BDX-613-1488
Distribution Category UC-38

**DESIGN MODIFICATION FOR HIGH VOLTAGE
ELECTRON BEAM WELDING MACHINE**

Published September 1976

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PDO 6984748
Milestone Report

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DESIGN MODIFICATION FOR HIGH VOLTAGE ELECTRON BEAM WELDING MACHINE

BDX-613-1488, UNCLASSIFIED Milestone Report, Published September 1976

Prepared by B. D. Fricke, D/822, under PDO 6984748

High voltage electron beam welding equipment control problems affecting weld penetration, weld width, and machine utilization have been experienced when power requirements are less than 5 percent of rated capacity. Design modifications for these machines have been developed to improve their performance when beam current requirements are less than 6 mA and to achieve control of multiple machines by a single computer. Modification of one production machine has been completed. Future equipment activities include modifying two additional production machines to the developed design and establishing computer control of both a laboratory machine and the production machines.

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A prime contractor for the United States Energy Research and Development Administration
Contract Number E(29-1)-613 USERDA

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SUMMARY

A program to modify electron beam welding equipment to improve operating characteristics and adapt it to computer control has been initiated.

Electron beam welding requirements at Bendix Kansas City are characterized by penetration depths of less than 0.060 inch (1.12 mm) and correspond to 1 to 5 percent of the equipment's rated capacity. Equipment control problems in this range resulted in parameter variations that were requiring weld schedule changes to maintain weld penetration and width controls, and that were negatively affecting equipment utilization as a result of unscheduled maintenance and qualification requirements.

Studies showed excessive beam current variations below 12 mA, non-linear beam current slope control, and transients during the weld sequence in the high voltage and beam current. As a result, modifications of three production machines have been designed to improve their operational control, achieve control similarity for maintenance and production scheduling flexibility, and facilitate computer control.

One production machine, a 60 kV hard vacuum Sciaky, had these machine parts modified: beam current control circuitry, high voltage power supply, weld sequence control, and high vacuum system. Increased beam current resolution and positive control with a minimum controllable beam current of 1 mA and linear slope was accomplished with a rangeable current regulating system. Transients associated with energizing the high voltage and beam current simultaneously were eliminated by initiating the high voltage prior to the start of the weld cycle. The vacuum pumping system was modified to reduce maintenance and improve performance by minimizing seal leakage and mechanical pump oil migration into the diffusion pump.

Future work is planned to complete the modification of the production machines and establish computer control.

DISCUSSION

SCOPE AND PURPOSE

Electron beam welded products produced at Bendix Kansas City are characterized by penetration depths of less than 0.060 inch (1.12 mm) and require 1 to 5 percent of the production equipment's 30 kW capacity. Equipment control problems in this operating range required weld schedule changes to maintain control of weld penetration and width and negatively affected equipment utilization as a result of unscheduled down time for maintenance, requalification for production requirements, and weld schedule adjustments.

Equipment design modification activities were initiated to do three things:

- Improve control of the electron beam welders in the operating range where production is concentrated,
- Provide more uniformity of operation and capability of all electron beam welding equipment, and
- Support ultimate computer control of electron beam welding equipment.

ACTIVITY

Machine Studies

A study of the characteristics of electron beam welders involved an investigation of five pieces of representative equipment:

- A 60 kV 500 mA hard vacuum Sciaky,
- A 60 kV 250 mA soft vacuum Sciaky,
- A 50 kV 250 mA hard vacuum Sciaky,
- A 150 kV 40 mA hard vacuum Hamilton Standard, and
- A 150 kV 20 mA hard vacuum Hamilton Standard.

A 14-channel magnetic tape recorder was connected to the electron beam welder to simultaneously record signals at various operating conditions. The following machine systems were investigated:

- Beam current,
- Beam current slope,

- High voltage,
- Weld sequence,
- Automatic weld sequence,
- Focus, and
- Vacuum system.

The study of the 60 kV hard vacuum machine and the 60 kV soft vacuum machine indicated a need to increase the resolution of beam current control, to eliminate voltage and current transients during the weld sequence, and to establish faster and more positive grid bias response.

