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Development of a Weld Quality Monitor

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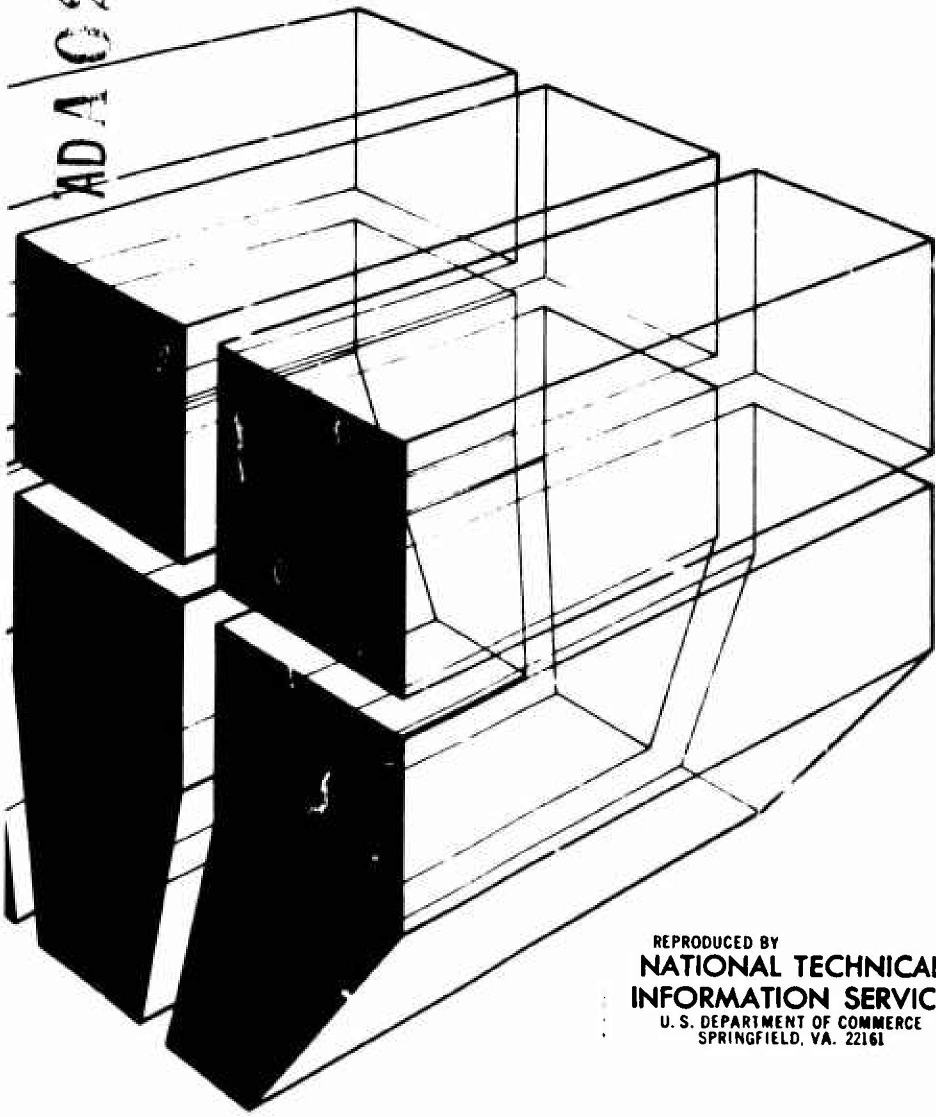
July 1976
Nondestructive Testing for Field Welds

DEVELOPMENT OF A WELD QUALITY MONITOR



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CERL

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A weld monitoring system has been developed based on conditioning the primary signals from the welding machine and comparing them with preset limits. A light is activated when a welding parameter such as voltage, current, or heat input is outside the control limits. The circuitry has been tested with simulated primary signals. The voltage channel has also been tested using primary signals from an automatic gas metal-arc welding machine.

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FOREWORD

This investigation was conducted by the Metallurgy Branch, Materials and Science Division (MS), Construction Engineering Research Laboratory (CERL) for the Directorate of Military Construction, Office of the Chief of Engineers (OCE). The research was funded under Project 4A762719AT41, "Design, Construction and Operations and Maintenance Technology for Military Facilities," Task 04, "Construction Systems Technology," Work Unit 009, "Nondestructive Testing for Field Welds." The QCR number is 1.06.004.

Mr. C. Damico is the OCE Technical Monitor.

Dr. A. Kumar is Acting Chief of the Metallurgy Branch, and Dr. G. Williamson is Chief of MS. COL M. D. Remus is Commander and Director of CERL and Dr. L. R. Shaffer is Deputy Director.

