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WELDING ELECTRIC TERMINALS ULTRASONICALLY

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WELDING ELECTRIC TERMINALS ULTRASONICALLY

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Prepared by G. S. Darner, D/862, under PDO 6984910

Ultrasonic welding has been investigated for use on foil conductor terminations. Equipment and tooling have been improved, material considerations and combinations have been evaluated to determine their effects on the process; and special configurations and techniques have been studied to extend the applicability of the ultrasonic welding process.

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SUMMARY

Ultrasonic welding uses high frequency vibratory energy to make welded terminations. With this process, solid state bonds can be made between most metals and alloys without the formation of brittle intermetallic compounds.

A Sonobond Model W-150-AW ultrasonic spot welder was purchased and modified to improve reliability and repeatability. Welding tip (Sonotrode) and anvil designs were evaluated to stabilize their resonant frequency characteristics over a broad static clamping force range. A sonotrode tip was developed which maintains a constant resonance frequency regardless of clamping force. Development of this tip design greatly enhanced weld consistency. Evaluations showed that anvil tip designs are not critical to the ultrasonic welding process.

Current-voltage phase deviation was evaluated, but results indicate no stable relationship between phasing and weld quality. The best results are obtained by nulling the weld frequency to the system resonance before welding a given configuration.

Weld schedules were developed and certified for several material combinations involving aluminum, copper, and nickel foil conductors. The configurations certified were chosen to represent the original material evaluation goals of this project.

Several weld material characteristics were evaluated to determine their effects on ultrasonic welding. Materials of matched hardness were found to be easier to join than materials of unmatched hardness. Three methods of cleaning materials were found acceptable but surface finish was found to have no apparent effect on the weldability of copper and aluminum samples. Plated materials were studied and found to be ultrasonically weldable.

Copper-to-aluminum samples were subjected to moisture resistance, thermal shock, and elevated temperature aging tests. No evidence of weld degradation or galvanic corrosion was present following the testing.

Recommended quality control methods have been established. Pull testing, metallurgy, and routine process control sampling are needed to certify and maintain ultrasonic weld schedules. Non-destructive test methods were found unsuccessful in evaluating ultrasonic welds.

Two circuit layers separated by Mylar insulation can be ultrasonically welded. By heating the welder anvil, the Mylar can be melted and flowed from the weld area to ultrasonically weld the two circuit layers.

Material combinations that were previously certified at ambient temperatures were welded at elevated temperatures and then pull tested. The results showed a slight improvement in weldability and strength at 65.5°C (150°F), but the benefits are offset by the disadvantages of handling hot materials and by reduced system efficiency.

Ultrasonic ring welding was evaluated for joining foil conductors to small eyelets. This technique proved to be ideal for this configuration and provides a technique for ultrasonically welding many circular configurations.

Ultrasonic welding provides the capability for joining aluminum foil conductors directly to connector hardware, eliminating the need for transitional joints required by other forms of welding. Simulated removable contacts and connector shells have been ultrasonically welded to aluminum foil conductors. Since most connector contacts are fabricated from beryllium copper, techniques were developed to overcome the significant material hardness mismatch which previously prevented ultrasonically welding this metal.

Methods were developed to make welds to foil conductors backed with Kapton insulation. Initial studies showed that the Kapton seemed to absorb the supplied ultrasonic energy, preventing successful welds. Further investigations, however, revealed a power point at which successful welds can be made, but beyond which it appeared to absorb the supplied ultrasonic energy. Tests on successfully welded samples indicate that no damage is done to the Kapton during this process.

DISCUSSION

SCOPE AND PURPOSE

The object of this project was to establish the capability to ultrasonically weld material combinations and configurations that cannot be successfully joined with other welding processes. Ultrasonic welding is especially useful on flat aluminum conductor terminations. Development activities included selection and modification of ultrasonic welding equipment, design of weld tooling, investigation of weldable material combinations, and studies of weld configurations suitable for the ultrasonic process.

PRIOR WORK

Prior work on this project is covered in several Bendix reports.¹⁻⁴

ACTIVITY

Ultrasonic welding is a process for joining similar and dissimilar metals by introducing high-frequency vibratory energy into the overlapping metals in the area to be joined. No fluxes or filler metals are used, no electrical current passes through the weld metals, and normally, no external heat is applied. The metals to be welded are clamped together under moderately low static force between a stationary support called the *anvil* and the vibratory element called the *sonotrode*. A solid state weld is achieved when ultrasonic energy is transmitted into the weld area.

