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COMPUTER AUTOMATION OF AN ELECTRON-BEAM
WELDER WITH AUTOMATIC, STORED
SEAM TRACKING

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OAK RIDGE, TENNESSEE

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Oak Ridge Y-12 Plant

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ABSTRACT

A Hamilton Standard 7.5-kW electron-beam welder has been extensively rebuilt, upgraded, and computer automated to provide accurate, repeatable, multipass, wirefed welds with stored seam tracking. Tests have shown that the seam-tracking system can keep the beam on a true line within approximately ± 0.05 millimeter, even in the presence of a strongly deflecting magnet.

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SUMMARY

A Hamilton Standard 7.5-kW electron-beam welder has been upgraded with a precise vacuum control system, new high-voltage and bias supplies, improved spindle drive motor and gearbox, redesigned part fixturing, a ribbon-filament gun, completely renovated optics, and improved controls and displays. Additional equipment has also been installed to provide new capabilities—a digital computer, programmable parameter instrumentation, and a programmable wirefeeder that provides repeatable, multipass, wirefed welds under computer control. A fast-response, beam-current controller has been provided for enhanced beam-current stability. A new video display/record/playback system provides recording and playback of a welding operation, including voice inputs. A new beam/seam tracking system provides fast, easy storage of a seam position and automatic tracking of the stored position in the auto-weld mode. A parameter recording system provides for recording all weld voltages and currents for future reference. Special care has been taken to keep the operating procedure simple, and extensive diagnostic routines have been prepared for computer-assisted fault tracing in the new electronic subsystems.

Tests have demonstrated the correct operation of the system as a whole. Multipass welds with stored seam tracking have been made under computer control. In one test, a deflecting magnet was strapped near the beam path; then a weld bead was made, once with and once without seam tracking. Without seam tracking, the beam was deflected approximately 7.5 millimeters away from a true line; but, with seam tracking, a true line was maintained within approximately ± 0.05 millimeter. The technology which has been developed for this project is being applied in a similar upgrading of another welder to be used in a production environment.

INTRODUCTION

The objective of this study is to produce a modified and upgraded electron-beam (EB) welder which will provide accurate, repeatable, multipass, wirefed welds, using stored seam tracking. The present report gives an overview of the project and discusses each major subsystem from a conceptual standpoint (ie, only to the first level of technical detail).

The project was undertaken in order to meet the demands of the Oak Ridge Y-12 Plant^(a) for very precisely executed EB welds and the demands for certain advanced types of welds (for example, multipass wirefed) which cannot be repeatably performed by using currently available equipment. In particular, some current and anticipated needs for precision (as regard to the placement of the weld) were already beyond the limit of existing technology. Some kind of control system was needed to keep the electron beam directed at the seam which was to be welded, but no such system was available.

ELECTRON-BEAM WELDING PROBLEM

The EB welding technique is used, typically, in certain situations wherein a precisely controlled flow of energy must be deposited with high positional accuracy. In the EB welder, an electron gun produces a stream of free electrons which are accelerated through a high-voltage (HV) electric field and are focused onto a small spot on the part which is to be welded, as illustrated in Figure 1. The beam parameters, such as beam current, HV, and focus current, must be closely controlled in order to achieve good results.

Typically, a weld is presently made via manual control of the welding parameters. Automation of the process would be desirable for several reasons. First, repeatability becomes a problem when fast reactions by the operator are called for, such as when several parameters have to be changed, "on the fly", within a short time span. Second, some technically promising

Figure 1. A SIMPLIFIED ELECTRON-BEAM WELDER.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

welding procedures involving multipass, wirefed welds with slope in/out on the beam parameters are too complicated to be done by hand. Last, there has always been a need for some system to provide real-time alignment of the beam spot with the seam which is to be welded. For these three reasons, a development team was formed at Y-12 for the purpose of creating an advanced experimental EB welder.

UPGRADED SYSTEM OVERVIEW

An existing Hamilton Standard 7.5-kW EB welder was completely disassembled, reconfigured, and upgraded with new equipment, as seen in Figure 2.^(b) Figure 3 is a

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Figure 2. UPGRADED HAMILTON STANDARD 7.5-kW ELECTRON-BEAM WELDER.

schematic diagram of the upgraded system. A new part fixture was fabricated to take a new spindle gearbox and a programmable pulse motor, along with a programmable

(b) The authors are also shown. From the left, they are P. C. Turner, G. L. Bowers, C. M. Davenport, J. H. Burkhardt, Jr, and L. M. Greene.

Figure 3. PRINCIPAL COMPONENTS OF THE UPGRADED ELECTRON-BEAM WELDER.

Figure 4. COMPUTER SYSTEM AND BEAM-DEFLECTION INSTRUMENTATION.

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wirefeeder. A new vacuum control system was installed for improved vacuum regulation. A ribbon-filament electron gun was chosen to replace the hairpin-filament gun (both guns manufactured by Hamilton Standard). Improved optics were installed to provide simultaneous eyepiece viewing and video display/recording. All of the basic weld parameter supply units were replaced with new, more stable, programmable units. In particular, the HV unit was redesigned with a closed-loop control system and a programmable set-point circuit. The beam-current supply unit was likewise redesigned. A parameter recording system using oscillographic and cassette recorders was installed. A completely new control console was fabricated, containing improved manual controls and digital readouts of the welding parameters. A computer interface with parameter set-point controllers was installed to provide computer-control capability, in addition to all-manual operation.

A beam/seam tracking system, utilizing the video camera output, was installed to provide real-time control of the beam position. A Digital Equipment Corporation PDP-11/45 computer (Figure 4) with fast-floating-point hardware and a fast, compact, executive software package was installed. During an automated weld, the computer performs three main functions: (1) the weld parameters are switched in and out as needed, based on the data in a stored file; (2) seam-tracking calculations are performed, and beam-deflection corrections are sent out; (3) the video camera lens filter is continually reset to avoid video washout or "blooming".

UPGRADED SYSTEM CAPABILITIES

Several significant advances are claimed for the upgraded system. First, it is a superior EB welder for manual operation because of the several new, more-stable current and voltage supplies; the newly developed precision beam-current controller; the improved controls and displays; the precise vacuum control system; the improved spindle drive, and the wirefeeder. Second, it can repeatably perform complicated multipass welds, many of which could not be done by hand. For example, it can accurately tie in one pass to the next by means of precisely timed switching and parameter sloping without stopping and restarting the weld sequence; and, it can smoothly "tie off" the last pass by a programmed slopedown of the beam current to zero. Last, the seam-tracking system can control beam wander due to any reason, such as the presence of ferromagnetic material near the seam. It also allows a programmed movement of the beam via storage of the desired path beforehand which, in turn, allows the tracking of a seam exhibiting considerable runout error (misalignment), or tracking of a seam obliterated by previous weld passes. The problem of part alignment during setup is thereby greatly reduced.

