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BDX-613-1016

ULTRASONIC WELDING OF ELECTRICAL TERMINATIONS

PDO 6984738, Milestone Report

D. E. Stittsworth, Project Leader

Project Team:
G. S. Darner
S. M. Hefley
L. E. Chandler
H. B. Pressly

Internal Distribution December 1973

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC

Bendix Kansas City Division

MASTER

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ULTRASONIC WELDING OF ELECTRICAL TERMINATIONS

BDX-613-1016, UNCLASSIFIED Milestone Report, Internal Distribution
December 1973

Prepared by D. E. Stittsworth, D/862, under PDO 6984738

Ultrasonic welding of electrical terminations is being investigated. Activity includes equipment evaluation and modification, weld tip design, and weld schedule certification on four different material combinations. The ultrasonic welding process has not been fully evaluated, but a potential for future production program applications is indicated.

THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

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

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SUMMARY

A distinct advantage of ultrasonic welding is the capability to terminate aluminum conductors to various metals. The ultrasonic action breaks down and disperses the aluminum oxide film, allowing direct metal-to-metal metallurgical bonding.

Welding equipment performance characteristics were investigated. It was determined that equipment purchased from the Sonobond Corporation would require modifications to assure repeatability and proper control. Modifications were incorporated in the timing, weld power, and resonance circuits of the power supply.

Present activity is primarily directed at true welding evaluations of various material combinations. These evaluations include development of weld schedules, certification of weld schedules, metallurgical cross-sectioning, and environmental testing.

Ultrasonic welding is well suited for terminating two flat electrical conductors. In the evaluations performed to date, the process has produced consistently high quality electrical terminations between copper and aluminum. Weld schedules were successfully developed and certified on four material combinations. Metallurgical cross-sections completed on two of these material combinations show 80 percent of the interface bonded.

Future activity will involve welding evaluations on various material combinations and environmental testing of welds.

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DISCUSSION

SCOPE AND PURPOSE

Ultrasonic welding is being investigated as a process for making high quality electrical terminations. Some material combinations and configurations cannot be satisfactorily bonded using state-of-the-art weld processes, especially where flat aluminum conductors are being terminated.

Through this investigation the material combinations, weld configurations, and weld equipment requirements will be defined for future production use.

A distinct advantage of the ultrasonic weld process is its facility for terminating aluminum conductors to various other metals. The ultrasonic scrubbing action at the interface breaks down the aluminum oxide film and disperses it outside the weld area.

PRIOR WORK

A literature search was conducted to identify commercial vendors of ultrasonic welding equipment suitable for electrical terminations. The equipment had to be capable of welding 0.005 (0.127 mm) inch-thick copper or aluminum to an equivalent thickness of copper or aluminum. The Sonobond Corporation was one of two vendors located. The other company had just entered the market and could not provide published literature on its equipment. Sonobond had two weld systems which appeared to fit the requirements. These systems, Models W-150-AW and W-375-AW, have outputs of 150 and 375 watts, respectively.

ACTIVITY

Five different material configurations were sent to the Sonobond Corporation for weld evaluation (Table 1). These configurations consisted of aluminum and copper configurations which cannot be successfully terminated with present state-of-the-art weld processes without special procedures.

A trip was made to Sonobond to review their evaluations 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 between two small diameter aluminum wires. It was learned that crosswire configurations cannot be satisfactorily welded by ultrasonics.

Table 1. Ultrasonic Weld Evaluation Material Combinations

Combination	Material (in.) (mm)	To Material (in.) (mm)	Configuration
1	0.006 diameter (0.1524) SAP-930 Aluminum	0.006 diameter (0.1524) SAP-930 Aluminum	Crosswire (90°)
2	0.006 diameter (0.1524) SAP-930 Aluminum	0.0026 thick (0.066) copper	Lap Joint
3	0.005 thick (0.127) copper	0.005 thick (0.127) aluminum	Lap Joint
4	0.003 thick (0.0762) copper	0.004 thick (0.101) copper	Lap Joint
5	0.010 diameter (0.254) 5056 Aluminum	0.0026 thick (0.066) copper	Lap Joint

The Model W-150-AW weld system features a continuously adjustable clamping force of 0 to 145 pounds (0 to 643.8N), can be bench mounted, and has a maximum power output of 150 acoustical watts. Under actual welding conditions, with those configurations tested, the W-150-AW weld system was deemed more appropriate than the W-375-AW welder.

Technical information was obtained on the ultrasonic welding process in the following areas:

- The Sonobond Corporation recommended that electrical discharge machined (EDM) sonotrodes be used to improve weld consistency on slightly contaminated materials. The EDM finish provides a somewhat rough finish on the tip which minimizes slippage between the interface of the sonotrode and the material in contact with the sonotrode. By minimizing this slippage more ultrasonic energy is transmitted to the weld interface.

- If harder metals are being welded, it is recommended that the weld tips be made of Udimet 700 for better wear characteristics.

- Continuous tip dressing probably will not be required when welding copper or aluminum, since soft metals have little wear effect on welding tips.

- A calibrated force gauge is recommended to consistently set the weld head clamping force.

- The maximum material thickness which can be welded by a particular ultrasonic welder is determined by the thickness and type of material in contact with the sonotrode tip (driven element).

- The stationary support (anvil) is tuned to oscillate at a frequency of approximately 2 kHz below the operating frequency of the sonotrode.

- A copper shim is recommended between the replaceable sonotrode tip and the sonotrode to improve ultrasonic energy coupling.

- When welding wire-to-wire configurations, the sonotrode and anvil tip surfaces must be specially designed. The anvil tip should have a groove approximately twice as wide and 2 1/2 to 3 times as deep as the maximum wire diameter. The sonotrode tip configuration is formed like a wedge to fit in the anvil slot.

Figures 1, 2, 3, and 4 show the terminations evaluated and metallurgical cross-sections of the weld joints. Based on this evaluation, a sonotrode Model W-150-AW (Figure 5) was procured.

Development Plan

A plan was developed for the evaluation of the weld process.

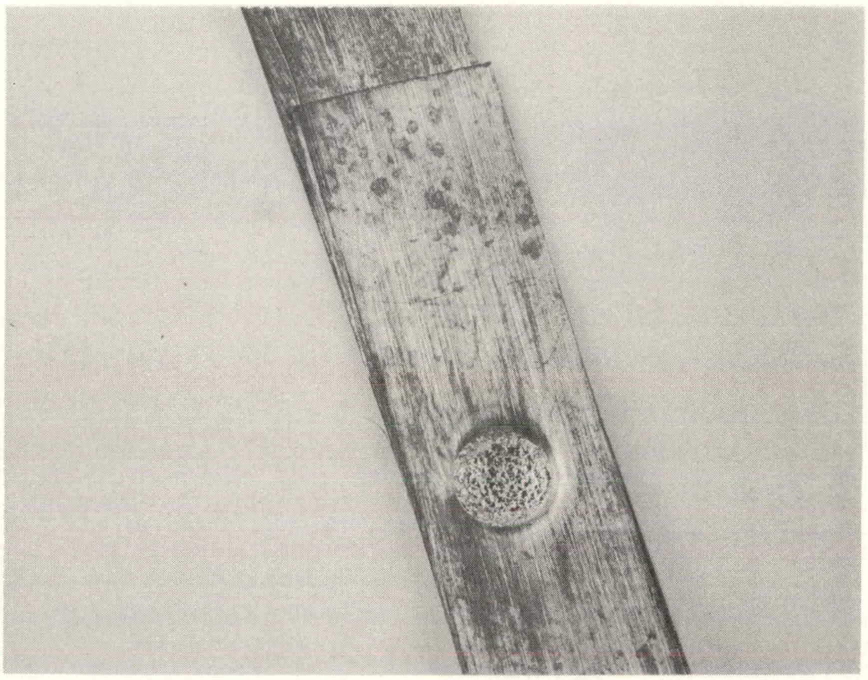
General Considerations

- The weld system will be adjusted according to the manufacturer's recommendations.