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CONTENTS

DEVELOPMENT OF A WELD QUALITY MONITOR

1 INTRODUCTION

Background

Certain parametric changes in the welding process, some of which can occur without the operator's knowledge, can cause defects in the deposited weld metal. These defects include porosity, slag inclusions, incomplete fusion, inadequate joint penetration, and undercut.

Porosity is a void or gas pocket trapped in solidifying weld metal. The reduced solubility of the gas in the metal caused by the lowering of the temperature forces the gases out of solution. The gases are originally introduced either by poor shielding, which entrains air, or by chemical reactions in the molten weld metal. With stick electrodes, too long an arc (i.e., high voltage) can reduce the shielding effectiveness, thus introducing gas.

Slag inclusion is the trapping of an oxide or other nonmetallic material under the weld bead. The major source of slag is the coatings on stick electrodes. Occurrence of slag inclusions can be reduced by increasing heat input or preheat temperature, thus slowing the cooling rate and giving the slag more time to rise to the surface.

Incomplete fusion is the failure of adjacent layers of weld metal or weld and base plate to fuse. Incomplete fusion may result when the adjacent metal is not heated to the melting point or when the joint surface has not been properly cleaned.

Inadequate joint penetration, which occurs when penetration is less than the amount specified, is most frequently caused by poor joint design or by using an electrode diameter that is too large.

An undercut is a groove melted into the baseplate at the toe of the weld and is caused primarily by excessive travel speed in relation to the welding current.

Problem

The cost of locating and repairing these defects can be a major portion of construction costs. In addition, the service life of welded joints would be longer if weld defects could be minimized.

Consequently, monitoring the welding parameters to show where possible defects are located is necessary. A weld monitor with real-time output would aid the inspector in designating suspect areas for nondestructive testing. If a certain percentage of weld joints is required to be inspected, then the monitor would alert inspectors to questionable areas that should be included in that percentage.

Objective

The objective of this study was to develop and fabricate a device to (1) monitor field welding parameters, (2) compare the data with preset limits in real time, (3) indicate whether a limit has been exceeded, and (4) aid inspectors in weld quality control.

Approach

Various nondestructive testing techniques were examined as possible candidates for real-time field weld analysis. Many methods were rapidly rejected because they were cumbersome, complex, or otherwise unsuitable for field use. It was decided that development of a special monitoring device was required.

The requirements established for the device were that it should:

1. Monitor the three primary signals from the weld system--arc voltage, current, and travel speed; compare them to preset limits; and alert the operator if these limits are exceeded.

2. Calculate the heat input, nugget area, and cooling rate from the three primary signals; compare these values with preset limits; and alert the operator if the limits are exceeded.

3. Be small enough to be field portable.

After these requirements were established, a block diagram of the weld quality monitor (Figure 1) was developed. From this diagram circuitry was designed and the prototype was fabricated. After fabrication, each circuit was individually tested with simulated input signals; all circuits were then tested concurrently.

The voltage channel was tested using input from an in-house fully automatic gas metal-arc (GMA) welding machine. The automated GMA process was chosen to simplify control of the welding variables for initial testing.

Scope

The initial circuitry was designed to monitor parameters of a fully automatic welding machine using the GMA process. Once this system has been perfected, it will be expanded to cover other welding systems and equipment setups.

