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NONDESTRUCTIVE TESTING OF WELDED
ELECTRICAL CONNECTORS

PDO 6984344, Final Report

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Department 142

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**Kansas City
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NONDESTRUCTIVE TESTING OF WELDED ELECTRICAL CONNECTORS

BDX-613-1190 (Rev.), UNCLASSIFIED Final Report, Published August 1976

Prepared by E. B. Cooper, D/142, under PDO 6984344

A search for a nondestructive test of the quality of small percussive arc welds is described. Ultrasonic pulse echo inspection showed a capability for almost complete discrimination between welds made with differing arc times and peak currents. Special circumstances in which piece parts could be inspected by ultrasonics are described. A new destructive test and proposed workmanship standard are described.

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SUMMARY

Investigations into nondestructive testing (NDT) procedures for percussive arc welds were begun at Bendix in 1966 under Process Development Order 06984211. This project was closed in 1967 with a recommendation that infrared determination of weld connection temperature be investigated further.

This project was initiated to develop a nondestructive inspection technology for welded electrical connections. Emphasis has been on percussive arc welds. While inspection of piece parts has been the primary goal, nondestructive inspection of special samples used to control production also was considered.

During the early phases of this project, efforts were entirely directed toward establishing a correlation between data from nondestructive tests and the tensile load required to break the weld. Nondestructive technologies covered were infrared emission due to ohmic heating, high-precision resistance measurements, acoustic emission, and ultrasonic pulse echo inspection. The most positive finding was that ultrasonic pulse echo data correlated well with variations in the weld schedule.

Later work confirmed that the ultrasonic pulse echo pattern of a percussive arc weld was changed when the weld schedule was changed. This technique discriminated between samples made by different schedules with better than 99 percent reliability. The cost and feasibility of translating this technology to a production line was not investigated.

The finding that ultrasonic pulse echo techniques correlated with weld schedule parameters such as arc time and peak current prompted re-investigation of previously studied NDT techniques. The average infrared emission from several samples of the same schedule was also found to correlate with schedule information.

During a brief search for alternative destructive tests, the Materials Test Laboratory found that a 30 g vibration test at the resonance frequency of the welded sample showed promise. This test showed good capability for discriminating between weld schedules and always resulted in failures of the weld, not the wire.

DISCUSSION

SCOPE AND PURPOSE

Activity was directed toward the development of a nondestructive method of evaluating welded electrical connectors with the primary emphasis on percussive arc welds.

Presently, destructive tensile tests, visual inspection, and weld schedule records form the basis for production weld evaluation. An effective nondestructive test method that will provide numerical data suitable for use in refining welding processes and supplement destructive tests is essential to ensure quality of large quantities of welded joints.

PRIOR WORK

This project was begun by Quality Control Engineering in December of 1967. Techniques investigated included resistance measurements, thermoelectric coefficients, and heat conduction (as measured by infrared emission and liquid crystals) to determine weld quality. Arc temperature measurement was studied as a possible method of in-process monitoring of welds. The only technologies which were reported to show promise were the detection of abnormal heat conduction by infrared emission and the monitoring of arc temperature.

In August of 1969, the project and its supportive equipment were transferred to the Advanced Inspection Engineering group. Review of previous work indicated a need to consider additional methods of nondestructive weld testing such as acoustic emission and ultrasonic pulse echo, and to further develop techniques of high precision resistance measurements.

No acoustical output could be detected until the weld failed. This lack of warning of weakness made acoustical emission tests unsuitable for testing welded electrical connections. High precision resistance measurements, which were quite difficult to make because of the irregular configuration of the weld, correlated poorly with the tensile loads required to break the welds.

Visual inspection of the broken weld samples showed that the majority of failures were in the wire rather than in the weld. This observation explained the poor correlation of all tests with the "strength of the weld".

The possibility of measuring weld quality by ultrasonic pulse echo examination was considered but showed little correlation with weld strength. However, the results correlated highly with variations in weld parameters.