The magnetic tape recorder studies of machine characteristics did not include the 50 kV Hard Vacuum Sciaky because this machine was not equipped to operate with an independently controllable beam current system (beam current is dependent on the diode gun configuration and high voltage). A decision was made, prior to the recorder studies, to equip the machine with a constant beam current regulating system. The circuits for controlling the focus current, work drive, and high voltage were obsolete with slow response rates and were to be converted to control circuits with faster response rates.

Beam Current

60 kV Hard Vacuum. The 60 kV hard vacuum Sciaky uses a triode gun to control the beam current. The machine had a single control range operating from 0 to 500 mA and the lower limit of beam current control was approximately 6 mA. At this level, the beam current signal to the feedback circuit had a noise component which oscillated from 0 to 24 mA as determined by the use of an electromechanical galvanometer recorder. The noise consisted of frequencies from 60 to approximately 900 Hz. The presence of this amount of noise in the feedback circuit resulted in a loss of control at beam currents lower than 6 mA. Figure 1 is a reproduction of an electromechanical galvanometer recording of the beam current for a machine parameter of 6 mA at 50 kV. The beam current feedback signal varied from 0 to 24 mA with oscillations of 60 to 360 Hz. The Faraday Cup beam current measurement, also reproduced in Figure 1, had a variation of 1.83 mA when set at 6 mA with the same harmonic noise as the beam current feedback control signal.

60 kV Soft Vacuum. The 60 kV soft vacuum Sciaky uses a triode gun to control the beam current with a single control range operating from 0 to 250 mA. The low limit of beam current control was approximately 6 mA and the noise was substantially the same

Figure 1. Reproduction of Electromechanical Galvanometer Recording of Beam Current

magnitude and frequency as observed with the 60 kV hard vacuum Sciaky.

50 kV Hard Vacuum. The 50 kV hard vacuum Sciaky uses a diode electron beam gun and was to be converted to a triode gun.

Beam Current Slope

The beam current sloping circuit did not provide linear slopes (Figure 2). The slope curves were exponential, making a gradual change on reaching the run penetration beam current level on the upslope and an abrupt change at the start of the downslope from the run current level. These transition points were all visible as cavities or undercuts in the welds.

High Voltage

60 kV Hard Vacuum. The high voltage investigation showed the same harmonic noise as the beam current but the percentage was smaller--approximately 8 percent peak to peak, particularly at the upper end of the high voltage range. This variation appeared to be amplified in the beam current when the voltage was applied to the electron gun.

Figure 2. Typical Beam Current Slope Operation

60 kV Soft Vacuum. The high voltage power supply was a six phase full wave rectified power supply compared to the three phase full wave rectified power supply of the 60 kV hard vacuum machine. A reduction in the noise was observed, but it was less than the expected 30 percent theoretical improvement.

Weld Sequence

The sequence of operation for the 60 kV hard and soft vacuum machines allowed the grid voltage control circuit to be energized prior to initiation of the high voltage.

The rate of response of the grid bias control circuit was too slow in establishing control of the beam current at the initiation of the high voltage to avoid a large transient spike in the beam

current (Figure 3). The rate of response was limited by the grid bias control circuit being operated at a frequency of 1 kHz which was inadequate for positive control of the beam current.

Automatic Weld Sequence

60 kV and 50 kV Hard Vacuum. The weld program was controlled by a set of microswitch cams controlling relays. These cams were difficult to set and no accurate angular scale was available on the machine. The graduation marks were 10 degrees apart and resulted in trial and error adjustment of the cams. The inaccuracy resulted in weld length variations.

60 kV Soft Vacuum. The weld program was controlled by a set of timers controlling relays. These timers were of the RC type and limited the accuracy attained. Timer inaccuracy resulted in weld length variations.

Focus

The focus coil current (60 kV hard and soft vacuum) was found to be direct current with the ripple being less than 1 percent peak to peak.

Vacuum System

The following findings resulted from the vacuum system (Figure 4) analysis and indicated improper vacuum techniques which resulted in unnecessary equipment maintenance.