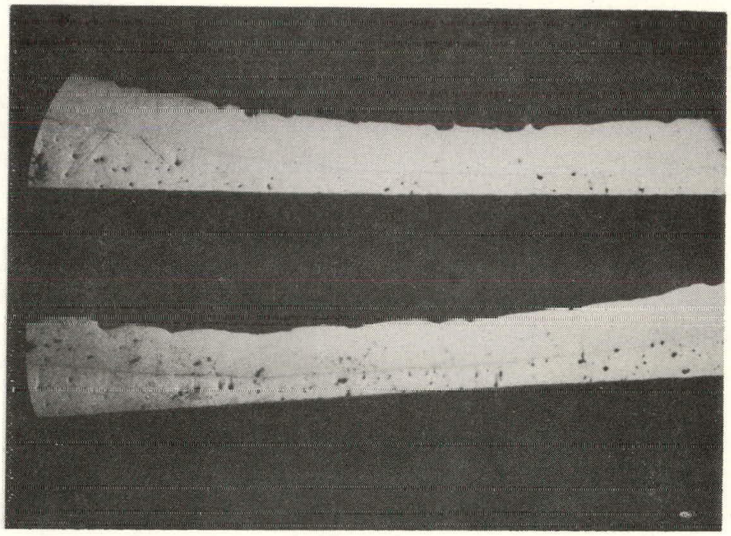
- All material combinations evaluated will be controlled dimensionally and metallurgically. The materials will be cleaned in trichloroethylene prior to welding.

- Destructive testing shall be in accordance with methods 3 and 4 of weld specification 9912264. Method 4 shall be used whenever one of the materials joined is greater than 0.010 inch thick (0.254 mm) or whenever the thickness ratio of the piece parts is greater than 3 to 1. All other material combinations shall be destructively tested according to Method 3.

Text continued on page 19.

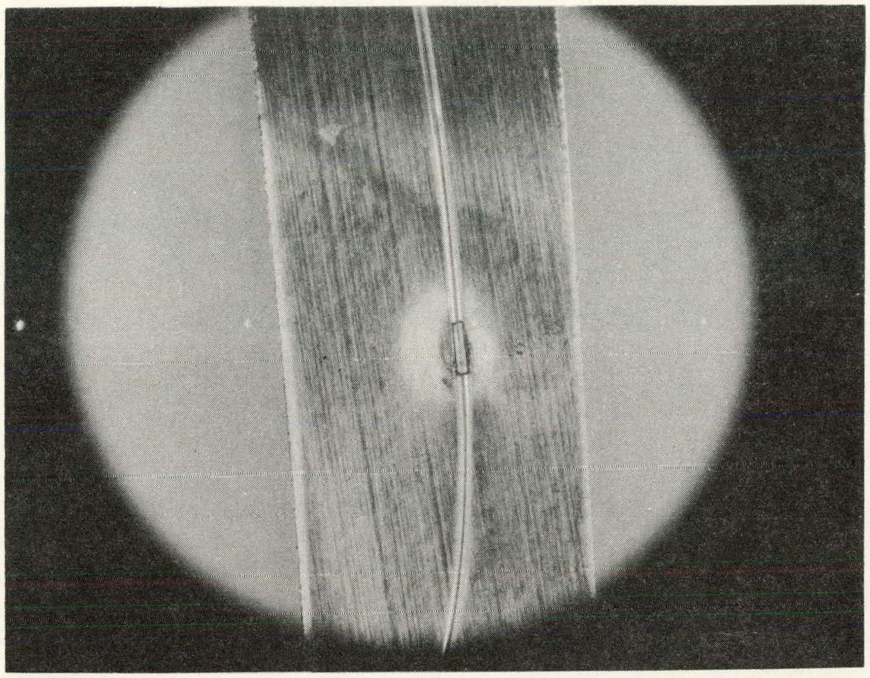


WELD JOINT
5X



CROSS-SECTION
50X

Figure 1. Ultrasonically-Welded 0.003 Inch (0.0762 mm) Copper to 0.004 Inch (0.101 mm) Copper



WELD JOINT
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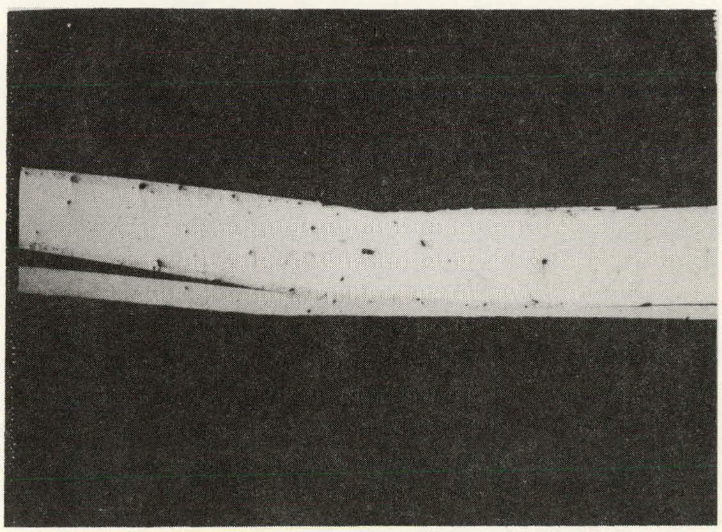