ACTIVITY

Experimental Plan

Previous efforts to develop a nondestructive inspection for percussive arc welds were hampered by difficulty in correlating NDT results with the load required to break a weld sample. With the discovery that ultrasonic pulse echo data could be correlated directly with some weld schedule parameters, a need to review previous investigations was indicated. For this reason the second phase of this project was a reinvestigation of previously studied NDT techniques and a new investigation of time domain reflectometry and eddy current inspection; all techniques to be correlated with weld schedule parameters.

Previously investigated efforts which were to be improved and correlated directly to weld schedules were ultrasonic inspection, infrared emission, and DC resistance.

Time Domain Reflectometry of Welds

Time domain reflectometry (TDR) is an electromagnetic pulse reflection measurement technique. A pulse or pulse burst is sent continuously down the transmission path. If the pulse encounters a short or open circuit, the reflection travels back to the sending point where it is compared in phase, time, and amplitude with the original pulse. This comparison shows the distance to the fault as well as an indication of its nature.

The equipment used for this investigation was a Hewlett-Packard 1415A Time Domain Reflectometer in a Hewlett-Packard 140A oscilloscope. The tests were conducted using percussive arc weld samples which were short lengths of seven-strand aluminum wire welded to alloy 52 connector pins. The second group of samples were two-conductor wires twisted together to simulate the weld zone.

The problem of trying to locate a weak weld does not appear to be aided by time domain reflectometry. A bad weld will still have a rather small resistance value. The inductance and capacitance values of good welds would not be expected to be significantly different than bad welds.

The equipment used in this project has a low resolution compared to present day state-of-the-art. TDR should be tried again using equipment with higher resolution.

Eddy Current Measurement Evaluation

Eddy current instruments measure electrical conductivity. Applying a high frequency alternating current to a coil creates an alternating magnetic field around the coil. When a conductor is brought near the energized coil, eddy currents are induced in the conductor. An alternating magnetic field associated with the eddy currents opposes the magnetic field of the coil. Interaction between the two fields affects the pickup coil impedance. By observing impedance changes, variations in properties influencing the material's electrical conductivity are monitored.

The eddy current instrument used in this study compares the phase angle or time of the driving coil with respect to the pickup coil. This phase varies as a function of resistivity changes and varies considerably more as a result of thickness changes. Consequently, a higher degree of accuracy and liftoff (probe to sample spacing change) is supposed to be achieved than by operating the instrument to sense amplitude changes only.

Two probes (50 KHz and 500 KHz) were available. Although the probes contain delicate coils, the epoxy base and aluminum shell allow the probe to be exposed to rugged conditions. A brass boot was placed over the end of the probe with a 0.005 inch diameter (1.27 cm) hole in the center of the boot so probe energy could be directed in one area.

Figure 1 is a block diagram of the instrument used in this evaluation. The instrument contains an oscillator to generate the operating frequency and a power amplifier to supply a 10-volt peak-to-peak signal to the driving coil of the probe. The return sig-

Figure 1. Block Diagram of Eddy Current Measuring Instrument

nal is received by the pickup coil of the probe and amplified by the pickup signal pass through a discriminator and differentiator into a flip-flop circuit. A zero triggering adjustment allows accurate measurement of the phase variation regardless of amplitude variation. This phase detection circuitry provides accurate measurement over a much greater range of liftoff than is possible by sensing amplitude channels. Figure 1 shows the instrument set up for comparison of the phase angle or time of the driving coil with respect to the pickup coil. Figure 2 shows the setup when only the amplitude of the eddy current signal is noted.

Figure 2. Eddy Current Instrument Set Up to Measure Amplitude Only

Figure 3 is a complete layout of the equipment used in this evaluation of eddy currents. Figure 4 is a closeup of the probe and the weld sample.