Almost every metal and alloy can be ultrasonically welded. Ultrasonic welding is particularly useful for materials and geometries that are difficult to weld by other processes. Since this is a solid state bonding process, there is no weld fusion zone and no brittle intermetallics are formed.

Initial Equipment Procurement

A literature search was conducted to identify vendors of suitable ultrasonic welding equipment. The Sonobond Corporation of West Chester, Pennsylvania, was found to be the only active manufacturer of ultrasonic welding equipment.

Five typical weld configurations were sent to the Sonobond Corporation (Table 1) to determine which of their welders was most suited for Bendix applications.

Table 1. Ultrasonic Weld Evaluation Material Combinations

Combination	Materials Welded	Configuration
1	0.1524 mm (0.006 in.) Diameter SAP-930 Aluminum to 0.1524 mm (0.006 in.) Diameter SAP-930 Aluminum	Crosswire (90°)
2	0.1524 mm (0.006 in.) Diameter SAP-930 Aluminum to 0.066 mm (0.0026 in.) Thick Copper	Lap Joint
3	0.127 mm (0.005 in.) Thick Copper to 0.127 mm (0.005 in.) Thick Aluminum	Lap Joint
4	0.0762 mm (0.003 in.) Thick Copper to 0.101 mm (0.004 in.) Thick Copper	Lap Joint
5	0.254 mm (0.010 in.) Diameter 5056 Aluminum to 0.066 mm (0.0026 in.) Thick Copper	Lap Joint

A trip was made to Sonobond to review the results and to obtain technical details on the weld process and equipment. The weld configurations submitted for testing were all successfully terminated by a Model W-150-AW weld system with the exception of the crosswire (90 degree) weld. It was learned that crosswire configurations cannot be satisfactorily welded by ultrasonics. Based on the test results and information obtained from Sonobond, a Model W-150-AW was purchased for Bendix evaluations.

Equipment Modifications

The Sonobond Model W-150-AW ultrasonic spot welder (Figure 1) delivers 150 acoustic watts maximum power output. The output power is controlled by varying the dc voltage to the output oscillators via a front panel autotransformer control. As received, there is no accurate indication of this voltage setting. The static clamping force is continuously variable from 0 to 643.8 N (0 to 145 lb) and is monitored by an air pressure gage mounted on the welding head assembly. The weld duration is controlled by a potentiometer on the front control panel; however, no accurate method of monitoring is provided.

Modifications to the welding equipment were incorporated to improve performance and repeatability and to allow continuous

Figure 1. Model W-150-AW Ultrasonic Weld Station

monitoring of weld parameters. The modified system is shown on Figure 2. A digital counter timer was attached to an improved timing circuit for weld duration setting and repeatability within ± 1 ms. A calibrated digital voltmeter was added to monitor the dc voltage supplied to the output oscillators and the autotransformer was modified to allow dc voltage settings down to 0. The previous lower limit was 42 V which proved to be excessive for some weld configurations. The system frequency adjustment control was relocated to the front panel and a frequency monitor was connected to the system. Phase detection circuitry was added, using the current meter supplied on the front panel.

Figure 2. Bendix-Modified Ultrasonic Weld System

Weld Tooling

The design of the sonotrode and anvil tips was found to have a significant effect on the results obtained on any particular material combination. Tip radius, hardness, surface finish, and geometry all have bearing on the size of the weld bond achieved and the range of weld system settings that achieve satisfactory weld quality. It was found that a sonotrode-anvil configuration whose own resonance matched the weld system resonance across the full range of available clamping forces resulted in the best process control.

Various weld tips were produced with different surface treatments to determine the influence of tip design on weld quality. The tips were produced with different tip radius, surface finish, and surface hardness treatment.

During tests using these tip designs, it was noted that some tips appeared incapable of producing satisfactory weld quality while others produced consistently good results. System resonance was checked with the various sonotrode-anvil configurations at

clamping forces of 0, 168, 261, 355, 448, 541, and 643 N (0, 38, 59, 80, 101, 122, and 145 lb.). As expected, some of the tips were more subject to drastic changes in circuit resonance than others as clamping force was changed (Figure 3). Those weld tips which provided a system resonance of near 19.7 kHz across the full clamping force range provided the best results. As can be seen in Figure 3, Sonotrode 9 and Anvil 2 provided more consistent welding than Sonotrode 4 with the same anvil.

Two sonotrode tips were designed and built to achieve a system resonance of 19.7 kHz across the total clamping force range; they featured an extended tip to allow tuning of the sonotrode to the natural system resonance (Figure 4).