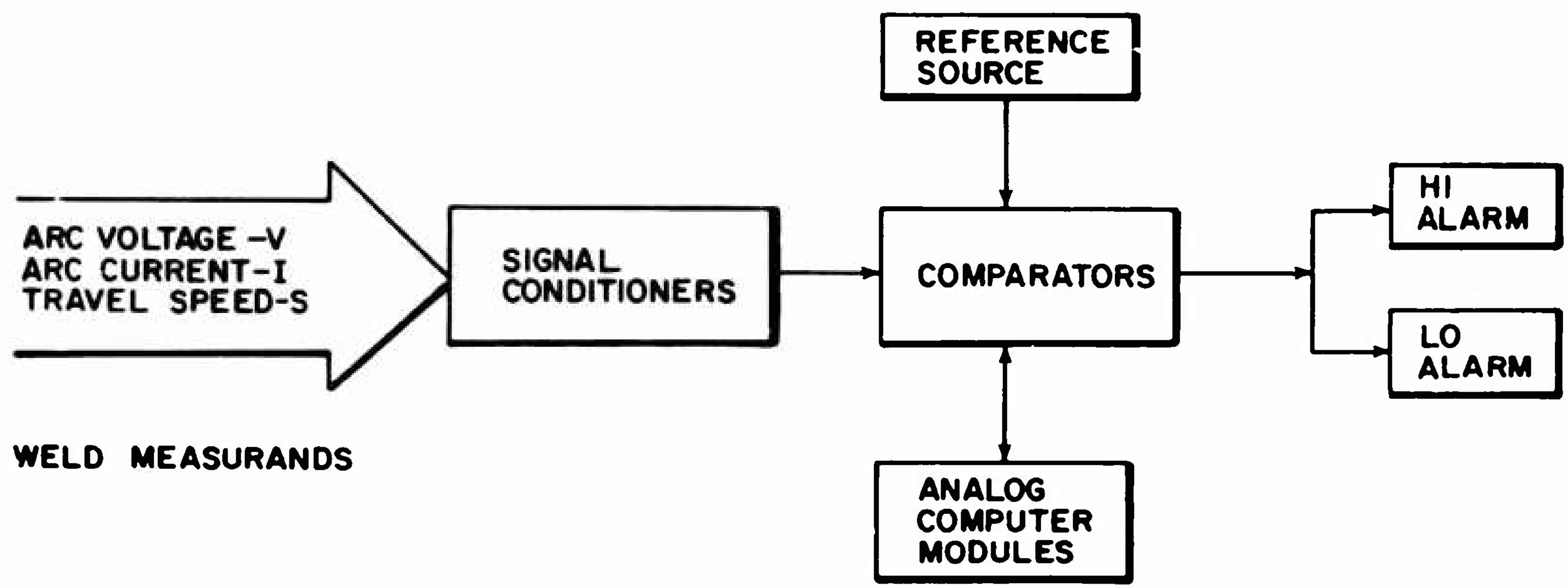

Figure 1. Block diagram of weld quality monitor.

2 FACTORS AFFECTING WELD METAL MECHANICAL PROPERTIES

In addition to the defects caused by improper parametric control, the heat generated by the welding process can cause changes in the base metal such as:

1. grain coarsening
2. softening (annealing effects)
3. hardening (phase precipitation or transformation)
4. segregation of constituents
5. grain boundary melting
6. loss of ductility
7. loss of toughness
8. residual stresses causing distortion or cracking.

The changes which occur depend on the chemical composition of the base metal and electrode and the heat history of the base plate.

In the two commonly used field welding processes--shielded metal-arc (stick electrodes) and gas metal-arc (bare-wire)--the source of heat for melting the materials is an electric arc. Control of the arc parameters will control the amount of heat generated, the length of time at an elevated temperature, and the cooling rate of the weld zone.

Base Metal Microstructure

The cooling cycle after a weld pass determines the microstructure of the weld metal and the heat-affected zone. With fast cooling rates, some steels become very hard due to a martensitic transformation. If the cooling rate is sufficiently slow, the metal may be more ductile and the structure ferrite and pearlite. The type of steel generally determines which of these structures is desired. For low-carbon and low-alloy steels, the pearlitic structure is desirable, while for high-strength quenched and tempered steel, the martensitic structure is desirable.

Martensite is undesirable in low-carbon and low-alloy steels designed for yield strengths less than 80 ksi (552 MN/m^2) because of its hardness and low solubility for hydrogen at ambient temperatures. This combination of characteristics increases the likelihood of hydrogen cracking in the joint. Use of low-hydrogen stick electrodes and the gas metal-arc welding system reduces this tendency toward hydrogen-induced cracking.

Martensite is desirable in quenched and tempered steels such as US Steel's T-1 (ASTM A-514), because the tempering of the plate yields a martensitic structure with increased ductility.

Cooling Rate Control

Control of the cooling rate is essential in preventing undesirable microstructure in the weld and heat-affected base plate. A mathematical combination of arc voltage, current, and travel speed known as heat input (HI) has been used as a means of controlling cooling rate for many years. The equation for calculating heat input is

$$\text{HI (J/in.)} = \frac{\text{Voltage x Amperage x 60}}{\text{Travel Speed (in./min)}} \qquad \text{[Eq 1]}$$

The normal maximum has been 55,000 to 60,000 J/in. (21654 to 23622 J/cm) for the field processes mentioned above.

Another means of controlling cooling rate has been application of preheat. Dorschu[1] has shown that the relationship between heat input, preheat temperature, and cooling rate is:

[1] K. E. Dorschu, "Control of Cooling Rates in Steel Weld Metal," *Welding Research Supplement* (February 1968).

$$CR = \frac{m\,(T-T_o)^2}{HI} + c \qquad [Eq\ 2]$$

where CR = cooling rate

T = test temperature, (1000°F [538°C])

T_o = preheat temperature

m,c = constants

HI = heat input (kJ/in.).

Eq 2 indicates that the higher the preheat temperature and heat input, the slower the cooling rate.