The remainder of this report will briefly discuss the structure and operation of each major component or subsystem, will discuss the general principles of operation of the system as a whole, and will give system evaluations and weld results.

COMPUTER AUTOMATION OF AN ELECTRON-BEAM WELDER

WELDER HARDWARE

Mechanical Equipment

Spindle Motor and Gearbox - A single-axis, continuous-path control system, consisting of an incremental servo controller, servo actuator, and encoder, was used to upgrade the spindle drive. A block diagram of the system is presented in Figure 5. With a

Figure 5. SPINDLE-DRIVE CONTROL LOOP.

500-pulse-per-revolution encoder, each pulse on the serial data line represents a 0.72-degree incremental movement of the motor shaft. The spindle drive motor connects to the spindle by means of a 36-to-1 gearbox. Thus, the spindle motor shaft turns 36 times for each revolution of the spindle and provides 0.02-degree incremental movement per input pulse. Spindle speeds, ranging from near zero to 21 rpm, can be controlled manually in a continuous mode, or in an incremental or continuous mode under computer control. Variations in part surface speed, due to spindle rotational velocity, have essentially been eliminated.

Part Fixturing - Components of the mechanical assembly located inside the welding chamber to support and rotate the workpiece are seen in Figure 6. Coupling between the workpiece and fixture is formed by the use of adapters and holding faceplates which are universally used in plant operations. The fixture can accommodate geometric workpieces of axial revolution to a maximum arc radius of 35 cm and a maximum length of 48 cm. A commercially available stepping motor with integral shaft encoder is used as the prime mover for the workpiece.

The tail stock and spindle-drive gearbox assembly are independently secured to the X-Y table using T bolts so that the interspacing may be adjusted as needed. Alignment is maintained by precision pins extending into the T-bolt slots which are machined into the X-Y worktable. The dimensions of the worktable are 137 by 71 cm.

In order to implement a beam-current control system, based on the electron current through the workpiece, it was necessary to electrically insulate the workpiece from the fixture and

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Figure 6. PART-FIXTURING AND SPINDLE-DRIVE COMPONENTS.

chamber. The insulation was established by placing epoxy barriers in the spindle faceplate and end-loading shaft, as indicated in Figure 6. Since these pieces remain in place when the workpiece is removed, no special preparation or setup is needed. The current is conducted away from the workpiece by means of a spring-loaded pickup that is located inside the end-loading shaft. The current is routed out of the weld chamber to external control circuits.

Optical System - Four goals of the upgrading program involved the optical system, namely:

1. Evaluate and, if possible, improve the quality of the telescope system used by the welding operator to view the weld region, making it easier for the operator to locate the seam to be welded.
2. Provide a closed-circuit television system to monitor and record the weld.
3. Provide improved lighting to illuminate the weld region so that both the weld seam and electron-beam weld pool can be viewed while welding.

4. Provide a closed-circuit television system for data acquisition to determine the location of the center of the weld seam and electron-beam weld pool. A horizontal resolution greater than 18 line pairs per millimeter is needed for this effort.

The University of Arizona Optical Sciences Center evaluated the original optical system, shown in Figure 7, and obtained the following facts:

1. The limiting aperture of the system is a "half-moon" aperture located in the lower column beneath the electron gun. This aperture limits the theoretical resolution to 26

Figure 7. COMPONENTS OF THE ORIGINAL OPTICAL SYSTEM.

line pairs per millimeter, vertically, and 78 line pairs per millimeter, horizontally, at the longest working distance (79 cm). At the shortest working distance (41 cm), the aperture limits theoretical resolution to 42 line pairs per millimeter, vertically, and 126 line pairs per millimeter, horizontally.

2. The optical viewing axis is horizontally displaced 17.4 millimeters from the center of the half-moon aperture, resulting in an eccentric pupil configuration.
3. The two very strong lenses ($f/2$ and $f/3$) used to form a real intermediate image have a large amount of spherical aberration that limits the telescope resolution to 9 line pairs per millimeter. This resolution value is constant within 2 line pairs per millimeter over the field and range of working distances.
4. The two metal mirrors used to direct the light rays from the weld region to the telescope introduce astigmatism.
5. The 75-watt tungsten halogen viewer lamp used to illuminate the weld region produces a luminance on polished tungsten that is 100 times lower than that required to permit a seam to be viewed while welding.

These evaluation results indicated that the optical system needed to be improved to meet the upgrading goals.

Two new optical systems were designed and fabricated. The first system, outlined in Figure 8, replaces the original one, utilizes the half-moon aperture, aligns the telescope's optical axis with the center of the half-moon aperture (Figure 9), provides constant magnification (1X) over the range of working distances, improves the worst-case horizontal resolution to

Figure 8. IMPROVED OPTICAL SYSTEM, UTILIZING COLUMN OPTICS. (Numbers Represent Dimensions in Centimeters; $A + B = 127$ cm; Folding Mirrors above the Half-Moon Aperture are not Shown)

Figure 9. RELOCATION OF THE TELESCOPE THAT IS USED TO ALIGN THE HALF-MOON APERTURE WITH THE OPTIC AXIS OF THE TELESCOPE.

25 line pairs per millimeter, and provides a port for attaching a closed-circuit television camera for weld monitoring and recording. The existing viewer light is presently used for weld-region illumination, but a one-kilowatt xenon arc lamp will be tested in the near future.

The second improved optical system, diagrammed in Figure 10, is designed for operator viewing and television camera data acquisition of weld-seam and electron-beam weld-pool positions. This system utilizes two new viewing ports located in the top of the welder

Figure 10. IMPROVED OPTICAL SYSTEM THAT UTILIZES THE NEW VIEWING PORTS, LOCATED IN THE TOP OF THE WELDER CHAMBER.

chamber. A telescope like the one used in the first improved system and a mirror assembly are attached to one port. (Figure 11 is a photograph of the external apparatus.) The television camera is attached to the telescope; the television scene is displayed on a monitor, recorded on a cassette, and transmitted to the data acquisition equipment. Worst-case horizontal resolution is improved to 36 line pairs per millimeter. A one-kilowatt xenon arc lamp will be attached to the second viewing port and will be tested in the near future for weld-region illumination.

Wirefeeder - Filler wire feeding has been shown to enhance the capabilities of EB welding in a variety of areas, including high depth-to-width ratio welding in thick sections and critical-partial penetration welds in thin-wall material.¹ The purpose of the wirefeeder is to introduce the wire into the weld pool, allowing it to be melted to form the fill material for the joint. The wirefeeder consists essentially of three subassemblies: (1) a control panel located in the operator console, (2) a stepping-motor translator chassis, and (3) a wire-feed motor positioner. Figure 12 provides a view of the wire-feed motor which propels the wire and the three-axis positioner which moves the motor relative to the workpiece.