The system resonance with these tips installed is shown in Figure 3. The redesigned sonotrode tips are numbered 23 and 24. Tip 23 has an electrical discharge machined surface (250 rms) treatment while Tip 24 has a smooth (9 rms) surface finish. The average system resonance with these sonotrode tips installed is 19.6 kHz which is extremely close to the true system resonance. Subsequent welding evaluations with these tips revealed a substantial improvement in weld consistency at various clamping forces. All future weld tips will be designed in basically the same manner to achieve a system resonance of approximately 19.7 kHz.

Anvil tip design has been determined not to be critical to the weld system performance; therefore, anvil tips can be fabricated in a variety of geometries suited to the configuration of the parts to be welded. However, the anvil tips should be mounted on the anvil supplied with the weld system to maintain an anvil contra-resonant frequency of 2 kHz below that of the system resonance.

An electrical discharge machined (EDM) finish of 250 rms on sonotrode and anvil surfaces was recommended by the Sonobond Corporation. The EDM finish reduces slippage between the welder and workpieces and improves energy transfer to the weld interface. Tips and anvils with EDM surface finishes of 250 rms were compared with tips and anvils having smooth finishes. The EDM surfaces caused material deformation that resulted in degradation of weld area strength. Acceptable welds were achieved on all material combinations evaluated using the smooth finished tips. To date, best results have been achieved with an 8 rms surface finish. Weld tips evaluated were made of M2 tool steel; anvils were made of A6 tool steel.

Frequency Relationship

Maximum power is transmitted to the weld when the welding system is operating at its resonant frequency. However, mechanical loading during the weld process causes the current-voltage phase

Figure 3. System Resonance With Various Sonotrode-Anvil Combinations

Figure 4. Extended Tip Sonotrode

relationship to vary considerably. The system can be seen to drift in and out of resonance during the weld process by oscilloscope monitoring of the current and voltage waveforms. A device that detects the average phase deviation during the weld cycle was employed to determine if phase deviation can be used as a quality control indicator. It was theorized that a frequency setting which results in the lowest average phase deviation would optimize power transmission to the weld.

Sample welds were made with several material combinations. Average phase deviation, pull strength, and failure mode were each plotted against the frequency settings. The average phase deviation reached a minimum at a frequency generally corresponding to the system resonance as determined by the welder's built-in phase detection circuitry. Average weld quality was observed to increase as this frequency was approached. Since this established a relationship between phase deviation and resonance, it was proposed that by monitoring average phase deviation the drift from resonance could be detected--thus indicating weld quality.

Sample welds were made at a fixed frequency while average phase deviation was forced to vary by contaminating the weld materials. The phase deviation and pull strength were recorded for each weld. No stable relationship was found to exist. Some welds with high phase deviation were found to be good while some with low phase deviation were unacceptable. Phase deviation, therefore, cannot be used as a quality control indicator.

Since the frequency resulting in minimum average phase deviation and the system resonant frequency are generally the same, the most expedient method of determining system resonance is with the built-in detection circuitry. The welder is set to a low power setting to eliminate phase shift caused by mechanical loading during actual full power welding, the material combination to be welded is clamped in position, and the frequency is varied until a null is obtained on the resonance meter: this is the resonant frequency of the system.

Weld Schedule Development and Certification

A weld schedule development plan was required which would take into account the controllable weld system parameters, including weld power, clamping force, weld duration, and oscillator frequency.

The method employed for developing a weld schedule initially involves selecting a weld power setting which is purposely on the low side. Clamping force, weld power, and weld duration are held constant while oscillator frequency is varied in increments of 50 or 100 Hz. An isostrength chart is developed as oscillator frequency is optimized. The pull strength average and destructive testing results will vary according to the effect oscillator frequency has on weld quality.

After an oscillator frequency search for a particular material combination is completed, the clamping force is changed and the search is begun again. As a result, oscillator frequency and clamping force are optimized on the basis of data developed from specimens destructively tested in a 180 degree peel mode. A weld power search is started following completion of the isostrength search for proper oscillator frequency and clamping force. This search involves holding oscillator frequency, time duration, and clamping force constant while slowly increasing weld power. Weld samples are destructively tested on each power setting and the results are plotted on another isostrength diagram. From this diagram the optimum point can be determined for certification of a weld schedule.

Weld duration has not proven to be highly critical. Weld durations of less than 50 ms have a tendency to result in erratic weld quality while durations in excess of 700 ms tend to cause sonotrode tip sticking. The weld schedules certified during this reporting period were confined to weld durations between 100 and 300 ms.