Shultz and Jackson[2] have shown that the cross-sectional area of the weld bead is a useful indicator of weld metal mechanical properties and that a relationship exists between the area and cooling rate. They also found that arc voltage has little or no effect on the nugget area and cooling rate. The relationship that Shultz and Jackson have developed for nugget area, arc current, and speed is

$$na = 1122 \times 10^{-7} \frac{i^{1.55}}{S^{0.903}} \qquad [Eq\ 3]$$

where na = nugget area (sq in.)

i = arc amperage

S = arc travel speed (in./min).

[2] B. L. Shultz and C. E. Jackson, "Influence of Weld Bead Area on Weld Metal Mechanical Properties," *Welding Research Supplement* (January 1973).

3 CIRCUIT DESIGN AND FABRICATION

Figure 1 is a block diagram of the weld quality monitor showing the input signals from the welding arc. These signals are conditioned to standard values and sent to the comparator module, which compares the input signals with a set of limit signals.[3] If the input signals are too high or low, the appropriate alarm is triggered. The input signals are also transmitted to the analog computer module for calculation of the heat input, cooling rate, and nugget area. The calculated values are then compared to reference signals and the appropriate alarm is triggered if needed. Figure 2 shows the completed weld quality monitor; its four principal modules are the signal conditioning, analog computation, comparator, and control limit preprogramming modules.

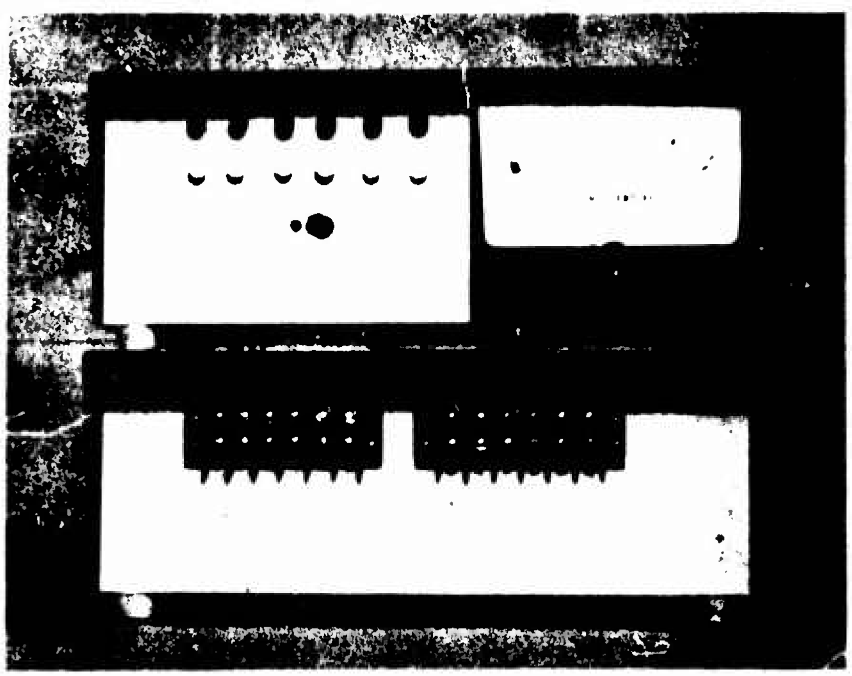

Figure 2. Weld quality monitor.

[3] R. A. Weber and C. E. Jackson, *Review of the Weldability of Construction Materials*, Technical Report M-168 (Construction Engineering Research Laboratory, 1976).

Signal Conditioning Module

The three primary signals from the weldi g machine--arc voltage, arc current, and travel speed--are all different and require conditioning to obtain a standardized signal for comparison with reference signals. A conditioned signal of 5 to 10 Vdc is required for compatibility with the circuitry of the comparator module.

The arc voltage signal, a dc potential ranging from 10 to 40 V, requires stepping down to 5 to 10 Vdc. The arc current is measured by the voltage drop across a shunt in the welding circuitry. The drop ranges from 0 to 50 mVdc and must be amplified to attain the range required by the comparator. The travel speed signal, an ac potential of .5 to 10 V measured by the output of a tachometer mounted to the carriage drive motor, requires rectification and amplification for compatibility.

Voltage Signal Circuit

The voltage signal circuit (Figure 3) has two operational amplifiers (op-amps) cascade-connected in an inverting amplifier mode. The first op-amp has an input resistance (R_{in}) of 5 MΩ. The feedback resistance (R_f) elements are a fixed 1-MΩ resistor and an 0.5-MΩ variable resistor in series so that

$$R_{in} = 5\ M\Omega \qquad \text{[Eq 4]}$$

$$R_f = 1\ M\Omega + (0 \text{ to } .5\ M\Omega) \qquad \text{[Eq 5]}$$

The amplification ratio of R_f/R_{in} thus varies between 0.2 and 0.3.