The weld sample was positioned so it could be rotated 360 degrees on one axis. The probe was in an X-Y holding fixture. The percussive arc welded sample was made of aluminum and alloy 52. The eddy current instrument was calibrated using aluminum for one calibration and alloy 52 for the second calibration standard. The probe was moved along the center of the pin and the wire. This was repeated when the pin and the wire were rotated 90, 180, and 270 degrees.

Figure 3. Equipment Used for Evaluation of Eddy Currents in Welds

Figure 4. Positioning of Probe and Weld Sample

There was no correlation between instrument response and weld conditions. The material properties affecting the eddy current are electrical conductivity and magnetic permeability. Apparently, neither of these properties change sufficiently for the various welds to affect the circulating eddy currents. The instrument is sensitive to geometry along with resistivity of metals. The weld junction is not symmetrical; therefore the instrument sees the unsymmetrical junction along with resistivity of weld zone, wire, and pin. Eddy current testing is not recommended for percussive arc welds.

Ultrasonic Testing

The continued investigation of ultrasonic pulse echo inspection dealt with samples used for process control and welds to type 13-19 and type SA-1810-3 connectors. All welds were classified by comparison of their pulse-echo patterns with those of welded samples whose schedules were known.

Experiment One

Sixty-two samples of percussive arc welds between an Alloy 52 pin and a seven-strand aluminum wire were fabricated using a hot schedule, a cold schedule, and two schedules considered normal but differing slightly in peak current. J. A. Brunk examined these samples with ultrasonic pulse echo equipment and reported "ultrasonic inspection can readily discriminate between the four weld schedules."

Experiment Two

Having demonstrated the ability of ultrasonic pulse echo technology to verify weld schedules in special samples, the next investigation was directed to welds made on connectors used in production.

Three type 13-19 connectors were prepared with welds attached to five of their 10 pins. Again, the various welds had been prepared using normal, cold, and hot weld schedules. To decrease the subjectivity which might exist in interpretation of pulse echo patterns, no identification of weld schedules was supplied with the samples. The only indication of sample differences was in the length of the lead wires. The ultrasonic test report indicated that samples with the longest length wires appeared cold, those samples with medium length lead wires appeared normal, and samples with shortest lead wires appeared hot, a completely correct interpretation. These results confirmed at least a limited capability for piece part inspection.

Experiment Three

This experiment was intended to examine the capability for ultrasonically inspecting welds between flat gold-plated Kovar leads and pins on an SA-1810-3 connector. Three connectors were fabricated, each with wires welded to eight of their female pins. One assembly was welded using a cold schedule, another hot, and the third normal. Again, cold welds were easily discriminated from normal welds but considerably less ultrasonic difference existed between normal and hot welds. The female pin which tended to trap air presented serious problems. During this experiment, the air was removed by immersing the connector pin in an ultrasonic cleaning bath. A better long-range solution appears to be using a solid dummy male pin inserted into the connector.

Infrared Evaluation

Previous infrared measurements of percussive arc weld samples resulting from heating by an electric current had shown a slight trend of increasing temperature for weld processes which tended to generate a poorly fabricated weld. However, there was little separation of the average weld temperature when grouped by hot, cold, and normal schedules.

To take advantage of the ability of ultrasonic tests to verify samples, an evaluation of the ability to check welds by measuring their infrared emission was repeated. Fifty-four weld samples, composed equally of hot, normal, and cold welds, previously checked by ultrasonic inspection, were used in the new evaluation of infrared measurements. Each weld was heated by a DC electric current of 20 amperes for a duration of four seconds. The temperature rise was measured with a Barnes Infrared Microscope. The direction of current was then reversed and the temperature rise again measured. Table 1 shows the temperature rise for each sample, its weld group, and the direction of current. Thermoelectric cooling resulted in all samples with one direction of current having a lower peak temperature than the same samples with the opposite current. The average temperature rise for welds made by a hot process was lower than the average temperature rise of normal welds. The normal welds' average temperature rise was lower than that for cold welds. Individual samples within each group tended to overlap with those of adjacent groups.