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Figure 11. VIEW OF THE EXTERNAL OPTICAL COMPONENTS, INCLUDING THE TELESCOPE, VIDEO CAMERA, AND VIEWING PORT IN THE WELD CHAMBER.

Figure 12. WIREFEEDER MECHANISM.

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The X, Y, and Z axes, as well as the wire-speed selection, are operable from the control panel during manual operation. Frequently, it is necessary to reposition the wire-feed motor along the Z axis to maintain the wire at the correct angle to the work as the weld joint fills. A manual indexing feature is incorporated into the Z-axis drive for this purpose with a selectable index distance (0 - 25.3 mm) and indexing speed (0 - 4.2 mm/sec) to allow for tapering the change over a specific distance on the work surface. In order to reach the objective of producing quality multipass wirefed welds, special consideration must be given to the synchronization of the wire and beam parameters toward achieving a smooth overlay of successive wire passes. Computer control was chosen as the most promising solution. In addition to those features previously mentioned as being part of the manual controls, the computer can also provide slope-rate control of wire-speed changes and more precise Z-axis indexing during pass overlap. Table 1 gives a summary of the wire-feeding parameters which are programmable by computer.

Ribbon-Filament Electron Gun - A significant portion of EB welding at the Y-12 Plant utilizes the Leybold-Heraeus (formerly Hamilton Standard) R-40A "hairpin-filament" electron gun. For making repeatable partial-penetration welds, several characteristics of this gun are undesirable, namely: (1) beam focus/beam current interdependence, (2) EB

Table 1
PROGRAMMABLE RANGES ON WIRE-FEED PARAMETERS

Parameter	Range	Resolution
Wire Speed (mm/sec)	0 - $\pm$ 108	0.43
Wire Slope Rate (mm/sec ²)	0 - 53.7	0.43
Z-Axis Index (mm)	0 - 3.20	0.025
Z-Axis Index Speed (mm/sec)	0 - 4.2	Continuous (manual adjust)
Wire Size (mm)	0.38 - 2.4	

cross-sectional asymmetry, (3) beam-energy distribution changes caused by filament sag, and (4) short filament life (typically less than 16 hr). These characteristics produce welding problems such as beam-focusing uncertainties, asymmetrical two-axis welding, and short and long-term changes in the EB properties, thereby affecting weld repeatability.

To reduce or eliminate these problems, a Leybold-Heraeus R-40R "ribbon-filament" electron gun is used on the upgraded welder. Significant reduction of beam focus/beam current interdependence has been demonstrated by observing that focus-current changes of 20% or less are required to obtain a sharp focus as the beam current is varied throughout its range. Improvements in beam cross-sectional symmetry have been verified by observing that a circular beam spot is formed by this gun while operating at various power levels spanning its full operating range. Insufficient data have been collected to date to form a statistical estimate of filament life. However, a typical ribbon-filament electron gun was removed and examined after about 25 hours of operation, and no visible erosion or narrowing of the filament was observed. Other advantages of the R-40R gun (claimed by the manufacturer) include homogeneous beam-energy distribution and decreased filament-position sensitivity.

Electrical and Electronic Equipment

Control Console - Figure 13 provides a view of the operator control console of the upgraded welder. All controls are functionally grouped and logically arranged to reduce operator fatigue and errors. The upper-left-hand panel contains all controls and status indicators that the operator needs for making a computer-controlled weld. In addition, this panel contains the spindle speed (in rpm) and angular position displays (in degrees). Just beneath this panel is the ionization-gage controller for monitoring and controlling the chamber pressure during welding. Beneath the controller are the controls and indicators for the vacuum pumps and for vacuum sequencing. Shown to the right of this panel are five subpanels providing for control and display of the filament current, accelerating voltage, beam current, focus current, and X and Y deflection currents. The relative positions of these beam parameter controls were made the same as on the original welder control panel in order to reduce operator confusion. To the right of these subpanels are the controls for video seam tracking, including closed-circuit television (CCTV) camera controls, video data displays, video seam marker positioning control, and lighting controls. Above the seam-tracking controls is a temporary lighting control panel to be replaced by the xenon-arc-lamp controls at a later date. All controls and displays for the wirefeeder and its positioning mechanism are grouped above this temporary panel.

Figure 13. CONTROL CONSOLE FOR THE UPGRADED ELECTRON-BEAM WELDER.

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Controls for positioning the spindle fixture inside the weld chamber are housed in the pendant shown in the lower right. The X and Y-axis-pattern-generator controls, located at the lower left, provide a selection of several beam-deflection patterns. A CCTV monitor and video-tape recorder, seen above the console, are used with the video seam tracker. Completing the operator console is the weld-viewing telescope which provides a magnified view of the welding zone.

Vacuum Control System - An experimental study, conducted at the Y-12 Plant, presented evidence of a chamber pressure/focus interaction.² This phenomenon results from changes in the effect of the electric field generated by the focusing coil because of ions trapped inside the electron beam. The ions are formed by collision of beam electrons with residual gas molecules prevalent at welding pressures from 1.33×10^{-2} to 1.33×10^{-4} Pa (10^{-4} to 10^{-6} torr). Due to pressure/focus interactions, pressure fluctuations introduced by workpiece outgassing or gettering add a dynamic-beam focal-point modulation which can contribute significantly to penetration variations. To enhance the capability of the welder, particularly with low-energy welding of low-density materials, a commercially supplied control system, seen in Figure 14, was installed.

The system is independent and does not replace the original monitoring or pump-and-valve sequencing controls. The pressure controller is located in the operator console and contains a complete ionization gage control unit and readout. It also houses additional circuitry to compare the measured-pressure with the programmed-pressure set point to provide a drive signal for the piezoelectric valve. When the chamber pressure reaches the operating region of the controller [5.32×10^{-2} to 1.33×10^{-4} Pa (4×10^{-4} to 10^{-6} torr)], the operator has two options that can be selected by the panel switches. (1) leave the valve closed and use the unit as a high-resolution ionization gage readout, or (2) activate the valve and use the system as a closed-loop pressure regulator.

Figure 14. VACUUM CONTROL SYSTEM.

Accelerating Voltage Supply - Figure 15 is a simplified block diagram of the accelerating-voltage power supply. This supply provides a precisely regulated (0.1% of full

Figure 15. PRECISION-REGULATED ACCELERATING VOLTAGE SOURCE.

scale) accelerating potential which can be manually or automatically programmed from -10 to -150 kV and also can provide beam currents up to 50 mA. Precise regulation of the output voltage is provided by a three-phase silicon-control-rectifier (SCR) feedback controller, as shown. This controller continuously compares the output-voltage feedback signal with either the manual or automatic-programming input signal. If the output-voltage feedback differs from the programmed input, the controller adjusts the input power to the unregulated high-voltage (HV) power supply to return its output voltage to the programmed value. The power control and interlock section provides for manual or automatic control selection, overvoltage and overcurrent protection, and safety interlocking, to eliminate shock hazards. The digital-to-analog converter changes the 12-bit computer word to a proportional voltage for automatic programming. Signals for driving the accelerating voltage

and beam-current digital meters on the console are provided by the external metering buffer.