50 and 60 kV Hard Vacuum. The guard vacuum on the work travel drive rotary seal and the sliding seal on the poppet valve were supported by the holding pump for the diffusion pump. Whenever leakage occurred in the seals, the holding pump operating pressure would rise above the breakdown limit for good diffusion pump operation. The holding valve for the diffusion pump was operated unnecessarily during each chamber evacuation cycle, resulting in periodic replacement of the valve.

There was no provision for relieving the vacuum on either the large roughing-backing mechanical pump or the holding mechanical pump when the machine was shut down. As a result, pump oil was drawn into the lines and excessive hydraulic pressure was exerted on the exhaust valve when the pump was restarted.

No provision was provided for automatic shutoff of the diffusion pump cooling water at the end of the automatic shutdown, resulting in condensation of water in the vacuum system cabinet which also contains a considerable amount of electrical wiring.

Figure 3. Typical High Voltage and Beam Current Operation Before Modification

60 kV Soft Vacuum. There was no provision at machine shutdown for relieving the vacuum on the mechanical pumps. This resulted in damage to the exhaust valves on subsequent startups because oil drawn into the pumping lines created hydraulic pressure on the exhaust valves.

The gun chamber pumping system did not have a baffle between the diffusion pump and gun chamber, and this caused contamination of the gun chamber by diffusion pump oil.

60 kV Hard Vacuum Machine Modification

As a result of the study, the following modifications were made to the 60 kV hard vacuum machine.

Figure 4. 60 kV Hard Vacuum Electron Beam Welder Vacuum System

Beam Current Control

Modification of the beam current control circuitry to provide increased resolution and positive control for beam currents less than 12 mA was accomplished by the installation of a new Sciaky Constant Current Regulating System. A Sciaky Reference Amplifier with linear slopes was installed to provide linear upslope and downslope of the beam current.

Beam current range selection was provided by installing three feedback resistors with values (2000, 200, and 20 ohms) corresponding to beam current ranges of 0 to 5, 0 to 50, and 0 to 500 mA. A range selection switch chooses the appropriate feedback resistor for the beam current range desired. For each range the feedback resistor develops 0 to 10 V which is applied to the beam current

control circuit and provides full operational control over each range. This increases the positiveness and resolution of control for the small beam currents.

The input from the feedback resistors to the beam current control is filtered to increase the signal-to-noise ratio of the feedback signal. This is important since the noise input without filtering remains substantially constant as the beam currents used become smaller.

The beam current control circuit operating frequency was increased from 1 kHz to 10 kHz. The control of this frequency was changed from transistor multivibrator to an operational amplifier controlled oscillator for more precise frequency control and faster response.

The beam current control circuit was arranged to apply maximum grid bias voltage to the electron beam gun before the upslope started and after the end of downslope control; that is, at any time the beam current is not being controlled by the beam current control circuit.

The reference circuit which is controlled by the beam current level potentiometers for initial, run, and final levels, was combined with a linear slope control through a summing amplifier. This resulted in the control of initial, run, and final beam current levels as well as control of the slope rate between the initial and run level and between the run and final level selected (Figure 2). The slope rates may be individually selected to provide linear slope rates corresponding to slope times of 0.1 to 10 seconds.

During the proveout of the beam current control system, it was observed that there was a pickup of the 10 kHz frequency in the high voltage control circuit. This was eliminated by rerouting the output line from the beam current control circuit to run directly to the input of the grid bias voltage power supply in shielded cable.

High Voltage Power Supply

A three-phase line inductance was connected in the input side of the power supply to suppress the effect of power surges from the electrical supply system. A second inductance was installed in the high voltage output filter to reduce the ripple in the beam current at low values.

A small resistance load was added to the high voltage output to reduce the high voltage value attained at zero beam current. The bleeder resistor draws a current of 4 mA at 60 kV from the power supply independent of the current feedback resistor.