Weld schedules were developed and certified on four different material combinations following the procedure explained above. The aluminum-to-aluminum configuration consisted of two pieces of 0.1397 mm (0.0055 in.) Aluminum Alloy 1145. The three other

weld schedules consisted of welding copper to copper in various thicknesses, alloys, and tempers. The weld schedules developed on these material combinations resulted in excellent process control during the certification run. Examples of the isostrength diagrams used in developing the weld schedules for these four material combinations are shown in Figures 5 and 6. Sample test results from a weld schedule certification are shown in Table 2.

During the destructive testing period of a weld schedule development and certification both the strength of the weld and the failure mode are recorded. A sample that yields a bond weaker than the strength of the weakest material is labeled an "A" break. A bond stronger than the weakest material is labeled a "B" break. A weld schedule is not considered certified unless all 100 destructively tested specimens yield "B" type breaks.

Weld Material Combinations

The following material combinations have been evaluated and successfully certified. Several of the combinations were certified using both smooth and EDM tips.

- ETP Copper Alloy 110-Hard T (0.127 mm or 0.005 in.) to ETP Copper Alloy 110-Hard T (0.127 mm or 0.005 in.).
- Aluminum Alloy 1145-Annealed (0.1397 mm or 0.0055 in.) to Aluminum Alloy 1145-Annealed (0.1397 mm or 0.0055 in.).
- ETP Copper Alloy 110-Annealed (0.0686 mm or 0.0027 in.) to ETP Copper Alloy 1100-Annealed (0.0686 mm or 0.0027 in.).
- OFHC Copper 102-Annealed (0.0813 mm or 0.0032 in.) to OFHC Copper 102-Annealed (0.0813 mm or 0.0032 in.).
- ETP Copper Alloy 110-Annealed (0.0686 mm or 0.0027 in.) to Aluminum Alloy 1145-Annealed (0.1397 mm or 0.0055 in.).
- ETP Copper Alloy 110-Hard T (0.1346 mm or 0.0053 in.) to ETP Copper Alloy 110-Hard T (0.1346 mm or 0.0053 in.).
- Aluminum Alloy 1100-Annealed (0.0127 mm or 0.0005 in.) to Aluminum Alloy 1100-Annealed (0.0127 mm or 0.0005 in.).
- ETP Copper Alloy 110-Annealed (0.0686 mm or 0.0027 in.) to Aluminum Alloy 7075-T6-Brinell 80 (3.683 mm or 0.145 in.).
- Aluminum Alloy 1100-H18 (0.0889 mm or 0.0035 in.) to Aluminum Alloy 1100-H18 (0.0889 mm or 0.0035 in.).
- Aluminum Alloy 1100-H18 (0.0889 mm or 0.0035 in.) to 99.5 percent Nickel-Annealed (0.254 mm or 0.010 in.).

Figure 5. Isostrength Diagram, Clamping Force Versus Frequency, Copper-to-Copper

- ETP Copper Alloy 110-Hard T (0.1346 mm or 0.0053 in.) to 99.5 percent Nickel-Annealed (0.254 mm or 0.010 in.).
- ETP Copper Alloy 110-Annealed (0.025 mm or 0.001 in.) to Aluminum Alloy 1100-Annealed (0.0127 mm or 0.0005 in.).
- Aluminum Alloy 1145-H19 (0.127 mm or 0.005 in.) to Aluminum Alloy 1145-H19 (0.127 mm or 0.005 in.).

The previous material combinations were chosen to represent the original material goals of this project. Combinations similar to the above but having different dimensions can also be successfully welded.

Figure 6. Copper-to-Copper Weld Voltage Isostrength Diagram

Weld Material Considerations

Material Hardness

Studies of material combinations have shown that the temper of the materials being welded should be closely matched to yield the best results. When materials of different hardness are welded, the power required to weld to the harder material will damage the softer material in direct proportion to the difference in hardness between the two materials. Welds on soft materials are more parameter-sensitive than welds made between harder materials. High quality welds can be obtained over a wider band of machine settings with harder materials, facilitating schedule search and enhancing process repeatability.

Material Thickness

There is no limit on the thickness of the material in contact with the anvil. However, maximum material thickness for the material

Table 2. Weld Schedule Certification, ETP Copper to ETP Copper

Date: 8-24-73

Weld Schedule: 5

Sonotrode: 23

Anvil: 2

Resonant Frequency: 19.675 Hz

Weld Voltage: 75 V

Material: 110 ETP Copper 0.686 by 6.35 by 38.1 mm
(0.0027 by 0.250 by 1.5 in.)