Assuming a typical voltage signal value as received from the welding machine of 25 V, the value of the output voltage (E_o) for this assembly ranges from -5.0 to -7.5 Vdc depending on the setting of the variable resistance in the feedback section of the op-amp assembly:

$$E_0 = (-25 \times .2) = -5.0 \text{ Vdc (Min)} \quad [Eq 6]$$

$$E_0 = (-25 \times .3) = -7.5 \text{ Vdc (Max)} \quad [Eq 7]$$

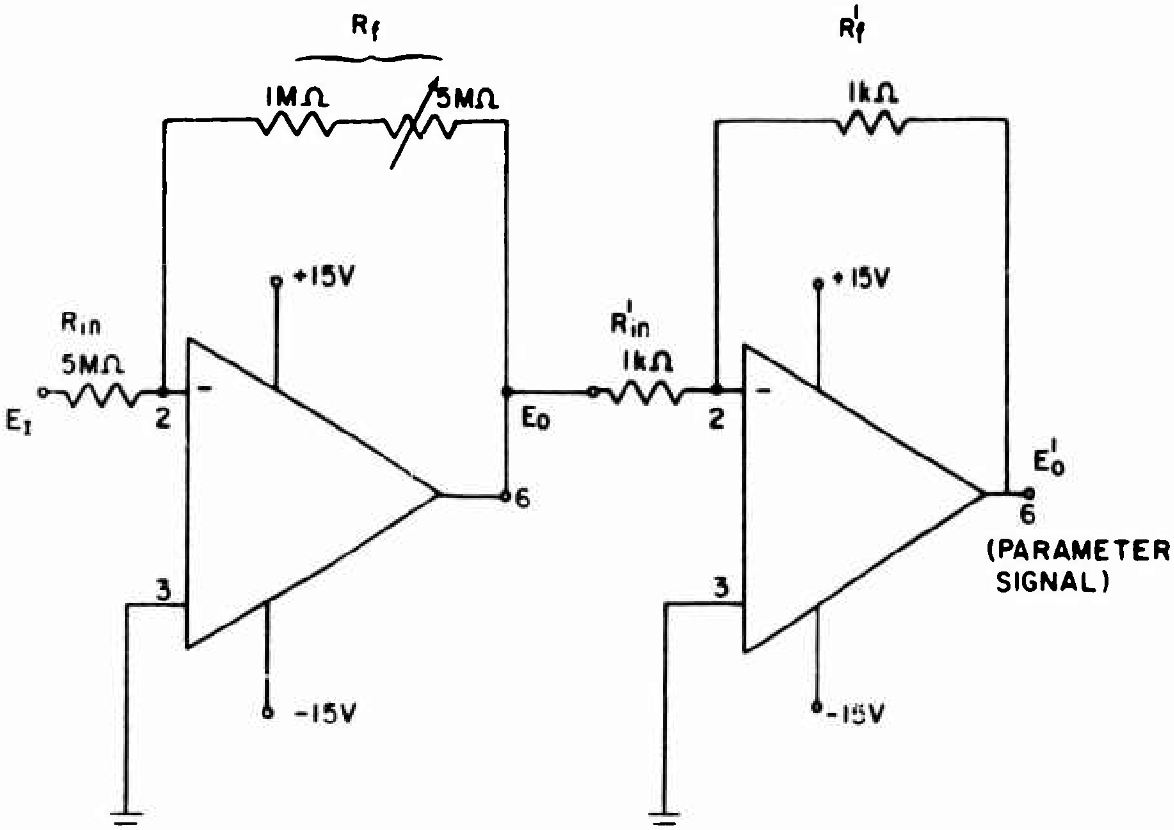

Figure 3. Voltage signal circuit.

The second op-amp, also assembled in an inverting amplifier mode, has an input resistance (R_{in}) of 1 kΩ and a feedback resistance (R'_f) of 1 kΩ. The ratio of R'_f/R_{in} is

$$R'_f/R'_{in} = \frac{1\ k\Omega}{1\ k\Omega} = 1 \qquad \text{[Eq 8]}$$

The output voltage potential (E'_o) is given by

$$E'_o = E_o \times \frac{R'_f}{R'_{in}} \qquad \text{[Eq 9]}$$

Based on a typical voltage signal of 25 V, the maximum and minimum E'_o are

$$E'_o = -(-5.0) \times 1 = 5.0 \text{ Vdc (Min)} \qquad \text{[Eq 10]}$$

$$E'_o = -(-7.5) \times 1 = 7.5 \text{ Vdc (Max)} \qquad \text{[Eq 11]}$$

If the voltage signal range is taken to be 15 to 30 V, the ranges of output values of the voltage parameter circuit are