Weld Sequence Control

The modifications of this section provide automatic control of the electron beam current through regulation of the grid bias voltage throughout the weld cycle after the high voltage has been turned on but before the initiation of the beam current. This change eliminates the transients and reduces the voltage variations caused by energizing the high voltage and grid bias voltage simultaneously. The automatic control cam switch programmer was modified to provide greater accuracy and easier setup.

A number of changes were made to the system.

- The weld sequence control was changed from turning on the high voltage, grid bias voltage, and beam current simultaneously to turning on the high voltage and grid bias prior to initiation of the beam current. The beam current is initiated after the elapse of an adjustable beam current delay time. This method of operation applies a maximum grid bias signal from the beam current control circuit any time the beam current is not being initiated and controlled. The high voltage is established and is controlled at the desired value before the beam current is initiated, thus eliminating fluctuations of the beam current on initiation.
- The cam control of the weld process was modified from cams operating microswitches to discs provided with actuation holes operating in conjunction with LED light sources, photodiodes, and solid state circuitry to provide faster and more accurate response than the microswitch-relay combination. The original cams were provided with 10-degree graduations. Accuracy of cam settings therefore was limited and could only be obtained by successive sample welds. The new system provided graduations on the disc at 5-degree intervals and 1-degree graduations on the index plate and thus permitted initial setup to less than 1-degree. The discs are set by driving a worm gear arrangement to produce smooth adjustment of the system.
- The beam current start delay timer was not accurate or reproducible to less than 0.1 second. This timer was replaced with a crystal controlled timer accurate to 0.01 second to increase the accuracy of this part of the sequence control.

High Vacuum Pumping System

The modifications made to the high vacuum pumping system were designed to prevent the occurrence of problems, reduce the maintenance required, and improve performance by maintaining good operating conditions.

A separate seal holding pump was installed to pump the guard vacuum areas of the rotary and sliding seals (Figure 4, Modification A), and a 0 to 30 inch vacuum Bourdon type gage was installed in the inlet line. This pumping arrangement eliminates any leakage in the guard vacuum system from directly affecting the operation of the diffusion pump. During normal operation, the gage registers 30 inches of vacuum. But if the guard vacuum seals begin to fail, vacuum registry will indicate the difficulty. In addition, a manually operated air inlet valve (Figure 4, Modification C) was installed at the intake to this pump so that when the pump is shut down, the operator can bleed its intake up to atmospheric pressure and equalize the pressure on the intake and exhaust sides of the pump to prevent the transfer of mechanical pump oil from the pump into the seal vacuum line.

The operating sequence of the holding valve was modified to provide continuous backing of the diffusion pump by the holding pump. In the original design, the bellows-sealed pneumatically-operated holding valve was cycled on each evacuation of the welding chamber. The bellows had a limited life and had to be replaced frequently.

During machine shut down it is important to isolate the holding pump from the diffusion pump so the intake of the mechanical pump can be backfilled to atmospheric pressure. This prevents the flow of mechanical pump oil into the pumping line while the diffusion pump is shut down under vacuum. To accomplish this, the sequence of control operations was changed as follows:

- The roughing-backing pump and the seal holding pump are both shut off;
- The backing valve is closed and the heat is shut off on the diffusion pump;
- The two mechanical pumps are vented manually;
- The holding pump continues to run, backing the diffusion pump, until the low temperature thermostat opens, closing the holding valves, shutting off the holding pump, and opening the solenoid air release valve on the holding pump line.
- The intake of the air release valve is limited by approximately 3 feet of fine capillary tubing having an internal diameter of 0.002 to 0.003 inch (0.05 to 0.08 mm). This delays the pressure rise in the holding line so that the slower operating holding valve closes before there is a significant pressure rise on the diffusion pump.

A manually operated air inlet valve was installed on the mechanical pump side of the roughing valve and the large mechanical pump

was arranged to be shut down at the start of the machine shutdown cycle (Figure 4, Modification C). The operator is then available to release the vacuum as soon as the pump stops.

