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EDDY-CURRENT SEAM TRACKER FOR
ELECTRON-BEAM WELDERS

J. J. Henry

OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

*prepared for the U.S. ATOMIC ENERGY COMMISSION
under U.S. GOVERNMENT Contract W-7405 eng 26*

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ABSTRACT

An eddy-current seam tracker has been developed for making high-precision welds with an electron-beam welder. This tracker employs an "E-frame" seam detector probe and operates as a servo follower for maximum tracking accuracy.

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SUMMARY

An eddy-current seam-tracking apparatus, for use in making high-precision welds with electron-beam welders, has been designed and tested. This unit is a noncontact tracking apparatus, capable of positioning the electron beam to an accuracy of ± 3 mils on a precision, no-offset seam. Offset errors less than 0.8 mil per mil of offset were realized. The unit employs a unique "E-frame" sensing probe operated at the null position by a digital servo to achieve this accuracy.

INTRODUCTION

Seam welding is a common method for fabricating and assembling hermetically sealed metal components. Electron-beam welding is a preferred joining technique whenever good mechanical and hermetic joining is desired, especially when the other joint requirements include minimum distortion, a small heat-affected zone, and low contamination. To meet these requirements, however, a very small, highly focused beam and a precise, stable, and accurate beam and work positioning are required. Precision alignment of the electron beam and the joint seam must be maintained throughout the welding process. Poor alignment contributes to a lack of penetration, loss of hermeticity, and weak mechanical strength in the weld joint.

Often, especially on larger parts, long, complicated, and tedious preweld operating procedures are required to achieve the desired results. The required alignment may lead to many preweld adjustments and inspections before sufficient accuracy is achieved to accomplish successful joining in the welder.

A system to track the seam position, while the weld is being made, and position the electron beam to correct for any misalignment would eliminate the setup problems. Design objectives were: (1) a system capable of tracking a precision seam to an accuracy of ± 5 mils (± 0.12 mm) at ± 80 mils (± 2.0 mm) maximum deviation, and (2) maximum deviation rates of ± 10 mils (± 0.25 mm) per second.

A system has been designed at the Oak Ridge Y-12 Plant^(a) which, when properly applied, can satisfy these requirements and reduce the required setup and alignment time. In addition, if care is exercised in joint mismatch (offset) it could possibly permit some relaxation of the machining precision requirements for precision joining.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

SEAM TRACKER FOR ELECTRON-BEAM WELDERS

DEVELOPMENT OF THE SEAM TRACKER

Preliminary Investigation

In order to determine the optimum method for detecting an almost invisible seam in the electron-beam welder environment, consideration was given to three noncontact methods of seam-position detection: (1) optical scanning, (2) electron-beam (backscattered-electron) scanning, and (3) an eddy-current detector with servo positioning. Contact methods were not considered because the extremely small seams were not amenable to mechanical sensing; and, in addition, such contact increases the likelihood of contaminating the finished part with material that would be scraped off the contact tip.

Results of this survey showed that optical-scanning techniques could be expected to have problems due to weld-vapor occlusion of the optics and interference of light from the weld melt. Problems with backscattered-electron techniques were mainly because of interference due to the welding electron beam (which can also backscatter electrons) or a widened heat-affected zone (if the weld beam is scanned to find the seam).

These considerations led to the selection of the eddy-current sensor for further development. Expected problems with eddy-current sensing were: (1) a low signal strength, (2) effects of material and seam contact resistance, (3) effects of "lift-off" (detector-to-work) distance variation, (4) effects of "offset" (unequal top surface position on opposite sides of the seam), and (5) electromagnetic interference with the electron beam. However, many of these problems are readily surmountable by judicious probe, electronics, and shielding design.

A low signal strength can be optimized by experimentally selecting a probe configuration to optimize the seam-motion sensitivity. Effects of material and seam-contact resistance can be almost eliminated by operating a differential probe in the servo-null mode. This same configuration could also improve the effects of lift-off variation. The effects of offset cannot easily be completely eliminated; but, by a careful selection of the standoff distance and joint alignment, these can be minimized. The effect of magnetic shielding is generally a reduction in signal; hence, a configuration in which the magnetic shielding has little effect upon the probe signals is desirable.