Clamping Force: 262.4 N (75 lb)

Weld Duration: 100 ms

Pull Test Failure Points

Sample	Force		Failure Type	Sample	Force		Failure Type
	Newtons	Pounds			Newtons	Pounds	
1	15.1	3.4	B	6	11.6	2.6	B
2	13.3	3.0	B	7	10.7	2.4	B
3	16.4	3.7	B	8	13.7	3.1	B
4	18.2	4.1	B	9	12.4	2.8	B
5	17.8	4.0	B	10	12.4	2.8	B

Table 2 Continued. Weld Schedule Certification, ETP Copper to ETP Copper

Sample	Force		Failure Type	Sample	Force		Failure Type
	Newtons	Pounds			Newtons	Pounds	
11	16.0	3.6	B	41	17.3	3.9	B
12	12.9	2.9	B	42	12.0	2.7	B
13	18.2	4.1	B	43	23.1	5.2	B
14	14.2	3.2	B	44	19.1	4.3	B
15	9.8	2.2	B	45	8.4	1.9	B
16	14.2	3.2	B	46	15.6	3.5	B
17	20.9	4.7	B	47	23.1	5.2	B
18	16.4	3.7	B	48	19.1	4.3	B
19	12.0	2.7	B	49	17.8	4.0	B
20	12.0	2.7	B	50	9.3	2.1	B
21	16.4	3.7	B	51	19.6	4.4	B
22	15.1	3.4	B	52	16.9	3.8	B
23	12.0	2.7	B	53	11.6	2.6	B
24	12.9	2.9	B	54	13.7	3.1	B
25	10.2	2.3	B	55	22.2	5.0	B
26	6.6	1.5	B	56	14.2	3.2	B
27	16.4	3.7	B	57	17.8	4.0	B
28	17.3	3.9	B	58	14.7	3.3	B
29	15.1	3.4	B	59	10.7	2.4	B
30	12.4	2.8	B	60	14.7	3.3	B
31	17.3	3.9	B	61	13.3	3.0	B
32	11.6	2.6	B	62	11.6	2.6	B
33	17.8	4.0	B	63	10.7	2.4	B
34	7.6	1.7	B	64	10.2	2.3	B
35	12.4	2.8	B	65	12.9	2.9	B
36	13.3	3.0	B	66	12.0	2.7	B
37	18.2	4.1	B	67	15.1	3.4	B
38	11.2	2.5	B	68	8.4	1.9	B
39	15.1	3.4	B	69	14.2	3.2	B
40	11.6	2.6	B	70	17.3	3.9	B

Table 2 Continued. Weld Schedule Certification, ETP Copper to ETP Copper

Sample	Force		Failure Type	Sample	Force		Failure Type
	Newtons	Pounds			Newtons	Pounds	
71	15.1	3.4	B	86	11.2	2.5	B
72	10.7	2.4	B	87	10.7	2.4	B
73	15.6	3.5	B	88	14.2	3.2	B
74	12.9	2.9	B	89	14.2	3.2	B
75	11.6	2.6	B	90	14.7	3.3	B
76	8.9	2.0	B	91	15.6	3.5	B
77	24.0	5.4	B	92	14.2	3.2	B
78	15.6	3.5	B	93	8.4	1.9	B
79	18.7	4.2	B	94	16.4	3.7	B
80	8.9	2.0	B	95	14.7	3.3	B
81	14.7	3.3	B	96	15.6	3.5	B
82	20.9	4.7	B	97	16.9	3.8	B
83	9.8	2.2	B	98	13.7	3.1	B
84	12.4	2.8	B	99	9.3	2.1	B
85	7.1	1.6	B	100	16.0	3.6	B

*Failure Types: A is a Weld Failure; B is a Material Failure

contacting the tip is 0.287 mm (0.015 in.). Thicker materials require a welder with more power output than the Sonobond Model W-150-AW.

Pre-Weld Cleaning

Surface cleaning in preparation for ultrasonic welding is not highly critical for most materials. The ultrasonic welding mechanism disrupts and disperses normal oxide layers and other surface films on the mating surfaces. The more readily weldable materials, such as aluminum and copper, usually require only the removal of surface lubricants. However, a few materials, such as heat treated metals and heavily oxidized materials, may require mechanical abrasion.

Three methods for removing surface lubricants were evaluated: ultrasonic cleaning, spray cleaning, and wiping, all using trichloroethylene as a degreasing agent. Samples of ETP Copper Alloy 110 (0.0686 mm or 0.027 in. thick) were coated with oil to represent a worst case condition. Some of the samples were cleaned by each of the three methods while a control group remained uncleaned. At a constant weld schedule setting, samples from all four groups were ultrasonically welded and then pull tested. The welds made on the cleaned materials were of high quality, regardless of the cleaning method. The uncleaned control samples could not be welded. Since all three methods are equally effective in removing surface lubricants, the choice of cleaning method can be based on the size and configuration of the part to be welded.

