultrasonic welder made by the Sonobond Corporation. It was rated at 750 acoustical watts, with an operational frequency of approximately 15 kilohertz. A transducer is used to convert the power to linear motion at the active sonotrode (Figure 7). Although a lateral drive welder is not particularly adapted to producing circumferential welds, best results were obtained with ring-type weld heads (Figure 8). Other weld head configurations for individual spot welds and three spot welds distributed around the periphery were attempted with only limited success. The radius on the tip was varied from 1/2 inch to infinity (flat), with acceptable results from any tip radius between 1/2 inch and 2 inches.

Figure 7. Ultrasonic Welding Setup

The weld is produced by the direct scrubbing action between the two pieces of work material. The high frequency linear motion imparted by the transducer allows the material to rub only in the area under the weld head, as a result of elastic deformation of the material next to the active head. The remainder of the material is relatively motionless, but it does transmit the vibration.

Before welding, the part is inserted between the weld head and anvil, and the clamping force is applied; the frequency of the welder is then adjusted for resonance, so that maximum power will be delivered to the weld tip. The resonance frequency is a function of clamping force, material thickness, and weld-tip configuration. Eyelet flange thickness must be closely

Figure 8. Ultrasonic Welding Tips

controlled because variations change the power requirements to produce an acceptable weld; otherwise, it would be necessary to alter the power setting for each weld. To prevent this additional effort, the thickness tolerance on the 0.010-inch flange should be ± 0.001 inch or less.

Surface preparation for ultrasonic welding is not as critical as for other welding processes because the surface oxide is partially broken up by the vibratory action during welding. Both the aluminum plating and eyelets were degreased with acetone and the plating was abraded with very fine steel wool to provide a smooth working surface, although the latter step was not necessary. The bonds formed by ultrasonic welding were not bonds where the metals were fused together, as in a resistance weld, but rather an intimate mechanical contact. In most cases the oxide interface was destroyed at only a few places.

The ultrasonically-welded samples always failed at the interface between the aluminum plating and electroless copper, as shown in Figure 10. For this reason it was assumed that a tensile or peel test would not give a true indication of weld quality. Tests were limited to removing a welded eyelet and visually observing the amount of plating which adhered by sectioning and observing the weld interface and measuring the contact resistance of the eyelet. The first photograph in Figure 10 shows a zone where the oxide interface has been broken up, indicating a good weld. The second photograph is an overall view of the same assembly. The dark spots which appear to be discontinuities in the aluminum plating occurred during the sectioning process. The best ultrasonic welds are usually developed with a high power-setting and a short pulse duration. A good weld

Figure 9. Ultrasonic Weld With Eyelet Removed

schedule was found to be a power-setting of 18, which is roughly equivalent to 600 acoustical watts input, and a duration of 0.5 seconds with a clamping force of 30 pounds. When too much power was applied, the aluminum plating was ruptured around the periphery of the flange. This defect is evident in Figure 9 and also in Figure 10.

The aluminum plated on the flat samples had a relatively smooth surface texture because of the smooth finish on the substrate, whereas on the actual part, the surface finish on the outside is relatively rough because of the machined surface of the glass/epoxy. The high points on the surface were usually exposed ends of fiberglass and the low points were the more-easily-machined epoxy. When a weld was attempted, the aluminum plating over the ends of the fiberglass were welded, but the areas over the low points were not. The resulting welds had low strength, with discontinuities in the surface plating. To get an acceptable weld on the outer surface of the PCB, the area around the eyelet holes should be spot finished to a smooth surface before the plating operation.

A second problem which would be encountered with a full-size part would be getting an ultrasonic welder designed to weld inside a cylinder. The present equipment at Bendix has the weld tip attached to a vertical bar which applies the clamping force. It could not be readily modified to weld inside an actual part.

Ultrasonic welding has not yet been applied to an aluminum/Mylar laminate, but is planned for future investigation. Welding to plated aluminum will continue using aluminum foils rather than eyelets, and heated welding tips. Future investigation will also include torsional ultrasonic techniques. Samples will be sent to manufacturers of ultrasonic welders to permit evaluation of their equipment for this application.

A. 200X Magnification

B. 25X Magnification

Figure 10. Ultrasonic Weld, 0.10 Eyelet to Aluminum Plating

Section 4

EYELET DESIGN

Several eyelet designs which may provide more reliable contact and easier welding are being investigated. Some of the proposed designs incorporate serrated flanges for penetration into the conductive aluminum layer; others employ spring tensioning devices.

The tension clip shown in Figure 11 is representative of a particularly promising area of investigation. Since such a device has a low profile, it may have potential application as a flat-cable connector.

Figure 11. Tension Clip Connector for Flat Cables

Section 5

TESTING AND INSPECTION

To date, no completely reliable inspection method has been developed to determine weld quality. Both electrical resistance and potting and sectioning have been used extensively for weld evaluation, but both processes are limited by poor resolution. Microsectioning can be used to detect gross flaws such as a lifted washer or ruptured plating. The small zone of inspection with this technique does not allow much qualitative interpretation. In addition, it is a destructive technique. Neither is electrical resistance a satisfactory test method, because it cannot distinguish between a weld and good mechanical connection. For a welded assembly, electrical resistance measurements do not provide information on the amount of area welded. A small spot weld will bring the resistance sufficiently close to the theoretical low limit that any additional welded area is a parallel connection which is overshadowed by the resistance of the path length used to measure the resistance. One of the most reliable inspection methods for ultrasonically-welded eyelets is to remove the eyelet and observe the amount of aluminum plating removed (Figure 9).

Infrared inspection techniques will be investigated in FY71 to determine any potential application toward qualitative weld evaluation. It is reasonable to assume that areas of localized welding will pass more current and increase in temperature faster than nonwelded areas. If infrared scanning can observe the transient temperature profile, it may provide a non-destructive method of weld inspection.

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