Probe Design

An eddy-current sensor works on the principle that when a varying magnetic field is impressed upon a conductor, a current is induced in the conductor. When the electromagnetic field is a small source directed into the surface of a metal, the induced currents tend to circle the magnetic field component; and, hence, the name "eddy" currents. The actual presence of these currents creates an opposing magnetic field which tends to reduce the overall field. If this field is being generated by a current flowing in a coil, the eddy currents effectively change the impedance of the coil. The actual resistance of the metal reflects as a resistance change in the coil by transformer action, while the reduction in magnetic field causes the coil inductance to decrease.

When the change of coil impedance is measured to determine the effects, no contact or attachment to the measured part is necessary. It is noted, however, that magnetic field intensity (from a point source) decreases in proportion to an inverse square law:

$$H = \frac{m}{\gamma^2}, \quad (1)$$

where:

H represents the field strength,

m the point-source magnetic intensity, and

γ the distance.

From this expression it would be expected that the eddy-current effects would decrease in proportion to the square of the distance between the coil and the metal surface.

Eddy currents also are affected by the phenomenon called "skin effect" in which currents flowing in the top surface of the metal oppose the magnetic field so that less current flows below the surface. Skin effect controls the sensing depth penetration and is affected by the resistance of the metal and by the frequency of the excitation:

$$t = \frac{1}{2\pi} \left(\frac{\rho \times 10^9}{\mu f} \right)^{1/2}, \quad (2)$$

where:

t represents the effective penetration in cm,

ρ the resistivity in ohm-cm,

μ the permeability of the conductor (a value of 1 for most nonmagnetic materials),
and

f the frequency in Hz.

This penetration depth is helpful in that it permits the operator to select a frequency which has full penetration of a desired material while limiting the spread of the signal at the surface.

From this discussion it can be seen that several phenomena readily affect the eddy current probe: (1) the probe-to-part separation distance, (2) part thickness and resistance versus the operating frequency, and (3) flaws, seams, edges, and other discontinuities. The desired effect, in this case, is the resistance discontinuity of the seam. Hence, the probe design, operating frequency, and probe-to-part separation effects must be optimized to give the best response in this region.

For optimizing this design, an experimental setup was devised, as outlined in Figure 1. The test seam consisted of a butt joint in two, 1/8-inch-thick aluminum plates. This seam was moved under a stationary probe using a micrometer-actuated slide. The probe was excited by a variable-frequency AC generator using a large series resistance to ensure constant current excitation. With constant current excitation, the coil voltage is a direct indication of coil impedance, and variation in impedance and rate of change of impedance can be inferred directly from this measurement.

Figure 1. COIL TEST SETUP.

The first probe tested was a small, solenoid-type, air (phenolic)-core coil, 1/2 inch long and consisting of 300 turns of Size 36 wire on a 1/4-inch-diameter rod. The coil-operating frequency was optimized for maximum percent impedance change as the seam was moved under the coil at a 50-mil (1.25 mm) liftoff (coil-to-aluminum plate separation distance).

The second probe was a coil with a shorter and flatter geometric configuration and consisted of 300 turns of Size 36 wire on about a 1/8-inch length of a 3/8-inch-diameter phenolic rod. It was tested in the same way as the first detector. Results of these tests are given in Table 1. Liftoff tests were conducted by hand, using 50 and 60-mil plastic shim stock to position the coil over the aluminum plate.

Since neither probe showed significant improvement in seam-motion sensitivity, it was surmised that merely changing geometry

Table 1
PRELIMINARY COIL TEST RESULTS

Coil	Size (in)			Number of Turns	Optimum Frequency (kHz)	Seam Motion Sensitivity (%/mil)
	H	ID	OD			
1	1/2	0.25	0.4	300	10 - 40	0.65
2	1/4	0.375	0.625	300	6 - 30	0.68
3(1)	1/4	0.125	0.200	120	10 - 38	0.16
Total Signal (seam)						
Change Percent V (0.050 in liftoff) (%)						
1	5			4		
2	8			6.5		
3(1)	14.5			5.6		

(1) This coil wound on ferrite rod, all others had a phenolic core.

was inadequate to give the desired sensitivity. There was, however, a strong possibility that a magnetic core could improve the configuration at the frequencies used in the first tests. A third probe, consisting of 120 turns of Size 36 wire wound on about a 1/8-inch length of 1/8-inch-diameter ferrite rod, was fabricated and tested. The results (see Table 1) show the distinct improvement in seam-motion sensitivity realizable using the ferrite core.