The large mechanical pump originally depended on a solenoid valve to shut off the oil flow into the pump interior during shutdown. This is adequate protection for short shutdown periods (a few hours) but experience has shown that it is not to be relied upon for longer periods. First the pump cavities fill up and then the oil is drawn into the pumping line and may contaminate the foreline to the diffusion pump. On subsequent pump startup following an extended shutdown, the oil filling the pump cavity exerts damaging hydraulic pressure on the exhaust valve. The valve must be replaced and the welder taken out of production. In addition, pools of oil from that left on the evacuation line walls will collect in any parts of the pumping line that do not drain back to the mechanical pump intake by gravity. In subsequent system cycling, this oil can be transferred to the diffusion pump and contaminate the diffusion pump oil. As a mixture of DC704 silicone diffusion pump fluid and the hydrocarbon mechanical pump oil is sensitive to atmospheric pressure at operating temperature, there is a danger of explosion in the diffusion pump.

A solenoid operated valve was installed in the main water supply line. Upon the completion of the diffusion pump cooling cycle, the main water solenoid supply valve closes, shutting off the total water supply to the welder (Figure 4, Modification D). The purpose of this feature is to prevent condensation of water on the diffusion pump and the water lines in the vacuum system cabinet which also houses a considerable amount of electrical wiring.

The water flow switch was replaced by a unit having a lower flow rating so the water cooling for the diffusion pump could be reduced to produce warmer operating temperatures. The original flow switch operated at too high a flow and this adjustment aids in speeding up the takeover by the diffusion pump from the mechanical pump.

Grid Bias Voltage Supply

Frequent failures of the elements used in this voltage supply resulted in the installation of components with increased ratings. The diode ratings in the bridge rectifier were increased from 1.5 kV to 15 kV and 180 mA. The filter condensers voltage ratings were increased from 1500 V to 2500 V.

Beam Current Overload Circuit

This circuit is desirable, particularly where small beam currents are being employed, since the high voltage power supply overload

is normally set to trip at 115 percent of the full load current of the equipment--in the present case, 575 mA. The beam current overload circuit is designed to operate when properly adjusted at 1 to 2 mA above the run level of beam current being used.

The beam current overload circuit existed on this machine prior to the modification but it was inoperative. The circuit was made operable by replacing several defective components. It was observed that during arcs it was possible to apply excessive voltage to the operational amplifier in the circuit. The problem was solved by applying back-to-back zener diodes across the input to this circuit--limiting the applied voltage to approximately 11.5 V. Under these conditions, the circuit operated properly and the operational amplifier was not damaged. An indicating pilot light was added to inform the operator that this overload had been actuated.

Monitoring System

A monitoring system based on solid state technology was designed, built, and installed to monitor beam current, high voltage, focus current, and oscillation of the grid bias control. Limits can be assigned and warning signals are actuated if any parameters exceed the selected limits.

ACCOMPLISHMENTS

The 60 kV hard vacuum machine modification has improved machine operating characteristics to the extent that the necessary control is achieved when power requirements are less than 5 percent of rated capacity and has reduced vacuum system maintenance requirements. Six specific improvements were made.

- Multiple beam current ranges have been provided which permit more accurate and reproducible beam currents with linear beam current slope rates and a minimum controllable beam current of 1 mA.
- The beam current feedback control signal variation has been reduced to a band width of 1 mA for a 6 mA beam current (Figure 5) and beam current variations have been reduced by 25 percent (Figure 6).
- High voltage and beam current transients encountered at the start of the weld sequence have been eliminated (Figure 7).
- Alarm circuits indicating deviations from preselected voltage, beam current, and focus limits have been provided.

Figure 5. Beam Current Feedback Control Signal After Modification

Figure 6. Faraday Cup Measurement on 60 kV Hard Vacuum Electron Beam Welder

Figure 7. Typical High Voltage and Beam Current Operation After Modification

- The migration of mechanical pump oil into the diffusion pump has been eliminated.
- The effect of seal leakage on the diffusion pump operation has been minimized.

FUTURE WORK

The drive system should be modified to replace the cam weld programmer with crystal oscillator controlled timers instead of the disc programmer.

Modifications of the 50 kV hard vacuum welder and the 60 kV soft vacuum electron beam welder should be completed.

Computer control of three production machines should be established using a single mini-computer.

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