Surface Finish Effects

Generally, rolled, extruded, and drawn surface finishes are satisfactory as received for ultrasonic welding. However, since machined surfaces are often encountered on production pieceparts, a study was made to determine the effects of material surface variations on ultrasonic weldability.

Sample test plates fabricated from 3.17 mm (0.125 in.) 7075-T6 aluminum were finished to roughness heights of 203, 406, 813, and 1600 μ m (8, 16, 32 and 63 μ in.). ETP Copper Alloy 110 (0.0686 mm or 0.0027 in. thick) samples were welded to the test plates at a constant weld schedule setting and destructively pull tested. The resulting welds to all of the finishes were of high quality and all exhibited similar pull strength. This test was then repeated by welding Aluminum Alloy 1100-H19 foil (0.051 mm or 0.002 in. thick) to the test plates. The resulting welds were also of this quality.

Surface finish has no apparent effect on the weldability of these materials. Pieceparts do not require special surface preparation

or tolerancing. Most machined surfaces encountered on production parts fall within the roughness range evaluated.

Plated Materials

Since plated materials are often encountered in actual production applications, an evaluation was undertaken to determine the effects of ultrasonic welding on plated materials. For this investigation, samples of ETP Copper Alloy 110-Hard T (0.1346 mm or 0.0053 in. thick) were gold plated in accordance with Process Standard 9902112, Type 2, Class 2. Samples of the same material were also nickel plated in accordance with Process Standard 9902105.

A weld schedule was developed for the gold plated copper welded to itself and sample welds were destructively pull tested and metallurgically examined. The weld joint was formed between the two layers of gold with no disruption of the gold plating. The welds were metallurgically sound and exhibited an average pull strength of 48 N (10.08 lb.).

The nickel plated copper material was welded to itself and sample welds were again pull tested and metallurgically cross-sectioned. With this material combination, the nickel plating was disrupted and most of the weld joint was a copper-to-copper weld. However, these welds were also metallurgically sound.

Plating appears to be no hinderance to the ultrasonic welding process. Although two types of bonding phenomena were observed, both produced good welds. The occurrence of one type of bonding over the other is seemingly related to the weldability of the plating material used.

Environmental Testing of Ultrasonic Welds

Samples of welds between ETP Copper Alloy 110-Annealed (0.0686 mm or 0.0027 in.) and Aluminum Alloy 7075-T6 (3.683 mm or 0.145 in.) have been environmentally tested in accordance with MIL-STD-202E. Samples were subjected to moisture resistance testing in accordance with Method 106D (3.4 omitted), thermal shock in accordance with Method 107D, and elevated temperature aging in accordance with Method 108A at 125°C (257°F). Following the environmental tests, the samples were destructively pull-tested and metallurgically sectioned. Results were compared with the original certification data for this configuration. The samples exhibited pull strengths as high or higher than the average certification pull strengths. Metallurgical evaluation showed the welds to be extensively bonded; as were the original certification samples. No evidence of galvanic corrosion was found.

Acceptance Criteria

A recommended quality control system has been established for ultrasonic welding. Original schedule certification will be based on 20 welded and destructively-pull-tested samples and 2 metallographic samples.

The pulled samples shall exhibit definite material rather than weld failure. A minimum acceptable pull strength should be established during the certification. Since there are no visual quality indicators, routine process control samples should be welded and pull tested. All samples will be required to exceed the minimum acceptable pull strength previously established.

A method has been proposed for determining weld quality during metallographic evaluation. The length of the bonded weld interface is expressed in multiples of material thickness.

From our evaluations, the bonded interface should be at least four times the material thickness. A bonded interface of less than four times the material thickness indicates an unacceptable weld. This method has been used in evaluating the quality of some certification samples on this project. Ultrasonic reflection mapping, ultrasonic transmission mapping, electrical testing, and thermographics have been used to establish a non-destructive evaluation method, but because of the irregular surface condition that results from the ultrasonic welding process, none of these methods yielded usable results.

Welding Through Mylar Insulation

Because of increased usage of multi-layer flexible circuitry, the capability was developed to ultrasonically weld two circuit layers separated by Mylar insulation by melting the Mylar between the circuit layers and forcing it from the weld area by static clamp force. Once the Mylar is removed from the weld area, an ultrasonic termination is made between the circuit layers.