E_o = 15 Vdc:

$$E'_o = -(-15 \times .2) = 3 \text{ Vdc (Min)} \qquad \text{[Eq 12]}$$

$$E'_o = -(-15 \times .3) = 4.5 \text{ Vdc (Max)} \qquad \text{[Eq 13]}$$

E_o = 30 Vdc:

$$E'_o = -(-30 \times .2) = 6 \text{ Vdc (Min)} \qquad \text{[Eq 14]}$$

$$E'_o = -(-30 \times .3) = 9 \text{ Vdc (Max)} \qquad \text{[Eq 15]}$$

Thus, the voltage signal output ranges between 3 and 9 Vdc considering the full range of the R_f resistor and an arc voltage between

15 and 30 Vdc. However, in actual welding on an automatic machine, a voltage of more than 30 V can be used. Since the op-amps used in this circuit have an input limit of 30 Vdc, a fixed voltage divider must be incorporated in the circuitry to step down higher voltages.

Current Signal Circuit

The current signal circuit (Figure 4) also has two cascade-connected op-amps. The first is assembled as a difference amplifier and the second as an inverting amplifier. The difference amplifier mode is used because the shunt (current signal source) may or may not be grounded.

The difference amplifier has input resistors (R_{in}) of 1 MΩ. The resistance (R_g) between the noninverting input and ground is 10 MΩ; the feedback resistor (R_f) is a 10-MΩ variable resistor. The inverting amplifier has an input resistance (R'_{in}) of 10 KΩ and a 500-kΩ variable feedback resistor (R'_f).

The amplification ratio for the difference amplifier (A_1) is

$$A_1 = \frac{R_f}{R_{in}} = \frac{10\ \text{M}\Omega}{1\ \text{M}\Omega} = 10\ (\text{Max}) \qquad [\text{Eq } 16]$$

The amplification factor of the inverting amplifier (A_2) is

$$A_2 = \frac{500\ \text{k}\Omega}{10\ \text{k}\Omega} = 50\ (\text{Max}) \qquad [\text{Eq } 17]$$

Both op-amps invert the polarity of the output so that the final signal has the same polarity as the input signal. The total amplification available (A_{tot}) is given by

$$A_{tot} = A_1 \times A_2 \qquad [\text{Eq } 18]$$

This gives a maximum amplification of 500 and a minimum of less than 1.