These results indicated the desirability of using a ferrite core in the probe design. The appreciable liftoff sensitivity (see Table 1) could only be overcome by using a balanced differential detector operated at the null as a servo device, or an equally complicated liftoff compensation scheme using a separate liftoff probe. Since both of these techniques require at least a dual element probe which can be shielded with minimum effect upon the probe operation, an evaluation of probe configurations was conducted.

After examining the many possible differential configurations (all using ferrite cores and shielding), an E-frame probe design using a core obtained from a miniature transformer kit was chosen. Other configurations including twin coils, triple coils, and quadruple coils on separate cores were considered, but the E frame was favored because of easier mounting, balancing, adjustment, and better mechanical and electrical stability. In addition, the E-frame design could be more easily shielded (because of its continuous magnetic structure) and could provide a simultaneous liftoff signal from the driven coil.

A drawing of the E-frame probe is given in Figure 2. The probe is driven by a constant current signal on the center leg only. The two outside coils provide differential sensing. The center coil can also be used to provide a signal proportional to liftoff so that proper height above the work can be maintained. Shielding on all sides except the tracking face is easily accomplished without interference with the tracking signals. The seam null position is normally positioned under the center of the center leg, and the probe is normally operated with the E-frame long axis at right angles to the seam.

Probe Electronics

The output signal from the E-frame probe consists of two in-phase signals. Their amplitudes are approximately equal when the seam is positioned in the center of the center leg. When the seam moves toward one of the sense coils, the output voltage of this coil increases (due to reduced eddy currents from the seam resistance position) while that in the opposite coil decreases. If these two signals are subtracted by a differential amplifier, the resulting signal will increase in magnitude whenever the seam moves out of the center position, but the phase of the resulting signal goes through an 180-degree phase shift as the center is crossed.

When this output is amplified and detected by a standard phase-magnitude detector, a response (indicated in Figure 3) is obtained. Note that the amplitude of the detector response varies due to changes in the standoff distance, while the null position remains stable.

In order to exploit the null-position stability, the tracking system is operated as a servo system. A bidirectional pulse motor operates a probe positioning system (see Figure 4) which tends to keep the probe centered over the seam. The motor is driven by up and down pulses obtained from the probe electronics chassis. These pulses are derived from a gated

Figure 2. E-FRAME SEAM-TRACKER PROBE SHOWING THE THREE COILS.

Figure 3. PHASE DETECTOR OUTPUT USING THE E-FRAME PROBE.

Figure 4. COMPONENTS OF THE SEAM TRACKER.

unijunction oscillator whose frequency is adjustable from 10 to 100 Hz. The frequency of this oscillator controls the motor drive speed (steps per second) for both directions of motion. A direction-sensor circuit gates this oscillator on and off in response to the phase-detector output. The phase-detector output also directs the pulses either up or down in order to maintain the probe centered over the seam. An off region near zero is employed so that hunting is prevented. This off region is adjusted to about ± 1 mil by adjustment of the voltage trip points.

The position of the probe is indicated by an up/down counter which monitors the motor-control pulses. A digital-to-analog converter (DAC) provides a signal to the electron-beam deflection coil amplifier to cause beam motion to correspond to probe motion and, hence, seam motion. The DAC input signals are derived directly from the position bidirectional counter.

An electronic limit circuit is established by monitoring the direction and magnitude of the position counter output. When the position counter reaches + 1,000 counts, no further "up" counts are allowed out of the "up" discriminator gate. When the counter reaches -1,000 counts, "down" drive pulses are disabled. With a calibration [set by the pulse-motor drive ratio of 20 mils (0.5 mm) per revolution and the 200-pulses-per-revolution motor] of 0.1 mil per pulse, this provides a ± 100 -mil (2.5 mm) tracking range with 0.1-mil resolution.