Table 2
MEASUREMENT RESULTS FOR THE
ACCELERATING-VOLTAGE-
SUPPLY CHARACTERISTICS

Parameter	Specification
Output Voltage Range (kV)	-10 to -150
Programming Precision	0.05%, Full Scale (FS)
Load Regulation	0.1% FS
Ripple and Noise, Peak to Peak	0.5% FS
Response Time (msec)	500
Output Current Range (mA)	0 to -50
Output Power, Maximum (kW)	7.5

This supply was tested under actual operating conditions to verify that it met its performance specifications. Table 2 summarizes these results.

Bias Voltage Supply - Figure 16 indicates the relationship that exists between the bias voltage supply, accelerating voltage supply, filament current supply, and the electron gun. In order to generate an electron beam, the filament current supply must heat the ribbon filament to produce a thermionic emission of electrons. When an accelerating

potential is present, the emitted electrons will migrate toward the anode (grounded), pass through the anode due to their kinetic energy, and finally strike the weldment. To control

Figure 16. RELATIONSHIP OF BIAS SUPPLY, ACCELERATING SUPPLY, AND ELECTRON-BEAM WELDER ELECTRON GUN.

the electron flow rate or beam current, a bias voltage more negative than the accelerating voltage is applied to the grid cup. Changing the bias voltage (with respect to the filament voltage) from 0 to -1 kV will change the beam current from 50 to 0 mA.

Since the bias voltage supply must "float" on the -150-kV supply, precisely controlling its output voltage from a ground reference source becomes complex. Further complicating this task is the need for a fast control response. Figure 17 provides a block diagram of the design which is employed to accomplish this control. As shown, a programming signal (V_p) is scaled to drive a voltage-to-frequency converter over a range from 20 to 90 kHz. The output frequency (F_p) modulates an infrared light-emitting diode whose light output is coupled to the high-voltage section via the fiberoptic coupler. A light detector converts these light

pulses into a frequency signal which is then reconverted to a voltage signal and scaled to drive the 0 to -1-kV power supply. As a result, the welder beam current is set by adjusting the bias voltage via the programming signal (V_p). Power is applied to the floating supply through an isolation transformer, as shown.

Figure 17. PRINCIPAL COMPONENTS OF THE UPGRADED BIAS VOLTAGE SUPPLY.

Tests of this supply produced the following results: (1) an output voltage step from 0 to -1 kV has a rise time of 12 msec when programmed with a 0 to 10-V input; (2) at full scale, the peak-to-peak ripple is less than 0.15%; (3) load regulation is 0.1% of full scale (FS); (4) programming nonlinearity is less than 0.2% FS.

Feedback Beam-Current Controller - Precise control of the beam current requires a feedback control circuit to drive the isolated bias voltage supply. For effective beam-current stabilization, the control network must compensate for beam-current changes caused by changes in the accelerating voltage, changes in the filament current, and bias-supply drifts. A mathematical model was found to give an acceptable description of the behavior of the beam current as a function of bias and accelerating voltage:

$$I_B = 0.034 (V_A + 0.213 V_B)^{1.5} \quad (1)$$

where:

I_B represents the beam current (Faraday cup current) in mA,

V_A the accelerating voltage in kV, and

V_B the bias voltage in V. (Note: V_A is entered as a positive quantity and V_B as a negative quantity.)

This model was developed by use of nonlinear least-squares analysis of experimental beam-current data.

To control this nonlinear process, a compensated feedback control system is used. A simplified block diagram is included as Figure 18. A programming voltage, V_p , from the

Figure 18. BIAS VOLTAGE FEEDBACK CONTROL LOOP.

parameters which would otherwise change the beam current.

To verify its performance, the control network was tested under actual operating conditions. The results, presented in Table 3, were obtained by measuring the Faraday cup current (total current at the weldment).

Table 3
MEASUREMENT RESULTS FOR THE BEAM-CURRENT
CONTROL PARAMETERS

Parameter	Measured Value
Beam Current Range (mA)	0 to -50
Programming Precision	0.02% of Full Scale (FS)
Ripple and Noise, Peak to Peak	< 2% FS
Response Time (msec)	20
Step Response Overshoot	< 10% FS

Focus and Deflection Current Supplies - Precise focus of the electron beam on the weldment requires a stable programmable current source to drive the existing magnetic lens. A 0 to 1-A current source with a 40-V compliance range, a 10-msec step response, and a stability of 0.01% FS is used. The supply output is programmed either by a manual adjustment at the operator console or by the computer, utilizing the 12-bit digital programming feature. Once programmed, the supply maintains a constant output current through internal regulation, thereby maintaining a constant beam focus (beam current density) at the weldment.

Figure 19. PARALLEL-DISPLACEMENT EFFECT DUE TO DOUBLE-DEFLECTION COILS. (Side View of One Axis is Shown)

A set of double-deflection coils (Figure 19) is used for changing or correcting the position of the beam on the weldment, for beam alignment, and for pattern generation. Double-deflection coils allow the beam to be deflected in any direction without changing the angle of incidence of

the beam on the weldment surface. Equal and opposite angular deflections of the beam are produced, as noted in Figure 19, by driving the coils with oppositely directed currents from the same stable current source.

Each axis (X and Y) requires a stable, programmable current source to drive the double-deflection coils. The voltage programming inputs to each of these sources provide manual adjustments at the console for X and Y-axis beam position, beam pattern height, and beam pattern width. In addition, a 16-bit binary digital programming input is provided on the X-axis current source to make beam-position corrections for beam/seam tracking. Each current source has a -100 to +100-mA range, a 20-V compliance range, and a stability better than 0.01% FS.

For producing a variety of beam-deflection patterns, two phase-locked function generators are used. Patterns composed of sinusoids, ramp functions, square waves, and triangular waves may be used in various combinations to produce the desired pattern. Pattern width and height ranges are ± 4 mm, with a frequency range from 0.01 to 1000 Hz.

Computer Interfacing - The basic welder functions that are provided with computer control are: (1) weld parameters, (2) parameter change points, (3) slope control for the beam and focus current, (4) spindle speed control, (5) beam/seam alignment, and (6) wirefeeder control.

A block diagram of the major control functions for the EB welder is given in Figure 20.

Parameter change or set points define the weld-parameter transitions during an actual weld. For circular parts, parameter set points may occur at any point on the surface of revolution. Weld files are created with angular position as a reference. A 3600-pulse/revolution encoder and gearing arrangement, attached to the spindle drive, accurately defines the angular position of the part. In the parameter data set-point control logic (seen in Figure 20), Register A counts the encoder output pulses (0.1 degree/pulse). A new data set point is loaded into Register B from the computer. When the pulse count in Register A equals the new data set-point value in Register B, an interrupt is generated and the weld-parameter data are updated to a new programmed set of values.