CROSS-SECTION
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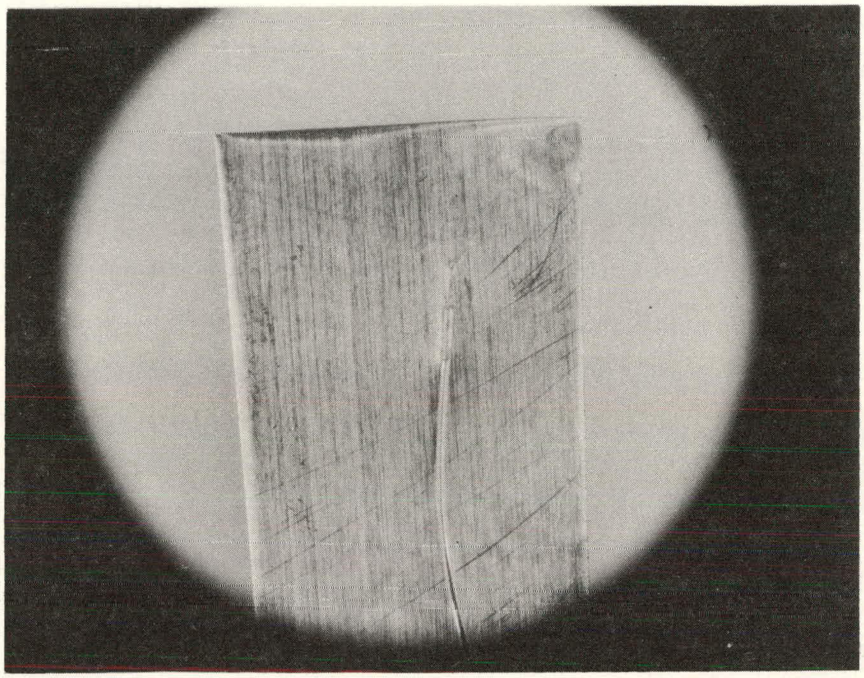
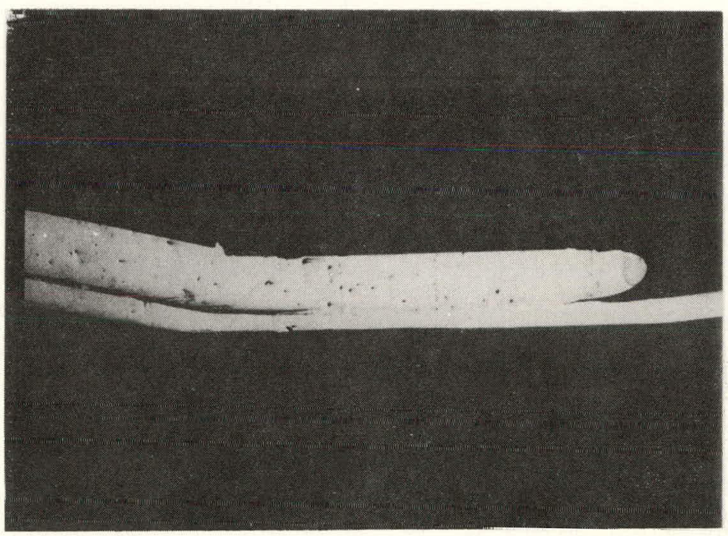
Figure 2. Ultrasonically-Welded 0.010 Inch Diameter (0.254 mm) Aluminum Wire to 0.0026 Inch (0.066 mm) Copper



WELD JOINT
5X



CROSS-SECTION
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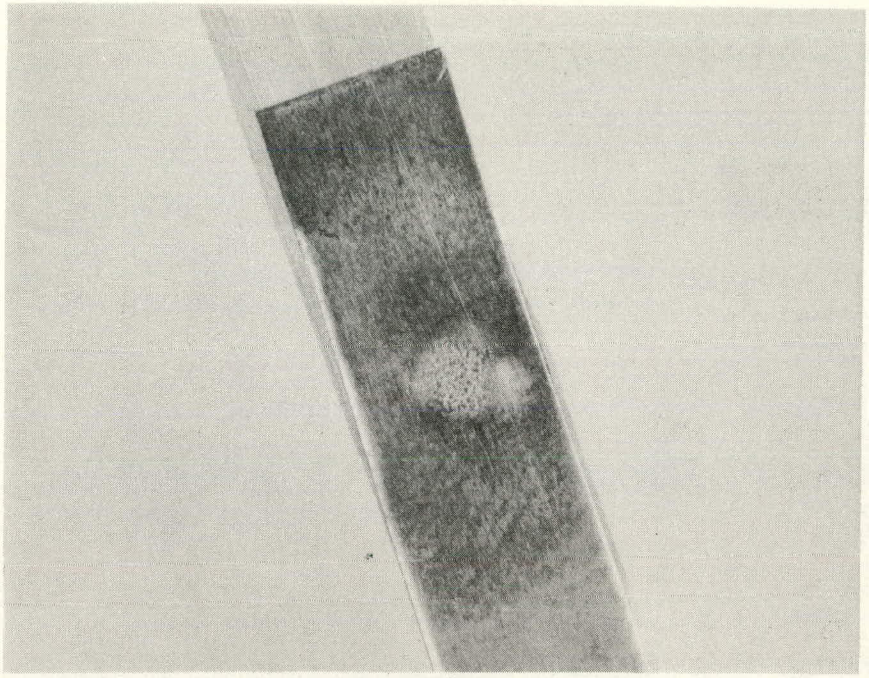
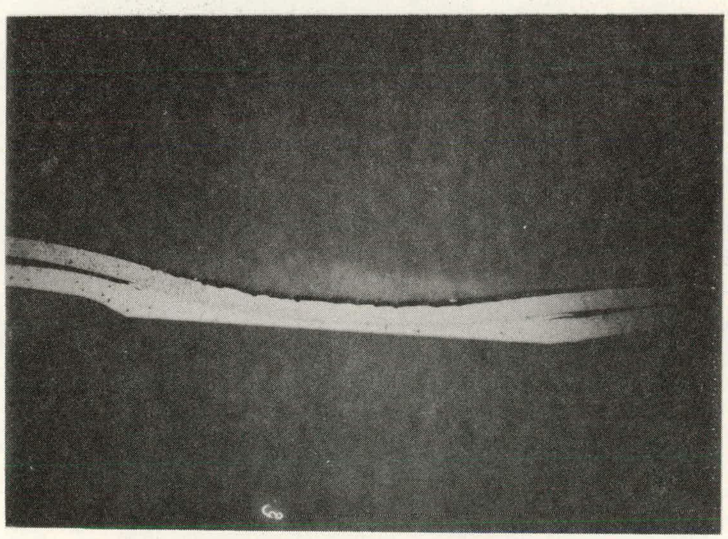
Figure 3. Ultrasonically-Welded 0.006 Inch Diameter (0.1524 mm) SAP 930 Wire to 0.0026 Inch (0.066 mm) Copper



WELD JOINT
5X



CROSS-SECTION
50X

Figure 4. Ultrasonically-Welded 0.005 Inch Thick (0.127 mm) Copper to 0.005 Inch Thick Aluminum