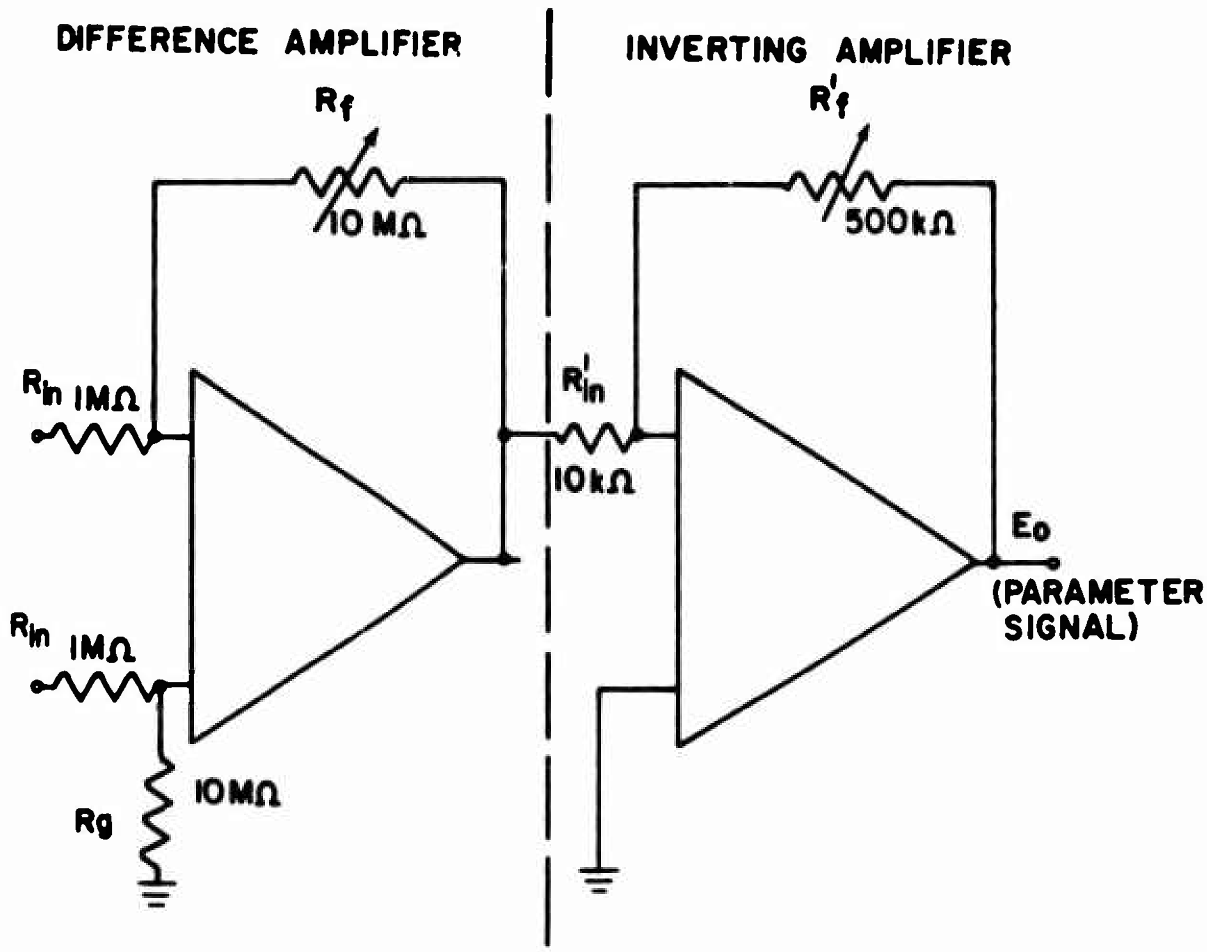

Figure 4. Current signal circuit.

Since the maximum output of the shunt installed on the equipment is 50 mV, it requires high amplification for compatibility.

The maximum voltage output of the current parameter circuit is

$$E_o = 50 \times 10^{-3} \times 500 = 25 \text{ Vdc} \qquad \text{[Eq 19]}$$

By adjusting the two feedback resistors, the output can be brought into the range of 5 to 10 Vdc. If the current parameter circuit is adjusted to a gain of 100 and the drop across the shunt is 25 mV with an arc current of 250 amp, then the output is 2.5 Vdc. In other words, every volt of output represents 100 amp.

Travel Speed Circuit

The travel speed conditioning circuit (Figure 5) consists of an amplifying and a rectifying section. A difference amplifier identical to that in the current parameter circuit is used to amplify the input signal (tachometer output). The total amplification is then adjusted by the variable resistor (R_f). The rectifying section converts the ac voltage input to a dc voltage output (E_0).

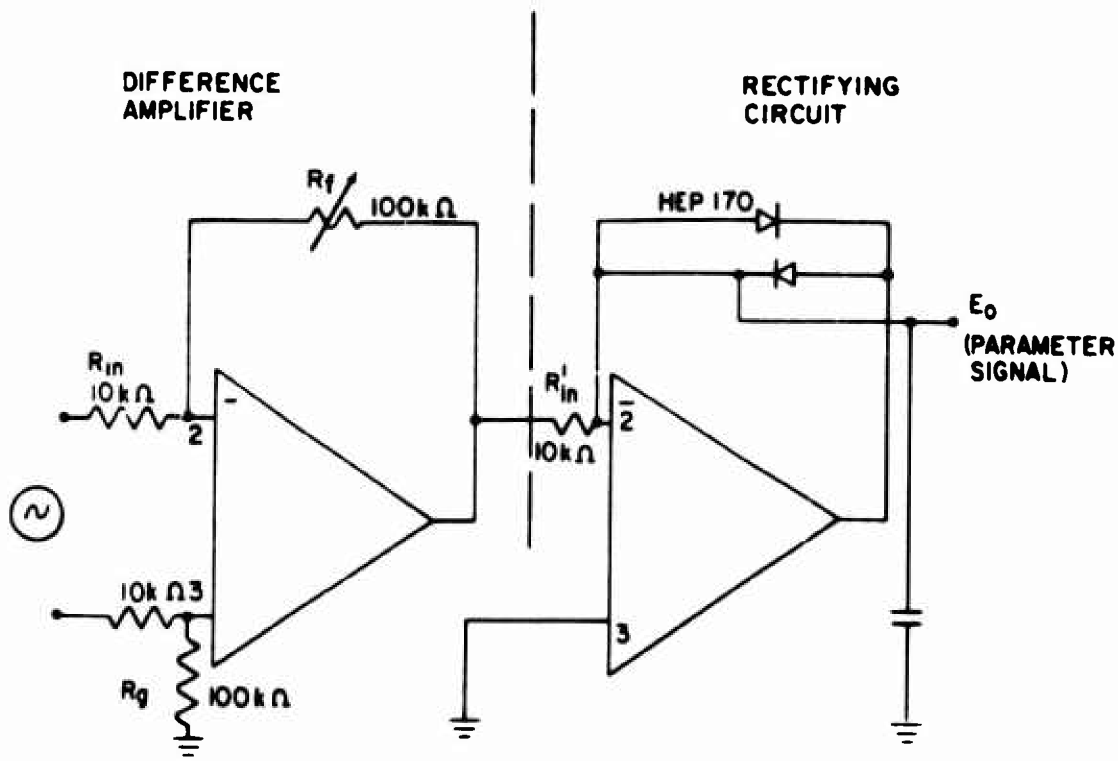

Figure 5. Travel speed circuit.