Figure 20. DATA SET-POINT CONTROL LOGIC.

Slope Control for Beam and Focus Currents - Two of the major welding parameters being controlled by the computer are the beam and focus currents. In order to avoid discontinuities in a weld it is desirable to provide a smooth transition when the parameter values are changed. To obtain the desired control characteristics, the slope-control circuitry (shown in Figure 21) was designed. When a change in the existing current is required, a new

Figure 21. SLOPE CONTROL LOGIC FOR THE BEAM AND FOCUS CURRENTS.

commanded current value is loaded by the computer into the static current register. At a rate defined by the magnitude of the slope-rate input word, the active current register (A) is counted up or down as determined by the $A > B$ or $A < B$ conditions of the comparator. When the two registers become equal ($A = B$), the binary-rate multiplier is disabled. Register A remains fixed until a new commanded current value is loaded into Register B. Other provisions have been made to change the currents with a step function when desired. The output of the active current register is fed to a 12-bit DAC to provide the 0 to 50 and 0 to 100-mA ranges for the beam and focus currents.

Spindle-Drive Circuitry - Precise automatic control of a weld sequence requires that the spindle be driven in a controlled state and the position of the spindle be known. A block diagram of the spindle control circuitry is given in Figure 22. With the 36:1 ratio in the

Figure 22. SPINDLE-DRIVE CONTROL CIRCUITRY.

gearbox, the 500-pulse/revolution encoder, and the 4X encoder pulse generator, a spindle pulse resolution of 0.1 degree is achieved, thus:

$$\text{Spindle Pulses/Revolution} = \frac{(500 \text{ pulses/revolution}) (4X) (36:1 \text{ gear ratio})}{(20)} = 3600, \text{ and}$$

$$\text{Spindle Resolution} = \frac{360 \text{ degrees/revolution}}{3600 \text{ pulses/revolution}} = 0.1 \text{ degree/pulse}.$$

Under computer control, the spindle can be moved in 0.1-degree steps (incremental mode) or in a continuous mode up to 21 rev/min. The CW/CCW pulses are counted and displayed to provide continuous angular position. A zero encoder pulse obtained by dividing the zero encoder pulse train by 36 is used to define the angular zero position of the part and initiate all weld sequences.

Beam/Seam Tracking System - For deep-penetration, narrow-melt-zone, electron-beam welds, precise beam/seam alignment is necessary. Faulty alignment will displace the root of the weld, causing a weak joint. Alignment within ± 0.05 mm is required in many applications.

An optical video technique was developed to determine and compare the weld-seam location prior to welding and electron-beam weld-pool location during welding. If the beam and seam positions are not identical, the beam is deflected to the seam. Figure 23 is a block diagram of the beam/seam alignment system. The weld region is imaged on the camera-tube target by the mirrors and video leg of the telescope, and is displayed on the closed-circuit television monitor and recorded on video cassette magnetic tape.

Seam position data are acquired prior to welding, as follows: The weld seam and a moveable cursor are displayed on the TV monitor, as illustrated in Figure 24. The

beam/seam interface electronics determines the peak video level in the lower half of the field of every television frame, updates a scratch-pad memory register, and generates an interrupt to the computer. The computer reads the register and positions the motorized neutral-density filters to obtain the proper video level. The operator then moves the

Figure 23. PRINCIPAL COMPONENTS OF THE BEAM/SEAM ALIGNMENT SYSTEM.

cursor to the center of the displayed seam and presses a button to generate an interrupt. The computer reads and stores the cursor position and workpiece angular position for use during welding.

Deflection-control parameters must be calibrated before welding. The electron beam is turned on a target and the computer reads the peak video level and adjusts the neutral-density filters

Figure 24. TELEVISION DISPLAY, SHOWING THE APPEARANCE OF THE WELD SEAM AND MOVEABLE CURSOR.

to obtain the proper video level (refer to Figure 25), the beam/seam interface electronics detects the electron-beam weld-pool video signal in the lower half of the field of every

Figure 25. TELEVISION DISPLAY, SHOWING THE SEAM AND WELD-POOL DETECTION SCHEME.

television frame, selects three horizontal lines that intersect the weld pool, and measures the time from the horizontal synchronous signal to the left and right edges of the weld

Figure 26. SCRATCH-PAD MEMORY REGISTER.

pool for each horizontal line. These data are stored in scratch-pad memory registers, illustrated in Figure 26, and an interrupt signal is generated. The computer reads these registers and calculates the location of the center of the weld pool, for the case of no beam deflection, then the computer changes the deflection-power-supply control input by a known amount, which deflects the electron beam. The new weld-pool position is detected, and a beam-position-versus-deflection-control conversion factor is calculated and saved for later use in the tracking mode.

During actual welding, the peak video level, workpiece angular position, and weld-pool position are determined by the computer at the television frame rate (30 Hz). The computer controls the position of the neutral-density filters to maintain the proper video level, compares the weld-pool position to the stored-seam position for the given workpiece angular position, and commands the deflection power supply to deflect the electron beam if the weld pool is not at the desired position. The weld-pool position is determined by the technique which is illustrated in Figures 25 and 26.

The initial successful beam/seam-alignment-system test was performed on the 5.7-cm-diameter stainless steel cylinder, shown in Figure 27. A horseshoe magnet was attached to the fixturing near the workpiece to intentionally deflect the beam in the vicinity of the magnet. The magnetic field had a strength of 30 gauss, maximum, in the weld region. The position of the machined reference groove was stored prior to welding. The workpiece was moved to the right, and an EB weld bead was then made to the left of the reference

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Figure 27. STAINLESS STEEL TEST CYLINDER, ILLUSTRATING THE BEAM/SEAM ALIGNMENT SYSTEM PERFORMANCE.

groove without using beam/seam alignment. (Surface speed was 0.5 cm/sec; the maximum deviation from the desired path parallel to the reference groove was 3.5 mm.) The workpiece was then moved to the left, and a weld bead was made to the right of the reference groove (nearest the magnet) with beam/seam alignment. (Surface speed was again 0.5 cm/sec; maximum deviation from the desired path parallel to the reference groove was less than ± 0.05 mm, as desired.)

Parameter Monitoring and Recording System - The weld-parameter monitoring and recording system, shown in Figure 28, serves as a machine-performance diagnostic tool as well as a postweld procedural accounting method. High-voltage, beam-current, focus-current, filament-current, chamber-vacuum, and X-Y beam-deflection data are simultaneously displayed on compact modular oscilloscopes within the operator's view. This real-time display gives the operator a fast-responding machine overview to aid in analyzing problems. There are two separate 3-channel, FM, magnetic-tape instrumentation recorders, with each channel structured, as indicated in Figure 29. The FM record/playback electronics operate on a standard $\pm 40\%$ deviation channel with a center frequency of 27 kHz, using chromium dioxide home-entertainment-type cassettes. The 10 - 90% response time of the record/playback electronics is 150 μ sec. Once recorded, the tape may be replayed at the recording speed or 10 times slower if greater detail is desired. During replay, each recording is displayed on its respective oscilloscope. On a real-time basis, or during replay, a side-by-side paper copy of any two channels can be made by using a light-beam oscillograph with a nominal full-scale deflection of 82.5 mm and with a response flat to within $\pm 5\%$ from DC to 400 Hz.