Seam Tracker Operating Characteristics

For optimum accuracy, certain alignments and adjustments need to be made on the seam tracker. These changes are necessary due to the effects of liftoff and probe alignment. Other effects which should also be considered, particularly if malfunction seems to occur, are material variations, flaws, and probe temperature.

Figure 5. VARIATION IN THE MAXIMUM PROBE SIGNAL WITH LIFTOFF.

141670
Figure 6. SEAM-TRACKER PROBE SHOWN IN PLACE IN THE CARRIAGE ARM WITH A MICROMETER-POSITIONED TEST SEAM.

The effect of liftoff variation is to decrease the coupling to the part by shunting some of the magnetic field through the air gap. This coupling changes approximately inversely with liftoff spacing, as noted in Figure 5. When the poles of the detector are parallel to the part surface this arrangement has little effect upon the null position, but may change the deadband slightly. When the poles are not parallel, however, a decrease in liftoff will cause the apparent null position to "sweep" toward the low pole. Adjustment of the probe is accomplished by varying the liftoff and leveling the probe using the thumb screws so that "sweep" is minimized. The adjustment screws can be seen in Figure 6.

When operating the probe to weld a seam, if the two surfaces of the seam vary in height (offset), a similar "sweep" is induced. The magnitude of this error is a function of the amount of offset and the amount of liftoff. The minimum value of the error due to offset would be equal to one half the offset if liftoff and tracking signals were both linear; but, since liftoff is non-linear, all offset errors should be greater than one half the offset. By operating at higher values of liftoff, the offset errors are minimized. Errors of 0.7 to 0.8 times the offset were realized by operating at a 80-mil (2 mm) to a 100-mil (2.5 mm) liftoff.

Material variations consist primarily of resistivity changes which have little effect upon the servo accuracy, but may change deadband by 50 percent or more. Flaws, or excessively thin materials, may cause errors, however, in that they can directly affect the probe in the same way that the seam does. Temperature has negligible effect upon the probe unless it exceeds the curie

point of the magnetic core (about 85° C). When this point is exceeded, however, the probe becomes inoperative until it cools off again. This temperature is not normally exceeded when welding, but may be exceeded due to high backscatters and radiant heat when setting up and focusing on the tungsten test target. A shield between the probe and test target will eliminate this problem.

TESTING AND OPERATION

Field Tests

A prototype seam-tracking apparatus was fabricated and installed on the 3-kw electron-beam welder in the Y-12 Welding Development Laboratory. Straight test seams were welded using this apparatus to control beam deflection. These seams were in flat butt-joint coupons and about 8 to 10 inches in length. They were welded using an already established work-positioning speed and the proper beam parameters for the type of material. The seams were positioned at a slight angle to the translating axis so that the tracker was always required to move more than 25 mils in order to follow the seam during the weld. These seams were not precision joints, and no great care in alignment was taken. Offset and offset position were obtained with a dial indicator after welding and before sectioning for metallurgical sample preparation. All welds were of the partial penetration type so that seam position could be determined to about a two-mil accuracy by examining the photomicrographs of the metallurgical samples.

In addition to the butt joints, a precision step joint of magnesium coupons was welded. This specimen was a full-penetration weld using a highly focused beam. Position accuracy can be measured from the offset step to an accuracy of about 1/2 mil (see Figure 7).

The apparatus was then installed in a 6-kw production welder so that tests could be conducted on rotating ring welds. Results of these tests are given in the Appendix. These tests indicated that a tracking accuracy of $\pm$ three mils could be obtained for a properly aligned zero-offset weld, and that offset errors as low as 0.6 to 0.8 times the actual offset could be obtained by operating the probe at a 80 to 100-mil standoff.

Final Design and Operation

Three seam trackers have been fabricated and installed on production electron-beam welders. A mechanical system for the digital servo employing a bellows seal was designed by Engineering Division personnel. This work was done in order to operate the positioning motors in air rather than in vacuum. Figure 8 provides a photograph of the mechanical assembly. This system normally mounts behind the electron-gun assembly with the arm positioned so that the probe is near, but not in, the welder beam.