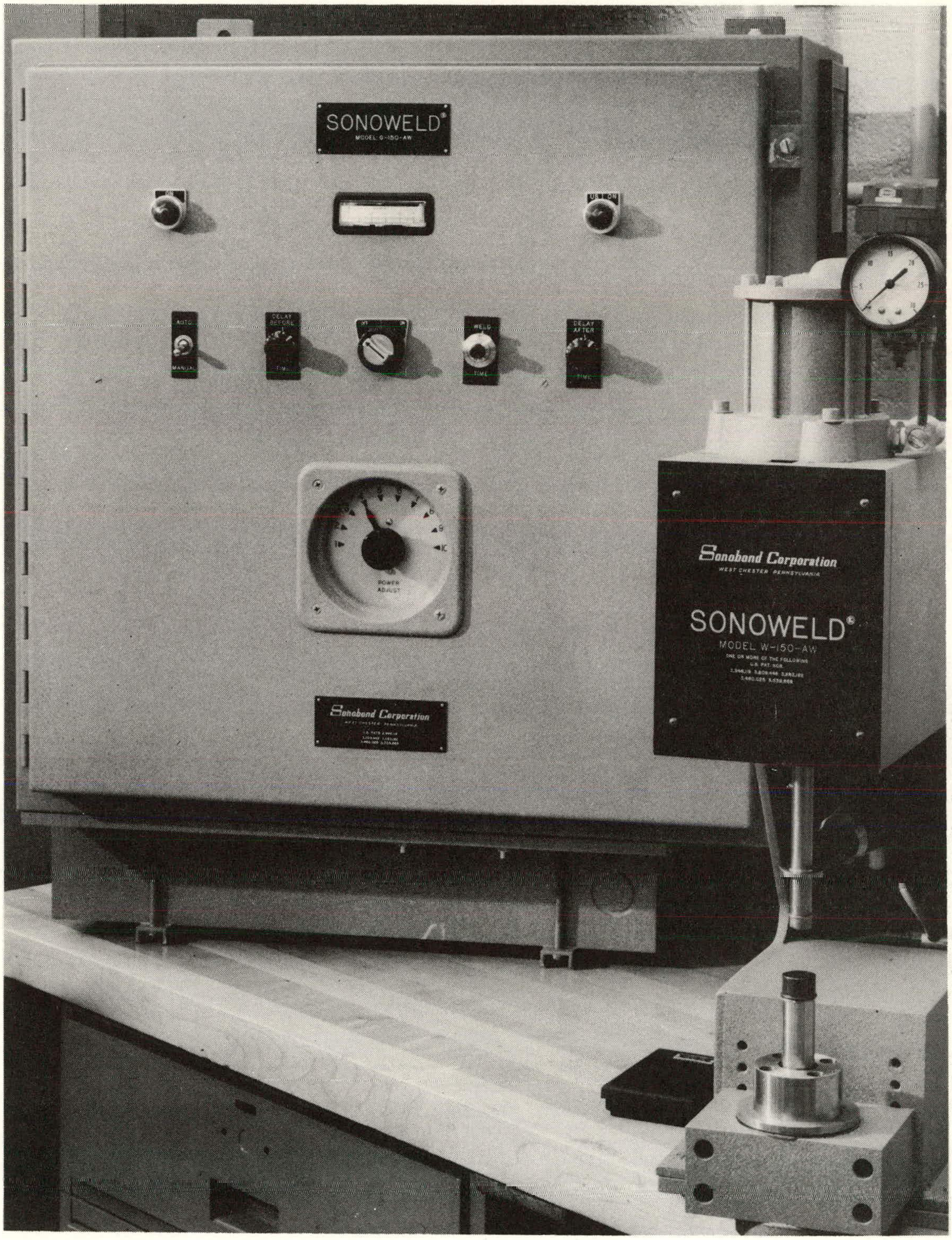


Figure 5. Model W-150-AW Ultrasonic Weld Station

- After development of a weld schedule for each particular material combination the system's ability to produce consistent weld quality will be determined by welding 105 consecutive weld samples. A total of 100 of these specimens shall be destructively tested. The remaining test specimens will be metallurgically cross-sectioned and evaluated.

- The visual qualities of each weld will be analyzed to determine if a reliable visual inspection criteria exists for this weld process.

Weld System Repeatability

- Overall welding consistency will be observed while developing weld schedules on three different material combinations. The high, low, and median points of weld power will be determined during weld schedule development. A weld schedule will be certified at the median power point.

- Concurrently, weld duration, electrical power output, oscillator frequency and clamping force will be continuously monitored. If these parameters are not repeatable, modifications will be made to the weld system before further evaluations are made.

Monitoring Capability

A monitoring capability will be developed for measuring displacement of the sonotrode tip. This monitor will consist of an accelerometer mounted on the tip, a charge amplifier, and an integrator circuit feeding a digital panel meter. A study will be made to determine if a relationship exists between weld quality and the measured parameter.

Material Evaluation

The following material combinations will be evaluated: copper to copper, aluminum to aluminum, nickel to aluminum, and aluminum to beryllium copper. The following materials will be used.

- Aluminum Alloy 1145

  Thicknesses: 0.0005, 0.001, 0.002, 0.004, 0.005, 0.0055, 0.006, 0.010, 0.016 inch (0.0127, 0.0254, 0.0508, 0.1016, 0.127, 0.1397, 0.1524, 0.254, 0.4064 mm).

  Width: 0.040 through 0.250 inch (1.016 through 6.35 mm).

  Temper: 0, H14, H18.

- Copper per CDA 102, 109, and 110

  Thicknesses: 0.001, 0.0024, 0.0027, 0.0032, 0.005, 0.0052, 0.0055, 0.010, 0.016 inch (0.0254, 0.06096, 0.06858, 0.08128, 0.127, 0.13208, 0.13970, 0.254, 0.4064 mm).

  Width: 0.040 through 0.250 inch (1.016 through 6.35 mm).

  Temper: Annealed, half-hard, hard.

- Nickel (99.9 purity)

  Sizes (thickness x width): 0.010 x 0.020 inch (0.254 x 0.508 mm), 0.015 x 0.031 (0.381 x 0.787 mm), 0.010 x 0.125 (0.254 x 3.175 mm), 0.005 x 0.060 (0.127 x 1.524 mm), and 0.002 x 0.060 (0.0508 x 1.524 mm).

  Temper: Annealed

- Beryllium Copper per CDA 172

  Thickness: 0.002, 0.006, 0.010 inch (0.0508, 0.1524, and 0.254 mm).

  Width: 0.040 through 0.250 inch (1.016 through 6.35 mm).

  Temper: AT, half-hard, hard.

  Plating: Bare and gold plated.

Weld Parameters

Welding conditions will be varied to determine what effect these changes have on weld quality. Parameters are:

- Sonotrode tip radius changes with respect to material thickness;
- Sonotrode tip surface finish;
- Dimensional changes in materials being welded;
- Weld duration;
- Changes in frequency from the nominal resonant frequency;
- Effect of incorrect clamping force;
- Surface finish on the piece parts being joined;

- Effect of incremental changes of input voltage to the weld system; and

- Effect of surface contamination on piece parts.

Quality Testing

One hundred test specimens shall be welded at a previously certified weld schedule using copper to copper and aluminum to copper weld configurations. Each tenth weld specimen shall be destructively tested to verify that weld quality is consistent with previous weld schedule certification results. The remaining 90 test specimens will be tested by the following schedule.

- Electrical resistance tests will be performed before and after completing humidity, thermal, and aging tests.

- Ten randomly selected test specimens will be cross-sectioned and examined before and after humidity, thermal, and aging tests.

- Humidity tests will be conducted in accordance with Military Standard 202, Method 106.

- All specimens will be subjected to thermal shock testing from -60 to 212°F (-51 to 100°C).

- All specimens will be subjected to an aging environment of 300°F (149°C) for 100 hours.