COMPUTER HARDWARE AND SOFTWARE

Computer

As indicated in Figure 4, the computer is a Digital Equipment Corporation PDP-11/45 model. It has 16K 16-bit words (16,384 words) of core memory and 4K words of metal oxide semiconductor (MOS) memory. The core memory has a cycle time of 900 nsec and the MOS has a cycle time of 500 nsec. The system includes a fast, hardwired, floating-point arithmetic unit, a 1.2-million-word disk storage unit, a paper tape unit, and a 30-characters-per-second console terminal.

The central processor unit (CPU) has 16 general-purpose registers which can be used as accumulators, pointers, index registers, and as auto increment/auto decrement registers. The CPU provides both single and double-operand addressing in either word or byte increments. A four-level hardware-priority-vectored interrupt facility automatically traps interrupts to designated addresses, while information required for reentering interrupted software is pushed onto a hardware-controlled stack. Power fail/automatic restart capability is provided. A real-time clock which is accessible from both FORTRAN and MACRO programs is included.

Figure 28. WELD-PARAMETER MONITORING AND RECORDING SYSTEM.

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Figure 29. PARAMETER-RECORDING AND DISPLAY-SYSTEM CIRCUITRY.

System Software

The computer software is organized, as outlined in Figure 30. The RT-11 executive software was chosen because it is a compact, fast-response system that is designed for real-time applications. The system utility programs perform the usual program development and debugging functions, but also have several exceptional features which are important in the present application. First, a fast-access, contiguous file structure is supported on the system disk. Second, the FORTRAN compiler and the MACRO assembler both use the fast-hardware, floating-point unit, which is very important for the seam-tracking algorithm. Third, the linking loader, together with the contiguous file structure, provides a fast-response program overlay structure. Last, the on-line debugging program is a powerful aid for debugging complicated real-time programs. The remaining programs in Figure 30 will be discussed in the topics which follow.

Data Storage and Manipulation

The auto-weld mode of operation is actuated by data from an ASCII-coded stored file, wherein one record is one set of welding parameters. The weld data files are kept on the system disk and may be edited or listed out by means of the system utility programs. A typical listing is presented in Figure 31. The files are stored under names composed of two-digit alphanumeric numbers and are automatically retrieved at actual weld time by reading the file number from the operator's console, where the operator has selected a file number via a set of thumbwheel switches.

A new weld-data program is created by use of the new file input routine (Figure 30). It provides prompting statements, handles all file opening and closing operations, writes the

Figure 30. ORGANIZATION OF THE COMPUTER SOFTWARE.

table headings into the file, asks for a line at a time of welding parameters in a relatively free format, provides gross error checks on each line, allows retyping if an error is found, respaces the data into evenly aligned columns, and writes the data into a file. Only those data elements whose values are within the design limits, as listed in Table 4, will be accepted. After a new file has been created, it may be edited or updated by use of the System EDIT program. A separate routine is provided for realigning the data columns after an edit operation.

18 2.0 BEAM TRACK TEST RINGS													
9-1-77													
SET													
SET	CHNGE	HIGH	FOCUS	SLOPE	BEAM	BEAM	BEAM	BEAM	WIRE	WIRE			SEAM
NO	ANGLE	VOLT	CURR	RATE	CURR	SLPE	X	Y	FEED	SLPE	WIRE	SPND	TRKG
							DEFL	DEFL	RATE	RATE	INDX	RPM	MODE
1	360	25.	0	0	0.00	0.0	0	0	0	0	0	2.0	0
2	700	60.	0	0	0.00	0.0	0	0	0	0	0	2.0	0
3	720	60.	276	0	0.00	0.0	0	0	0	0	0	1.6	0
4	1110	60.	276	0	0.00	0.1	0	0	0	0	0	1.6	0
5	1440	60.	276	0	0.00	0.1	0	0	0	0	0	1.6	0
6	1465	0.	0	0	0.00	0.0	0	0	0	0	0	1.6	0

*

Figure 31. A TYPICAL WELD DATA FILE.

Welder Operating Routines

During computer-assisted operation, the operator exerts control from the control console by means of thumbwheel switches and pushbuttons. A short memory-resident routine responds to pushbutton interrupts by reading the thumbwheel settings to determine which action is to be taken and with which stored file; then, by calling in the proper subroutine (overlay), to perform the desired work. At present, there are five types of work (or modes) which can be performed:

- I. Seam storage with manual seam tracking.
- II. Seam storage with automatic seam tracking.
- III. Video/tracking mode setup.
- IV. Autoweld with stored seam tracking.
- V. Flat plate auto weld.

(See Figure 30 for their relationships to the other welder software routines.)

Before the various modes are discussed, it is important to discuss the approach which was used in the solution of the problems of variable part heights, variation of beam deflection with HV when the deflection current is held constant, and the choice of engineering units, all as related to the seam-tracking algorithm. All have a direct bearing on the complexity of the algorithm; hence, on the response time of the seam-tracking system. For example, calculation of the absolute positions of the seam and beam in space and the

Table 4

ALLOWED RANGES ON THE WELDING PARAMETERS

Parameter	Range
High Voltage (kV)	0 - 150
Beam Current (mA)	0 - 50
Focus Current (mA)	0 - 1000
Beam Current Slope (mA/sec)	0 - 20
Focus Current Slope (mA/sec)	0 - 400
X Deflection Amplitude (mils)	0 - 300
Y Deflection Amplitude (mils)	0 - 300
Wire Feedrate (in/min)	0 - 255
Wire Slope Rate (in/min/sec)	0 - 127
Wire Index (mils)	0 - 127
Spindle Speed (rpm)	0 - 21

calculation of the correct deflection current in the presence of varying HV are significantly complex and time-consuming tasks. Fortunately, the preceding calculations are not necessary in the new system.

Basically, the way it works is that the video camera serves as an "eye" for the seam-tracking system, and the tracking algorithm works strictly in units of the digitized data taken from the video image. The objective is to line up the beam spot with the seam, in the video image. The beam-deflection response curve is measured in a preweld setup (Mode III) under actual weld conditions.

The list of modes of operation may now be discussed. Mode I provides a computer-assisted means of storing the seam position. The computer adjusts the video intensity, drives the spindle until a spindle zero reference point is found, and then repeats the following for each location around the part: It drives the spindle through a specified angular increment, adjusts the video intensity, and waits for the operator to align the video pointer with the seam and press a button. When the button is pressed, the computer reads the video pointer position and stores it on disk.