A special welding setup was devised to melt the Mylar (Figure 7). A heat insulating anvil shaft was fabricated from machinable ceramic, a thermocouple was welded to a standard anvil tip and threaded onto the top of the insulating shaft, a 125 W band heater, attached to the anvil assembly, was regulated by temperature feedback control circuitry, and a digital readout monitored the temperature of the anvil.

Experimentation proved 315°C (600°F to be the best temperature for this process. The weld material is clamped between the sonotrode and anvil and held for several seconds for the Mylar to melt and be forced from the weld area. The actual time required depends on the weld configuration, material combination, and

Figure 7. Special Welding Setup

material thickness. Once the Mylar is displaced from the weld area, metallurgically sound ultrasonic welds are produced between the circuit layers.

Three material combinations were evaluated.

- Aluminum Alloy 1100-0 (0.102 mm or 0.004 in. thick) to Aluminum Alloy 1100-0 (0.0127 mm or 0.0005 in. thick) separated by two 0.127 mm (0.005 in.) layers of Mylar.
- Aluminum Alloy 1100-0 (0.127 mm or 0.005 in. thick) to annealed ETP Copper Alloy 110 (0.127 mm or 0.005 in. thick) separated by 0.254 mm (0.010 in.) of Mylar, and

- Annealed ETP Copper Alloy 110 (0.127 mm or 0.005 in. thick) to annealed ETP Copper Alloy 110 (0.127 mm or 0.005 in. thick) separated by 0.254 mm (0.010 in.) of Mylar.

Figure 8 shows a cross section of an ultrasonic weld between the 0.102 mm (0.004 in.) aluminum and the 0.0127 mm (0.005 in.) aluminum separated by two 0.127 mm layers of Mylar. The weld quality is good and all Mylar has been displaced from the weld zone. The welds made between the other material combinations exhibit the same high quality as the one shown.

Hot Ultrasonic Welding

Hot ultrasonic welding involves the external application of heat to the materials being welded to increase molecular activity in the materials and theoretically increase their weldability. To evaluate this procedure, several material combinations, previously certified at ambient temperatures, were welded at elevated temperatures and the resulting data were compared to the original certification data.

The welding setup used in the studies of welding through Mylar insulation (Figure 7) was used to heat the weld metals before they were ultrasonically welded. The materials were clamped between the sonotrode and anvil and held there until the desired temperature was reached. Weld schedules were developed at several temperatures ranging from 37.7°C (100°F) to 260°C (500°F) and pull test data were plotted for each schedule data point. The graphs were then compared to the graphs of the original certification data taken at ambient temperatures. Three material combinations were evaluated.

- Aluminum Alloy 1145-H19 (0.127 mm or 0.005 in.) to Aluminum Alloy 1145-H19 (0.127 mm or 0.005 in.).
- Aluminum Alloy 1145-H19 (0.127 mm or 0.005 in.) to annealed ETP Copper Alloy 110 (0.0686 mm or 0.0027 in.).
- Hard T ETP Copper Alloy 110 (0.1346 mm or 0.0053 in.) to Hard T ETP Copper Alloy 110 (0.1346 mm or 0.0053 in.).

On all material combinations evaluated, heating the material to 65°C (150°F) resulted in a slight improvement over welds made at ambient temperature. Both weld strength and repeatability were improved.

At temperatures above 65°C weld strength and quality were reduced on both of the material combinations involving copper. While aluminum-to-aluminum welds exhibited slightly increased weld strength at these higher temperatures, the weld parameter range was significantly reduced and repeatability was decreased.

Figure 8. Cross Section of Ultrasonic
Weld Through Mylar Insulation

With the material combinations studied, the slight benefits derived by this process are offset by the disadvantages of special material handling methods and reduced system efficiency. Heated materials and the hot welding apparatus require special handling to protect the operator from burns. The use of the ceramic anvil "de-tunes" the weld system resonance and reduces system efficiency. Therefore, this procedure is recommended only for marginally weldable material combinations that cannot be satisfactorily welded at ambient conditions.

Ultrasonic Ring Welding

Ultrasonic ring welders are used throughout industry for hermetically sealing transistor cans, explosive containers, pyrotechnic packaging, and for other configurations that cannot be welded by the more conventional arc or resistance processes. Ultrasonic ring welders have proven ideal for joining round parts such as eyelets and terminal studs to foil conductors and other component pieceparts.

Ultrasonic ring welders employ torsional motion as opposed to the linear motion of an ultrasonic spot welder. This is accomplished by using a multiple transducer arrangement; since there is no linear motion, shear damage to small, delicate components can be avoided.