While the ability of infrared measurement to verify weld processes appears to be much improved, it also is less selective than the ultrasonic tests, which have nearly zero overlap between groups. The improvement in the capability of infrared measurements suggests that further work (with more carefully prepared samples) should be undertaken if production difficulties should dictate a need for further work.

Table 1. Infrared Measurements of Maximum Temperature

	(1) Hot (+)	(2) Hot (-)	(3) Normal (+)	(4) Normal (-)	(5) Cold (+)	(6) Cold (-)
	159	119	190	136	194	146
	140	132	180	139	261	233
	180	125	178	132	190	156
	168	117	178	130	168	140
	165	114	166	136	181	140
	160	116	187	146	192	141
	192	124	165	129	174	131
	108	110	168	136	182	138
	166	130	183	144	172	146
	164	128	187	142	179	137
	170	128	172	125	202	142
	164	114	195	154	192	140
	170	116	180	131	172	140
	155	122	181	124	180	139
	180	129	198	134	182	137
	164	122	171	123	176	129
	172	126	183	130	194	151
	156	114	189	146	195	140
SUM	2933	2186	3251	2437	3386	2626
MEAN	162.9	121.4	180.6	135.3	188.1	145.8

DC Resistance Measurement

A Kelvin Double Bridge was used to measure the resistance across the weld including an unspecified length of the pin and the sleeve on the stranded wire. To cancel the effects of thermo-electric EMF's, the resistance of each weld was measured for two directions of current. From these two resistance values, the resistance of the weld was calculated. The analysis of this data

showed that there was no significant difference in the average resistance reading of a normal weld when compared with either cold or hot welds.

Alternative Destructive Tests

Percussive arc weld schedules are developed primarily through measurement of the tensile strength of the weld and a visual inspection.

Throughout this project, tensile testing frequently has resulted in failure of the wire rather than the weld, which places a lower limit on the strength of the weld but yields little variables information.

The Materials Test Laboratory, which conducted the re-evaluation of infrared weld inspection and DC resistance measurement of welds also investigated two other forms of destructive weld testing, vibration, and resistance to torque.

Fifteen weld samples representing the three categories of weld processes were vibrated at their natural frequency under 30G acceleration. Table 2 displays the time-to-failure, natural frequency, and energy required for failure. This test resulted in failures of the weld rather than in the wire. The average energy for failure is clearly different for each category of weld samples, but there was no overlap between normal and cold groups. The natural frequency of hot welds and normal welds was also different. The natural frequency of cold welds had a smaller difference. There was little difference between the average time-to-failure between hot and normal welds but the average time-to-failure of cold welds was one-third that of hot or normal welds.

The torque required to shear the weld was measured on 15 samples, again representing the three categories of weld processes (Table 3). The tests were satisfactory in that all resulted in weld failures, but again even through the average torsion for each group is different, the samples within groups tended to overlap. As with the tensile tests, it is necessary to use the average of several tests to determine weld quality.

Visual Inspection

Two materials test laboratory groups working on this project have reported that different weld schedules can be distinguished by both visual inspection and by measurement of sleeve length. During the weld process, a thin aluminum sleeve used to restrain the stranded aluminum wire tends to be shortened by melting as weld energy is increased. This melting also is accompanied by

Table 2. Vibration Test, Alloy 52 to Aluminum

Specimen	Time to Failure (Minutes)	Frequency (Hz)	Relative Energy*

HOT

8	6	100	1.07
14	5.5	100	0.98
24	6.0	100	1.07
27	----	100	----
33	11	100	1.97
Avg.	7	100	1.27

NORMAL

37	1	190	0.18
58	8	190	1.43
62	7	190	1.25
63	7	190	1.25
65	5	190	0.89
Avg.	7	190	1.00

COLD

71	0.01	216	0.00
74	2.5	216	0.51
83	1.0	216	0.20
86	2.0	216	0.41
89	2.75	216	0.56
Avg.	1.6	216	0.34

*Average of Normal Samples = 1

increasing amounts of material expelled at the weld interface. Both groups measured the sleeve length of the various groups of weld samples supplied for their investigations of nondestructive testing techniques. Summaries of their data appear in Tables 4 and 5.