After all positions have been stored, the computer does a four-point high/low throwout test and a nine-point least-squares, cubic smoothing operation³ on the data to reduce the effects of operator error. The stored-seam data remain valid as long as the part is not manually moved in some manner.

Mode II performs the same actions as Mode I except that, instead of waiting on the operator to push a button and then reading a pointer position, the computer automatically reads the video seam data and calculates the seam position. This mode provides fast and accurate seam-position storage for seams which are clearly distinguishable to the video electronics (60-degree chamfered edges on the seam are desirable).

Mode III performs a preweld setup of the video intensity and calibration of the beam-deflection control loop. These actions are performed on a test block of the same or similar material as the actual weld material. At the operator's pushbutton command, the computer retrieves the desired weld file, sets in the first beam-on set of welding parameters, and adjusts the optics filter for the weld conditions. It then sets in a known deflection control value and measures the resulting beam deflection in the video image. The deflection response is linear, hence a scale factor for the deflection control values can be constructed, effectively calibrating the deflection control loop.

Mode IV performs a fully automatic weld, including automatic parameter switching and tracking of a stored-seam position. A position encoder on the spindle drive keeps track of the part position, and new parameter sets are sent out to the programmable parameter controllers at those positions which are specified in the weld data file.

The seam-tracking operation is performed as follows: Every 1/30 of a second, the tracking circuit scans the beam spot in the video data and stores, in a data buffer, its edge points, as

seen in three separate scan lines (Figure 25). As soon as the beam data are stored, the tracking circuit generates a tracking interrupt to the computer. The computer reads the stored data and the part angular position from the position encoder, calculates an average beam position from the beam data, and interpolates the stored-seam data to get the current seam position. A beam/seam error is calculated, converted to deflection control limits, and sent out to reposition the beam and remove the error.

A second interrupt loop updates the video-intensity settings as fast as the lens filter can respond, in order to control video blooming and washout. When a filter interrupt is received, the computer sets a software flag and goes back to whatever it was doing. Upon receipt of the next beam/seam tracking interrupt, the video intensity is read. If it is above a certain fixed value, the lens filter is closed (increased in density) by a small fixed increment; if it is below, the filter is opened by the same fixed increment. The result is that if the video intensity suddenly moves away from the desired value, the computer will drive it back at the fastest rate allowed by the filter-drive mechanism. In order to prevent "hunting" about the desired intensity, no correction is generated if the intensity falls within a small band about the desired level. Anytime the filter motor has been commanded to move, the completion of the move will cause the tracking circuits to generate another filter interrupt, thereby keeping the video intensity control loop "live".

Mode IV may be operated without seam tracking or video-intensity control by simply switching off the electrical power to the tracking circuits.

Mode V provides a mechanism for flat-plate welding, using the automatic parameter switching. Special fixturing must be used, and the part must be moved manually under the beam at a speed which will synchronize with the parameter change interrupts which are coming from the independently moving rotating part fixture. This mode is primarily useful for making test welds on flat samples.

Interface/Instrumentation Test Routines

The sophistication (hence the complexity) of the electronic equipment on the upgraded welder creates a need for dynamic test procedures, should an electronic failure occur. The computer manufacturer supplies such capability for the computer and its peripherals in the form of a series of computer diagnostic programs which isolate and test individual subsystems and functions of the computer. It was decided to emulate this approach for the interface and other instrumentation and create a diagnostic package which would aid in the initial debugging and later maintenance of the system.

Since most such routines are short, they were collected into one package under one program name having (at the present time) 27 options. The equipment to be tested includes 8 interrupt lines, 23 input data registers, 17 output data registers, and 48 separate functions program-selectable by means of individual bits in three general-purpose registers. Other equipment may be tested in major subsystem groupings. The available tests, shown in Figure 30, are as follows:

1. Test any of eight individual interrupt circuits.
2. Test the spindle incremental motion.
3. Test the spindle continuous motion.
4. Read the seam-tracking data registers.
5. Load the welding parameters.
6. Read the video marker position and beam intensity.
7. Set the lens filter.
8. Read the spindle angle.
9. Clear/disable all interrupts and all parameters.
10. Read the file number and mode from the control panel.
11. Set/clear the control panel lights.
12. Feed and retract the wire.
13. Enable all interrupts.
14. Beam-position-read test.
15. Beam-deflection test.
16. Column-alignment routine.
17. Dynamically read the tracking data.
18. Position the spindle routine.

These routines have several times proved themselves to be indispensable in the isolation of faults which occurred in the initial checkout.

Most of the 18 test routines are self explanatory. The possible exceptions are among the last five. Test 14 allows the operator to set up the beam spot and adjust the video manually, then have the computer read and print out the beam position. The result can be visually verified by use of the video display. A significant portion of the seam-tracking circuitry is tested by this routine. Test 15 isolates and tests the beam-deflection circuit. A back-and-forth movement is programmed by the computer, and the response can be verified

by use of video display. Test 16 provides computer-programmed variation in the depth of focus of the beam optics to be used as an aid to mechanical alignment of the upper column on the EB welder. Test 17 provides a "snapshot" of 200 points of the tracking data (beam and seam positions) taken at operating speeds. Any instability in the circuits which detect beam and seam positions in the video data will show up as erratic variations in the data. Test 18 allows the operator to position the spindle via computer commands giving the number of degrees to turn. If the spindle passes the electronic zero reference point, the computer causes it to stop. In this way, reference points can be established or relocated on the part (a LOGIC CLEAR button is provided to initially set a reference point).

ELECTRON-BEAM WELDER OPERATING FEATURES

The system has been designed to be operated either manually or under computer control. Under computer control, the system performs certain predetermined sequences of operations. For example, in the auto-weld mode, the computer takes its instructions from a user-specified weld-parameter file. This section of the report will briefly discuss the main points of the operating procedure for the system under computer control.

First, the welder operator is not involved with the operation of the computer, except when a weld parameter file must be created or edited. At actual weld time, the operator exerts control from the welder console via pushbuttons and thumbwheel switches. As a result, the procedures for computer-controlled operation are of the same nature (for example, Push Button A, Set Switch B) as those for manual operation. Starting the computer program is as simple as turning a switch, pressing a button, and typing R WELDER.

New-File Input

Creation of new files is accomplished by means of a prompting and error-correcting program named NEWFIL, which is started by typing R NEWFIL. The parameter sets are typed in line by line, as illustrated in Figure 31, in a very loosely defined format. For example, the data elements must only be separated by one or more spaces, and may be typed with or without decimal points. The NEWFIL program puts the data elements into a standard ASCII-coded file with the proper spacing and format. File numbers are assigned by the user.