<u>Welding Equipment Evaluation and Modification</u>

Equipment modifications were incorporated to improve performance and allow continuous monitoring of weld parameters. A counter timer was attached to the timing circuit to measure actual weld time and to aid in setting weld duration. An improved timing circuit was incorporated to assure weld duration repeatability within plus or minus one millisecond. A calibrated digital voltmeter was attached across the rectified and filtered output of the autotransformer to provide more precise control of weld system output than was possible with the uncalibrated dial of the autotransformer. The autotransformer was modified by removing mechanical stops on the lower segment of the autotransformer, thus allowing the dc voltage to be reduced to zero. The previous lower limit provided a dc output of 42 volts which was too high for some weld configurations. The modified weld system is shown in Figure 6.

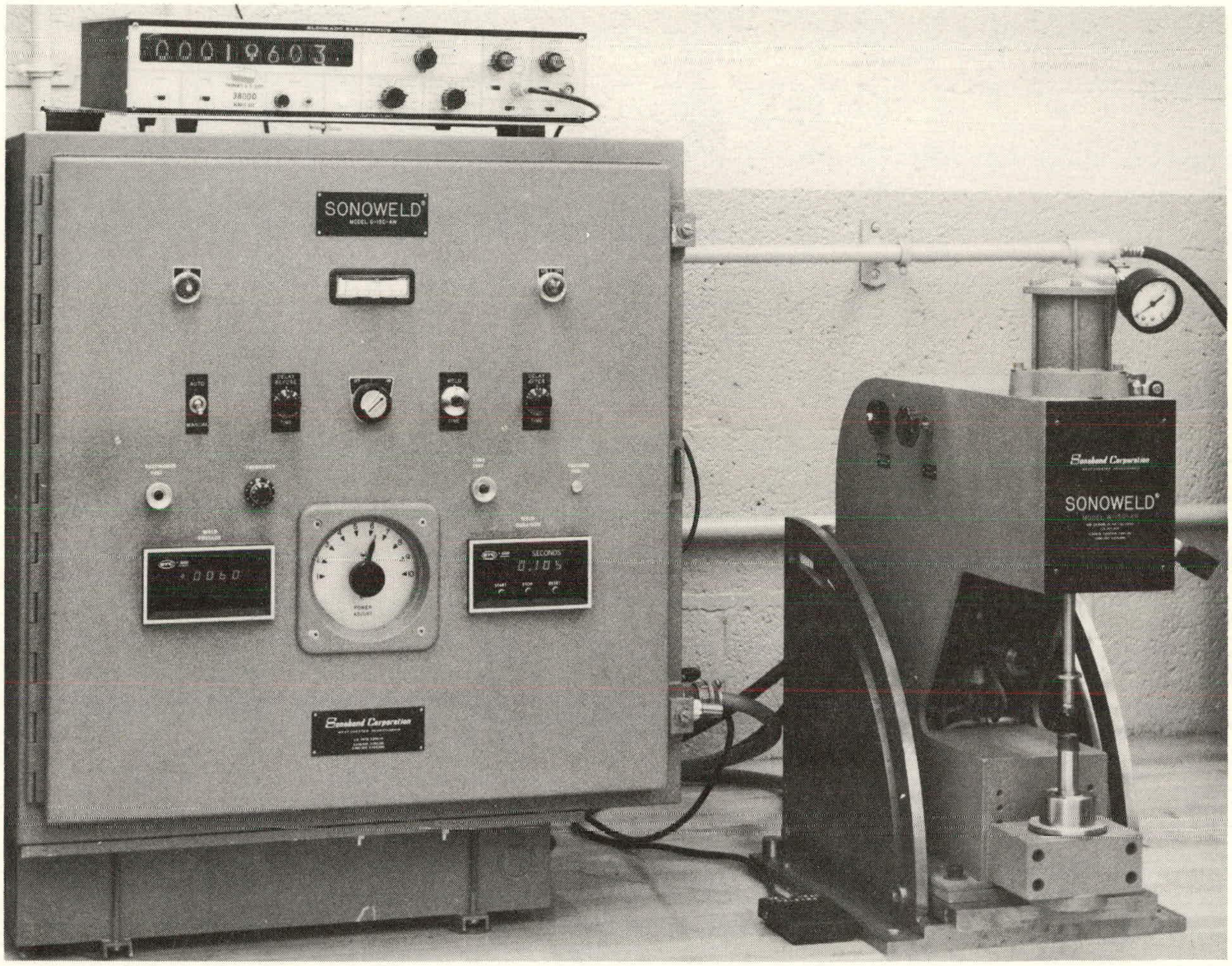


Figure 6. Bendix-Modified Ultrasonic Weld System

An attempt was made to monitor actual weld conditions by measuring the displacement of the sonotrode tip or anvil during welding. This measurement was accomplished by attaching an accelerometer to one of the tips. The attachment of the accelerometer on the sonotrode tended to load the sonotrode unacceptably and yielded meaningless data. The accelerometer was then relocated on the anvil. Any measurement at the anvil would be a result of energy transfer through the materials being joined and possibly could be correlated with process control.

An instrument was built to measure the output voltage waveform produced by the accelerometer and to digitally display the average root-mean-square (RMS) value. The output of the Intronics module is fed into an integrator with a time base which can be set to the actual weld duration. The integrator is gated by a pulse from the ultrasonic power supply.

A series of tests were performed on various material combinations to determine if the output of the accelerometer could be correlated with weld quality. As weld power was increased the accelerometer output increased as expected. When a weld schedule was selected which would achieve both good and bad welds the accelerometer could not differentiate between the extremes of weld quality. Due to the lack of correlation between the accelerometer output and process control this method of process monitoring was discontinued.

The design of the sonotrode and anvil tips was found to have a significant effect upon the welding results obtained on any particular material combination. Parameters such as 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 resonant frequency matched the weld system resonance across the full range of available clamping forces resulted in the best process control.

As a portion of the investigation of this weld process, various weld tips were produced with different surface treatment 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. A test was performed where system resonance was checked with the various sonotrode-anvil configurations at clamping forces of 0, 38, 59, 80, 101, 122, and 145 pounds (0, 168, 261, 355, 448, 541, and 643 N). As was expected, some of the tips were more subject to drastic changes in circuit resonance than others as clamping force was changed (Figure 7). Those weld tips which provided a system resonance of near 19.7 kilohertz across the full clamping force range provided the best welding results. As can be seen in Figure 7 sonotrode tip 9 and anvil 2 would provide more consistent welding than sonotrode 4 with the same anvil.