MS-70-0219-10
Figure 7. PHOTOMICROGRAPH OF A
MAGNESIUM STEP-JOINT WELD. (14X)

141671
 Figure 8. SEAM-TRACKER MECHANICAL ASSEMBLY SHOWN MOUNTED ON A TEST STAND PRIOR TO INSTALLATION ON A WELDER.

A view of the weld-seam-tracker electronics chassis is given in Figure 9. The bottom chassis is the beam-deflection coil amplifier. Above this, in order, are the probe electronics chassis, the bidirectional counter (seam position indicator), the digital-to-analog converter and electronic limit, and the tracking motor drive unit.

Figure 9. SEAM-TRACKER ELECTRONICS CABINET.

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In operation, tracking is enabled or disabled from the probe electronics unit. Calibration of the deflection amplifier is accomplished through use of the DAC calibrate pot located above the counter. Calibration of the deflection amplifier is necessary whenever the gun-to-work distance, or the beam voltage, is changed. Normal setup and calibration is made by impinging the beam on a smooth tungsten block positioned immediately adjacent to a short

precision aluminum test seam. Observation of the welder beam glow on the tungsten block allows zeroing and calibration of the probe, and the deflection amplifier. It is important that this block be positioned at the same distance (electron gun to block) as the final weld, or calibration errors will result. It is also important not to overheat the probe in this operation, and a backscatter shield is helpful (as part of the test seam design).

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APPENDIX

SUPPLEMENTAL TABLES AND GRAPHS

The following tables and graphs summarize the data from the field tests of the seam-tracking apparatus. It is to be noted that when setup and zero adjustment are made with offset present, the sweep error is apparent in a "zero setup" error.

Table A-1

DATA TAKEN BY OPTICAL COMPARISON OF
SECTIONS FROM WELD COUPONS WELDED
IN DEVELOPMENT WELDER

Sample	Tracking Motion From Setup (mils)	Offset (mils)	Measured Tracking Error (mils)
<u>Weld Coupon 1(1)</u>			
1	+ 3	+ 1.7	- 2.15
2	+ 6	+ 4.0	- 0.55
3	+12	+ 3.0	- 1.35
4	+21	+ 5.8	+ 2.3
5	+24	- 9.6	- 4.3
6	+27	-18.9	-12.4
7	+30	-21.2	-11.7
8	+33	+ 8.6	+ 3.2
<u>Weld Coupon 2</u>			
1	- 3	- 9.6	- 0.05
2	- 6	-15.9	- 1.60
3	-15	-11.8	- 0.20
4	-18	- 7.6	+ 3.15
5	-21	- 1.7	+ 5.95
6	-24	- 0.4	+ 5.80
<u>Weld Coupon 3</u>			
1	+ 4.3	0	+ 1.5
2	+ 8.6	0	+ 2.0
3	+12.9	0	+ 1.0
4	+17.3	0	- 3.0
5	21.6	0	- 1.0

Table A-2

DATA TAKEN FROM PHOTOMICROGRAPHS OF
SECTIONS FROM THE TEST-RING WELDS
MADE ON A PRODUCTION WELDER

Angular Position (degrees)	Offset (mils)	Tracking Error (mils)
<u>Test Ring 1</u>		
30	0.00	+ 3.75
150	+10.00	+10.90
210	- 3.75	+ 0.94
330	+ 4.40	+ 4.10
<u>Test Ring 2</u>		
60	0.0	- 1.6
150	-12.5	-10.0
240	+ 9.0	+ 4.0
<u>Test Ring 3</u>		
105	+ 2.0	+ 3.8
150	+12.5	+ 8.75
285	+ 1.0	+ 2.5
330	-11.5	- 5.0

- (1) The first two test seams were butt-welded, rough, sheared coupons which were aligned with the welder X-axis motion so that the indicated tracking motion was necessary in order to hit the seam. The third coupon was a precision machined step joint with no offset. Correlation of offset versus tracking error is indicated in Figure A-1. Weld Coupon 3 is not shown in Figure A-1 because no measurable offset occurred.

Figure A-1. COUPON-WELD OFFSET ERRORS.

Figure A-2. RING-WELD OFFSET ERRORS.

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