Ultrasonic ring welding has been evaluated for Bendix applications by the Sonobond Corporation. Small Aluminum Alloy 1100-H18 machined eyelets were welded to 0.051 mm (0.002 in.) Aluminum Alloy 1100-H19 foil laminated on both sides with Kapton insulation (Figure 9). The Kapton in the weld area was removed before the lamination process. Figure 10 is a cross-section view of a sound eyelet-to-foil bond.

Sonobond also ring welded the gold plated stainless steel connector shell and 0.051 mm (0.002 in.) aluminum conductor shown in Figure 11. Again, the resultant bonds were of high quality.

Terminations to Connector Hardware

Ultrasonic welding has been evaluated for direct terminations to connector hardware because of the increased use of aluminum conductors in interconnection applications and the difficulty of applying arc and resistance weld processes to these thin foils.

Previous welding processes used on aluminum foil conductors employed a series of transition joints to make electrical connections between cable conductors and component hardware. Ultrasonic welding can make direct terminations and reduce the required number of weld joints on a given system.

With ultrasonic welding, the material in contact with the anvil must be rigidly held. Connectors with removable contacts are ideal.

Two simulated removable contact styles have been studied. Figure 12 shows a round style contact with the weld performed on the rear of the contact. This design requires a weld anvil drilled to hold the contact rigid in a vertical position and is best suited for a 90 degree conductor breakout from the pins. Figure 13 shows a contact with a flat tab machined on it. The ultrasonic weld is made to the tab while the contact rests on a conventional anvil. This contact is well suited to a straight out conductor breakout but requires more space in the connector. Figures 12 and 13 both show Aluminum Alloy 1100-H19 welded to beryllium copper Alloy 172.

Since most connector contacts and shells are fabricated from beryllium copper, techniques had to be developed to overcome the material hardness dissimilarity between beryllium copper and aluminum which had prevented the welding of these materials. A sonotrode weld tip was designed to maximize scrubbing at the weld interface by minimizing energy absorption in the sonotrode itself. It was found also that the beryllium copper surface must be abraded to yield satisfactory weld results.

Figure 9. Aluminum Eyelet

Figure 10. Cross Section of Weld
Between Aluminum Eyelet
and Aluminum Conductor

Figure 11. Cross Section of Weld Between
Gold Plated Stainless Steel
Connector and Aluminum Conductor

Ultrasonic Welds to Metals With Kapton Backing

Initial attempts to weld to foil conductors having Kapton film backing indicate that the Kapton absorbs the ultrasonic vibratory energy even with full weld power applied. Attempts were made to freeze the Kapton by subjecting the samples to a liquid nitrogen bath and harden it to reduce energy absorption. However, successful welds still could not be made.

With unbacked foils, significantly exceeding the required weld power damages the foils being welded; holes are rubbed through the foils in the weld area. It was assumed that the same effect would be found when welding to Kapton backed foils but investigation proved otherwise.

A power setting, usually of moderately low magnitude, exists at which successful welds can be made to a Kapton backed foil. Exceeding this power point does not result in damage to the materials but instead appears as if inadequate power is being applied.

Figure 12. Round Connector Contact

Figure 13. Tab Connector Contact

Sample welds have been made and evaluated with good results. Visual and metallurgical examination reveals a sound metallurgical bond with no damage to the Kapton. High voltage standoff tests have shown that the welding process does not degrade the dielectric properties of the Kapton in the weld area.

ACCOMPLISHMENTS

The ultrasonic weld process has been established as a successful method for terminating foil conductors such as aluminum and copper which previously could not be welded by other processes. This is a significant capability since many production applications use these thin foil conductors. Having been proven successful, this process is being incorporated into Bendix production activities. A Sonobond Model W-150-AW ultrasonic spot welder, incorporating the modifications developed during this project, has been purchased for Bendix production use. This project resulted in five significant accomplishments.

- Modifications to the purchased welding equipment were incorporated to improve repeatability and reliability of the equipment.
- Sonotrode tips were developed that greatly improve ultrasonic weld consistency over varying clamping force settings.
- Weldable materials were identified and several combinations of these materials were scheduled and certified.
- Material parameters were studied to determine their effects on the ultrasonic welding process. Hardness, thickness, cleaning, finishing and plating were all evaluated.
- Special configurations were evaluated and processing techniques were established for ultrasonic welding. They include welding through Mylar insulation, ultrasonic ring welding, welding to connector and cable hardware, and welding to Kapton-backed foil conductors.

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