Two sonotrodes were designed and built to achieve a system resonance of 19.7 kHz across the total clamping force range. These sonotrodes featured an extended tip which was designed to allow tuning of the sonotrode to the natural system resonance (Figure 8). The system resonance with these tips

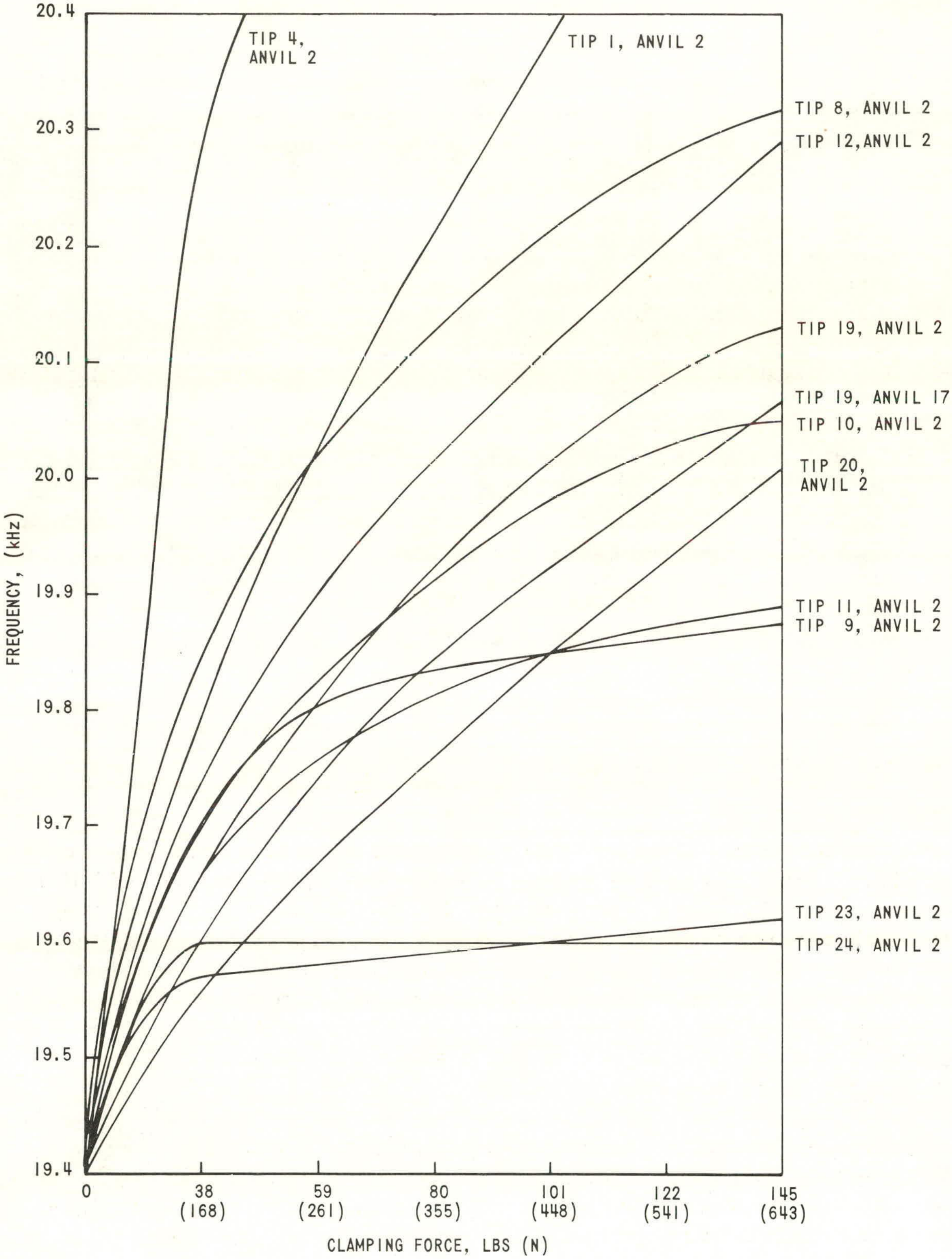


Figure 7. Sonotrode Anvil Resonant Frequency Curves

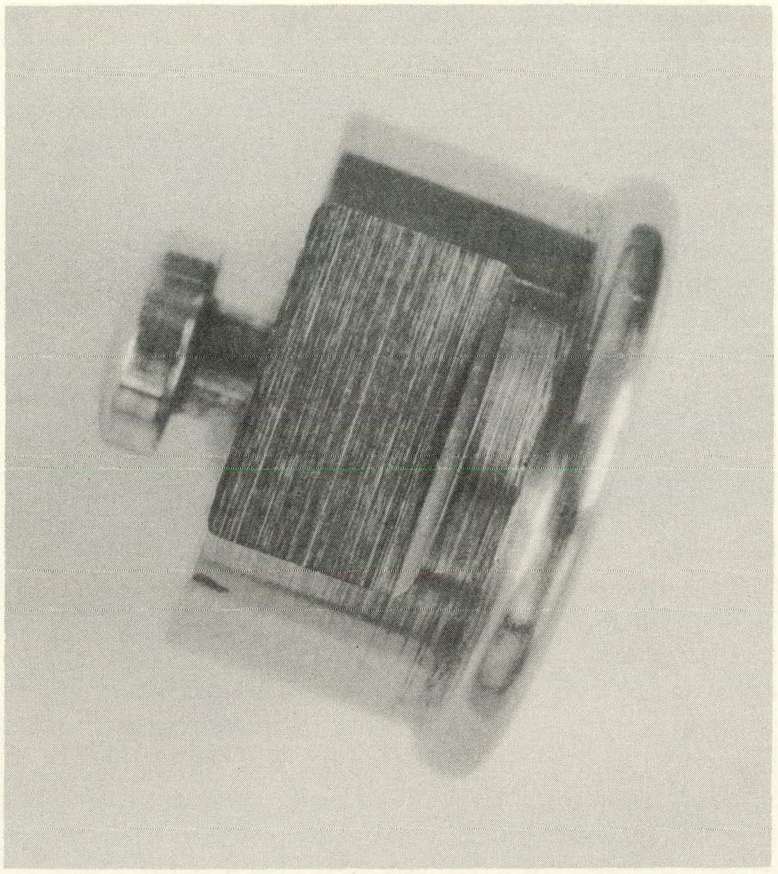


Figure 8. Extended Tip Sonotrode

installed is shown in Figure 7. The redesigned sonotrodes are numbered 23 and 24. Tip 23 has an electrical discharge machined surface (250 RMS) treatment while tip 24 has a smooth (8 RMS) surface finish. The average system resonance with these sonotrodes installed is 19.6 kilohertz 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 kilohertz.

The knowledge obtained on weld tip design has significantly improved the outlook for ultrasonic welding of electrical conductors. What previously appeared as a marginal welding process has now proven to be highly repeatable with consistent weld quality. Additionally, the quantity of test specimens required for developing a satisfactory weld schedule has been reduced by a minimum of 50 percent.

Weld Schedule Development and Certification

A weld schedule development plan was required which would take into account the controllable weld system parameters. The parameters investigated during development of each schedule included 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. The parameters of 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.

Upon completion of an oscillator frequency search for a particular material combination, the clamping force is changed and the search is begun again. As a result, the parameters of oscillator frequency and clamping force are optimized based upon the data developed from the destructively tested specimens. All specimens are destructively tested in a 180 degree peel mode. Upon completion of the isostrength search for proper oscillator frequency and clamping force, a weld power search is started. 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 proven not to be highly critical. Weld durations of less than 50 milliseconds have a tendency to result in erratic weld quality while durations in excess of 700 milliseconds tend to cause sonotrode tip sticking. The weld schedules certified during this reporting period were confined to weld durations between 100 and 300 milliseconds.