Editing and Listing Files

Editing and listing operations are accomplished by means of the EDIT and PIP (data transfer) system utility programs. The EDIT program provides the means to examine a file, line by line, and change any character or string of characters. (EDIT is basically a string-oriented editor.) While EDIT is a powerful general-purpose editor, it is, in general, complicated to operate. A small subset of its commands may be extracted such that an unsophisticated user may accomplish the simple editing tasks required for an EB welder project. The PIP program provides the means for listing out any stored-weld-parameter

file. All in all, a practiced operator can make minor changes in a stored file and then list out the corrected file for inspection in a matter of a few minutes.

Tracking-Mode Setup

This mode adjusts the video intensity and measures the beam-deflection response for the conditions which will be present during the first beam-on pass of an auto-weld operation. Since it requires the presence of a beam, it must be done on a test block and must be done before the seam storage operations, as it requires moving of the part fixturing.

The operation is performed as follows: The operator manually moves a test block under the beam, then selects a weld-parameter file by setting thumbwheel switches on the control panel. The INITIALIZE button is then pressed to start the action. The computer retrieves the proper data file, searches out the first beam-on set of weld parameters, and waits for the operator to press the foot switch. When this is done, the computer sets in the weld parameters, turns on the beam, adjusts the video intensity and saves the filter settings for later use, and measures the beam-deflection response for later use. The deflection response is determined by setting in a known deflection control value and measuring the resulting deflection. The computer is then left in a "wait" state, waiting for the next command from the control panel. The operator must manually move the part back under the beam.

Manual-Seam Storage

Before a weld can be made, using automatic stored seam tracking, the seam position must be measured and stored in a disk file. This operation is accomplished with the aid of the computer, using the manual-seam-storage mode which was described earlier. (The word "manual" refers to the fact that the operator positions a pointer in the video display to mark the seam position.)

To start the manual-seam-storage mode, assuming that the part is ready for welding and that the WELDER program is running, the operator sets a thumbwheel switch to select manual-seam storage, then presses the INITIALIZE button. The computer adjusts the video display for the proper intensity and then waits for the operator to press the foot switch. When the foot switch is pressed, the computer causes the spindle motor to drive to an angular zero reference point, then through a five-degree movement, and stop. The operator positions a pointer (by means of a thumbwheel control) so that it is over the seam in the video display, then presses a button to cause this position to be stored. The computer automatically drives to the next five-degree position, adjusts the video, and waits. The operator repeats this procedure (align pointer, press button) at each of 72 positions around the part. When all points are taken, the computer error-checks and least-squares smooths the data, stores them in a disk file, and waits for the next command from the welder control panel. The stored-seam data remain valid as long as the part fixturing is not moved.

Automatic-Seam Storage

This operation proceeds exactly as for manual-seam storage, except that the operator does not have to position a pointer and press a button at each stop. Instead, the computer reads the seam-tracking data and calculates the seam position automatically. Once the operation is started, it is carried to completion automatically unless the foot switch is depressed to indicate an abort or emergency stop condition. This operation requires a clean, uniform seam which is clearly visible in the video display. The computer is left in a "wait" state, waiting on the next pushbutton command from the welder control panel. The stored-seam data remain valid as long as the part fixturing is not physically moved.

Auto Weld, Using Stored-Seam Tracking

This mode automatically performs a weld as prescribed by a specified weld parameter file, and also automatically tracks the previously stored seam position. The tracking setup and seam-storage modes must be done beforehand.

The operation is started by setting the mode thumbwheel switch to 4, the file thumbwheel switch to the desired file number, and then pressing the INITIALIZE button. The computer retrieves the data file, starts the spindle motion and brings up the HV, sets up the proper video intensity as determined in the tracking setup mode, and waits for the operator to press the foot switch. When the foot switch is pressed, the weld is executed automatically as described in the data file, and the beam is kept centered on the seam by the automatic seam-tracking provision. An abort or emergency stop may be made by pressing the foot switch a second time, then all parameters will be cleared and the beam will be turned off. In any case, the computer is left in a "wait" state, waiting for the next command from the control panel.

Interface and Instrumentation Testing

The interface and instrumentation diagnostic routines are maintained on the computer system operating disk, at the fingertips of the system operator. If there is a desire to test some welder system function or component, CTRLC and RWLDTST are typed on the computer terminal. The operator then goes through a question and answer session to input the test parameters for any of the 27 test options which are available. The tests are sufficiently detailed that any computer interface or instrumentation malfunction can be quickly isolated to the malfunctioning subassembly.

RESULTS AND CONCLUSIONS

Test results for the various subassemblies and subsystems have been given throughout the body of this discussion. For completeness, the major results are summarized here.

The new spindle motor and gearbox provide programmable positioning and angular-speed programming which is essentially free of errors. The new optics system provides a resolution

of 36 line pairs/mm, compared with only 9 line pairs/mm for the original optics. (A minimum of 18 line pairs/mm resolution is needed for the tracking application.) Optical ports are provided for attaching a video camera and a high-intensity xenon arc lamp for weld-scene illumination. The ribbon-filament electron gun is more stable than the hairpin type and lasts approximately twice as long (more than 25 hours, in one test). The new vacuum control system can maintain a chamber vacuum in the order of 2.66×10^{-4} Pa (2×10^{-6} torr) to within $\pm 5\%$.

The new accelerating voltage supply is accurately controllable by use of computer set points and is stable to within 0.1% of full scale. It has a response time of 0.5 second to programmed changes in its set point. The new bias voltage supply is likewise accurately programmable and stable to within 0.1% of full scale. Its risetime is 12 msec. The feedback beam-current control loop, which incorporates the new bias voltage supply, is programmable to within 0.02% of full scale and has a risetime of 20 msec. Its step response overshoot is less than 10%. These components, together with the new focus and deflection current supplies, provide an exceptionally stable, controllable beam spot with excellent repeatability.

The beam/seam tracking system has been tested in actual operation and has proved to be effective, accurate, and reliable. Results, such as those depicted in Figure 27, show that the system can follow a stored-seam position to within ± 0.05 mm, even in the presence of a strong deflecting magnet. Automatic programming of the weld parameter set points and the automatic execution of a weld have functioned almost without a flaw from the beginning. The wirefeeder and parameter-recording systems have also worked very well. Overall, the system, consisting of the computer, the interface electronics, and the welder instrumentation, has performed acceptably, even though it is in an electromagnetically hostile area. Any problems which have occurred have been isolated by conventional means or by computer-aided diagnostic tests. No exceptionally difficult or unusual problems occurred during system development, other than the inability to locate a vendor capable of constructing the very stable acceleration-voltage supply unit.

FUTURE WORK

Future work on this project includes a round-robin test program which will compare the upgraded welder with similar, conventional welding equipment. Several different materials will be welded under different conditions on both systems and the results will be evaluated by use of standard weld quality criteria. Other planned work includes the development of an auto-spiking control circuit and an automatic-focus capability.

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