Figure 5 clearly shows typical features of hot, cold, and normal percussive arc welds. An article on visual inspection practices at the Martin Marietta Corporation describes a system of visual workmanship standards. The use of a similar workmanship standard should greatly assist the visual inspector to discern conformance of piece part welds to a weld schedule.

Table 3. Torsion Test, Alloy
52 to Aluminum

Specimen	Ultimate Torsion (oz-in.) (mN·m)

HOT

10	0.142
19	0.160
25	0.247
28	0.172
30	<u>0.153</u>
Avg.	0.175 (1.24)
Std. Dev.	0.042 (0.30)

NORMAL

43	0.203
50	0.158
55	0.195
59	<u>0.118</u>
Avg.	0.168 (1.19)
Std. Dev.	0.039 (0.28)

COLD

79	0.173
85	0.125
87	0.083
90	<u>0.193</u>
Avg.	0.143 (1.01)
Std. Dev.	0.049 (0.35)

NOTES:

Results of two-sided T-test revealed no significant differences between average performance of these three schedules with respect to torsion.

All tests resulted in failures in the weld.

Shortened Sleeve

Expelled dark material at weld interface - Greater than pin diameter

Discoloration of sleeve near weld

HOT WELD

Intermediate sleeve length

Little expelled material at weld - just covers connector pin

No discoloration of expelled material or sleeve

NORMAL WELD

Negligible shortening of sleeve

Negligible amount of expelled material

Weld area less than diameter of pin

No discoloration

COLD WELD

Figure 5. Typical Features of Three Types of Percussive Arc Welds

Table 4. Variations in Sleeve Length With Weld Schedule

Connector	Average Sleeve Length, Inch (mm)
Hot	0.125 (3.18)
Normal	0.167 (4.24)
Cold	0.187 (4.75)

Table 5. Comparison of Optical Measurements on Three Weld Schedules of Alloy 52

Weld Schedule	Mean Sleeve Length, Inch (mm)	Standard Deviation, Inch (mm)	Mean Pin Length, Inch (mm)	Standard Deviation, Inch (mm)	Mean Angle	Standard Deviation
HOT	0.093 (2.4)	0.015 (0.38)	0.489 (12.4)	0.004 (0.1)	6.50	1.43
NORMAL	0.120 (3.05)	0.008 (0.2)	0.492 (12.5)	0.003 (0.08)	6.53	1.48
COLD	0.127 (3.23)	0.011 (0.28)	0.494 (12.5)	0.002 (0.05)	6.56	2.43

ACCOMPLISHMENTS

Numerous investigations were completed on the ability of non-destructive test methods to verify percussive arc weld quality. Two destructive tests were briefly studied as alternatives to the presently used tensile test. The limits of usefulness imposed by sensitivity of available equipment, applicability to the weld process, and functionality of weld definition have been determined.

The most promising nondestructive technology is ultrasonic pulse echo measurement. In the NDT Laboratory, this technology consistently showed a capability for nearly 100 percent discrimination between samples whose weld parameters of arc time and peak current varied as little as 20 percent. This same capability was also exhibited on type 13-19 connectors. The capability of this technology to be configured for operation by a production inspector was not determined.

A destructive test consisting of measuring the time-to-failure of the weld when vibrated at its resonant frequency under 30g acceleration was briefly investigated. Groups of hot, cold, and normal welds had significantly different times-to-failure and resonant frequencies. There was no overlap between samples of the cold and the normal groups. All samples failed within the weld.

Incidental to the ultrasonic investigation, some color photos of different classes of welds were produced. Use of a combined pictorial and narrative workmanship standard is suggested by these photographs. Because all weld tests seem to discriminate against cold welds better than against hot welds, the best possible visual inspection is required to complement other weld tests.

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