Weld schedules were developed and certified on four different material combinations per the procedure explained in the previous text. The material combinations evaluated were aluminum to aluminum and copper to copper configurations. The aluminum to aluminum configuration consisted of two pieces of 0.0055 inch (0.1397 mm) 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 9 and 10. Sample test results from a weld schedule certification are shown in Table 2.

Text continued on page 30.

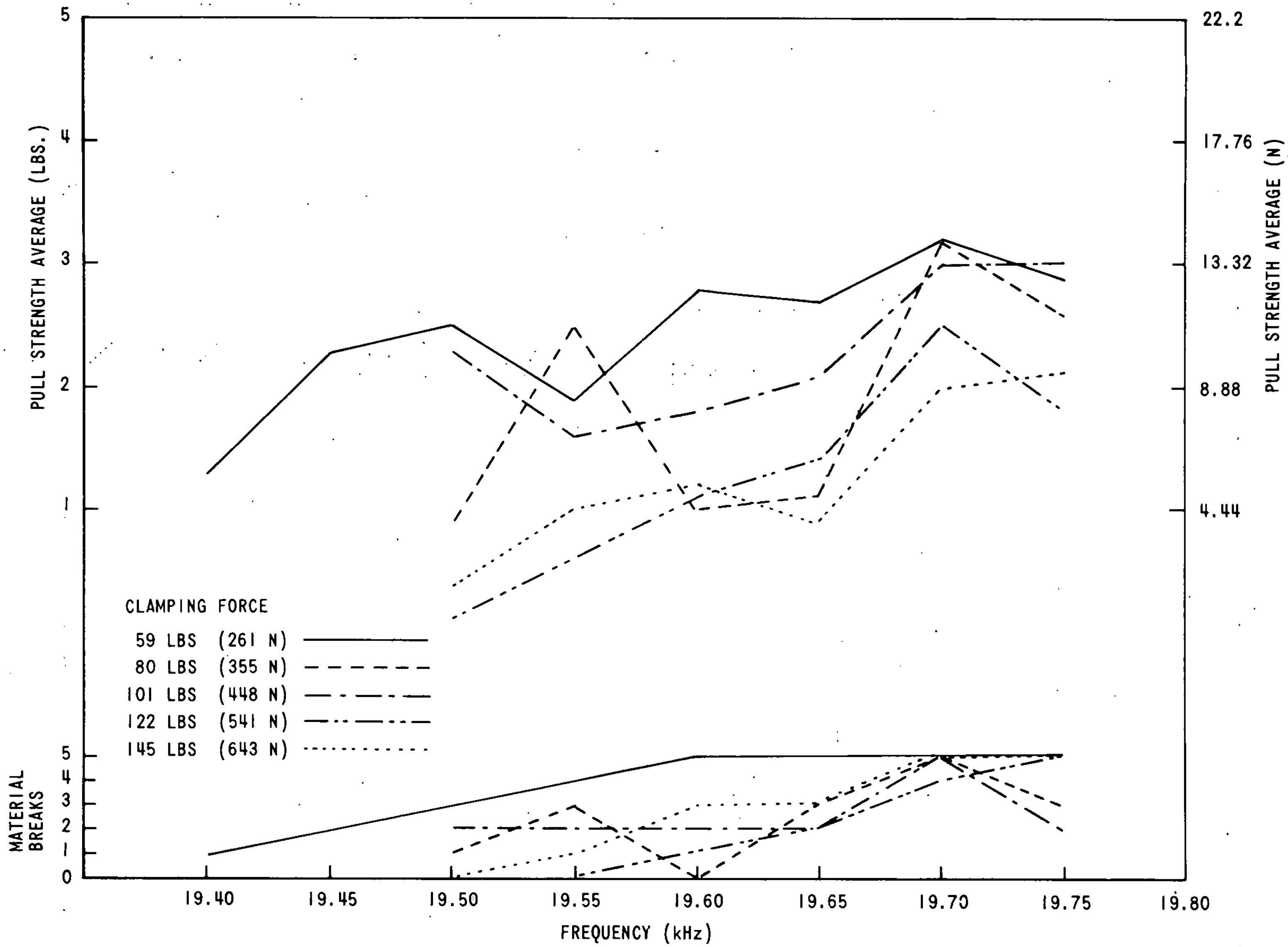


Figure 9. Iso-Strength Diagram, Clamping Force Versus Frequency, Copper to Copper (ETP)

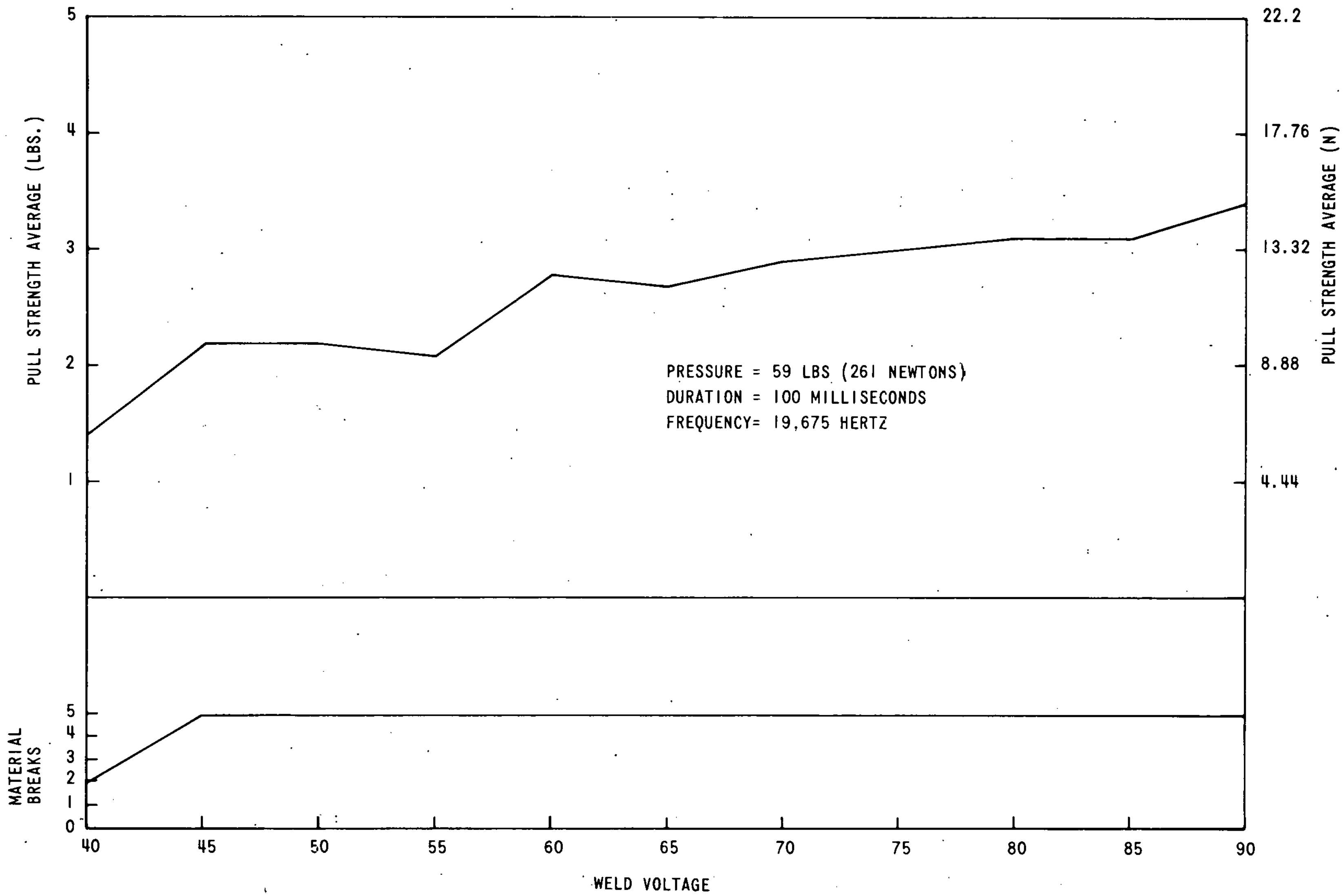


Figure 10. Copper to Copper Weld Voltage Isostrength Diagram

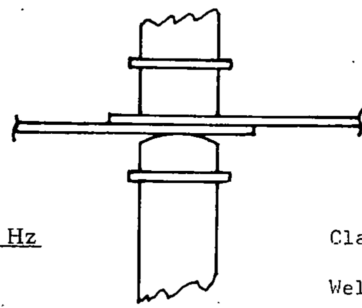
Table 2. Weld Schedule Certification, ETP Copper to ETP Copper

Weld Schedule No. 5

Date 8-24-73

Sonotrode No. 23

Anvil No. 2



Material 110 E. T. P. Copper (0.0027 x 0.250 x 1.5 in.)*

Material 110 E. T. P. Copper (0.0027 x 0.250 x 1.5 in.)*

Resonant Frequency 19,675 Hz

Clamping Force 59 lbs (262.432 N)

Weld Voltage 75 V

Weld Duration 100 milliseconds

1. 3.4-B**	21. 3.7-B	41. 3.9-B	61. 3.0-B	81. 3.3-B
2. 3.0-B	22. 3.4-B	42. 2.7-B	62. 2.6-B	82. 4.7-B
3. 3.7-B	23. 2.7-B	43. 5.2-B	63. 2.4-B	83. 2.2-B
4. 4.1-B	24. 2.9-B	44. 4.3-B	64. 2.3-B	84. 2.8-B
5. 4.0-B	25. 2.3-B	45. 1.9-B	65. 2.9-B	85. 1.6-B
6. 2.6-B	26. 1.5-B	46. 3.5-B	66. 2.7-B	86. 2.5-B
7. 2.4-B	27. 3.7-B	47. 5.2-B	67. 3.4-B	87. 2.4-B
8. 3.1-B	28. 3.9-B	48. 4.3-B	68. 1.9-B	88. 3.2-B
9. 2.8-B	29. 3.4-B	49. 4.0-B	69. 3.2-B	89. 3.2-B
10. 2.8-B	30. 2.8-B	50. 2.1-B	70. 3.9-B	90. 3.3-B
11. 3.6-B	31. 3.9-B	51. 4.4-B	71. 3.4-B	91. 3.5-B
12. 2.9-B	32. 2.6-B	52. 3.8-B	72. 2.4-B	92. 3.2-B
13. 4.1-B	33. 4.0-B	53. 2.6-B	73. 3.5-B	93. 1.9-B
14. 3.2-B	34. 1.7-B	54. 3.1-B	74. 2.9-B	94. 3.7-B
15. 2.2-B	35. 2.8-B	55. 5.0-B	75. 2.6-B	95. 3.3-B
16. 3.2-B	36. 3.0-B	56. 3.2-B	76. 2.0-B	96. 3.5-B
17. 4.7-B	37. 4.1-B	57. 4.0-B	77. 5.4-B	97. 3.8-B
18. 3.7-B	38. 2.5-B	58. 3.3-B	78. 3.5-B	98. 3.1-B
19. 2.7-B	39. 3.4-B	59. 2.4-B	79. 4.2-B	99. 2.1-B
20. 2.7-B	40. 2.6-B	60. 3.3-B	80. 2.0-B	100. 3.6-B

Break Code A - Weld Failure
B - Material Failure

Metallurgical ____________________

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Metric Conversion Factors
*0.001 inch = 0.0254 millimeters
**1 pound force = 4.448 newtons

During the destructive testing period of a weld schedule development and certification both the strength of the weld and 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.

ACCOMPLISHMENTS

Control and repeatability modifications to the vendor-supplied equipment have provided a satisfactory weld system and no further activity of this type is anticipated.

A plan was developed for evaluating ultrasonic welding which will provide sufficient knowledge to judge the future production adaptability. The prime areas of investigation are: identification of weld parameters associated with process control; determination of weldable material combinations; metallurgical evaluation of welded specimens; and environmental testing.

A method was devised which isolates the various controllable weld parameters during the development of a weld schedule. The controllable weld parameters are weld duration, weld power, oscillator frequency, and clamping force. The method of weld schedule development involves varying one parameter while holding the other three constant and observing the effect upon weld quality. This method was used successfully in the development and certification of weld schedules on four different material combinations.

The most significant accomplishment of this reporting period was the knowledge obtained on sonotrode tip design and the effect design has upon weld quality. Through experimentation it was found that the natural resonant frequency of the sonotrode-anvil configuration at any clamping force should be the same as the natural resonance of the weld system. The anvil has a minimal effect upon the resonant frequency of the sonotrode-anvil configuration provided it is hardened to a RC 60-64. To properly tune the sonotrode-anvil a special sonotrode configuration was designed which features an extended shank tip. By altering either the length or diameter of the shank, the sonotrode can be tuned to the resonant frequency of the weld system. This finding has resulted in significant improvement of the weld process control qualities and has minimized the quantity of test specimens required to develop a weld schedule.

The ultrasonic weld process proved its ability to satisfactorily terminate aluminum to aluminum and copper to copper weld configurations during this reporting period. This capability is significant since the termination of flat aluminum conductors to flat aluminum conductors has not be accomplished with present state-of-the art weld processes. Flat copper conductors can only be joined by the parallel-gap process and require the use of a braze medium such as electroless nickel plating or a Sil-Fos braze preform. The ability of this weld process to successfully terminate these and other material combinations will likely be an important factor in the design of flat flexible circuits for future production programs.

FUTURE WORK

Evaluation of the ultrasonic weld process will continue. Terminating aluminum to copper and the long term effects of severe environments on such welded terminations will be studied. A future production program application presently exists which requires this material combination to be welded by the ultrasonic process. A prime concern of such a termination is the possibility of galvanic corrosion degrading weld quality to an unacceptable value.

Definition of acceptable limits of weld quality with respect to visual inspection and metallurgical bonding will be investigated. Ultrasonic nondestructive testing of welds will be evaluated to attempt to map the total area bonded by any particular ultrasonic weld instead of metallurgical cross-sectioning of a single plane. It is expected that this method would prove to be more economical and provide more definitive information.