Analog Computation Module

Calculation of heat input and nugget area requires performing analog operations (multiplication, raising to a power, and division), as shown in Eq 1 and 3 in Chapter 2; these operations can be performed by the 433J Programable Multifunction Module manufactured by Analog Devices. This module is extremely versatile due to implementation of the transfer function (e_o):

$$e_o = \frac{10}{9} V_y \left(\frac{V_z}{V_x}\right)^m \quad .2 \leq m < 5.0 \qquad \text{[Eq 20]}$$

where $V_{x, y, z}$ = independent voltage inputs.

Figure 6 illustrates the heat input computation circuit showing the conditioned input signals, the programable module (type 433J), and the conditioned output to the comparator.

Comparator Module

The comparator module compares the parameter signal (conditional primary signal or computed output signal from the analog module) with preprogrammed high and low control limits by means of a master channel assembly. This master assembly contains six subassemblies or channels (Figure 7), each consisting of two op-amps in parallel with high and low limit inputs for comparison. If the input signal is within the preset limits, the diodes (D1 and D2) block current flow. If the input signal exceeds the upper limit or falls below the lower limit, the diodes permit a potential to exist at the base of the transistors. The transistors then act as switches for the signal lights which indicate input voltages outside the design limits.

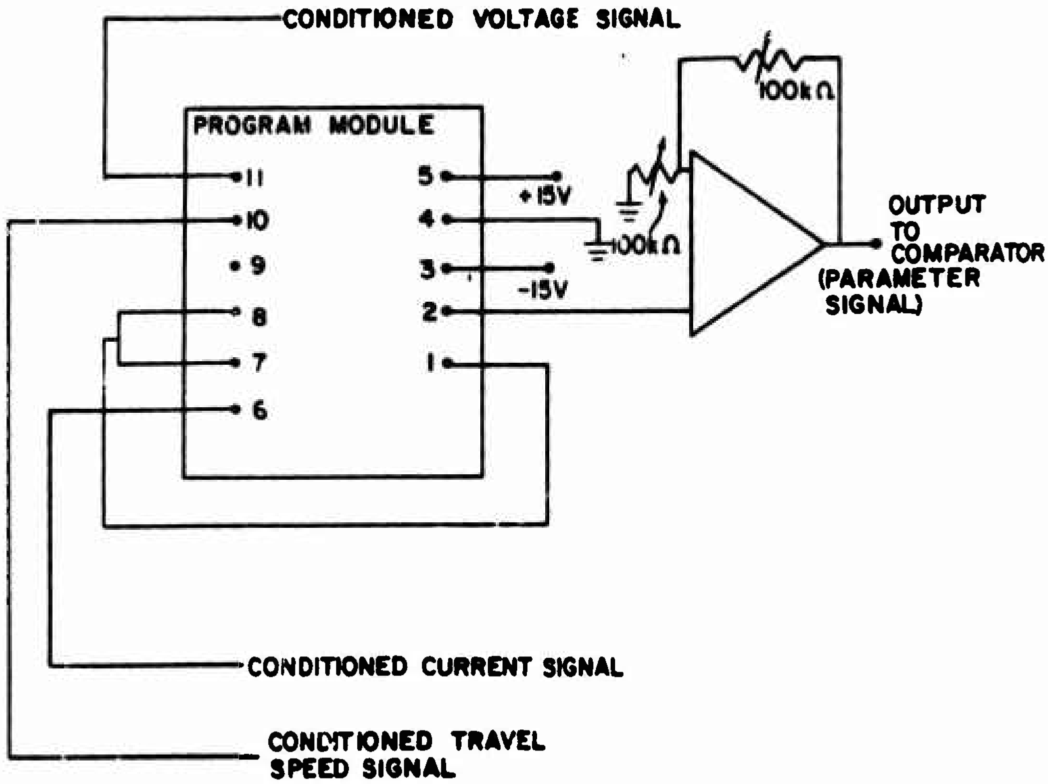

Figure 6. Heat input computation circuit.

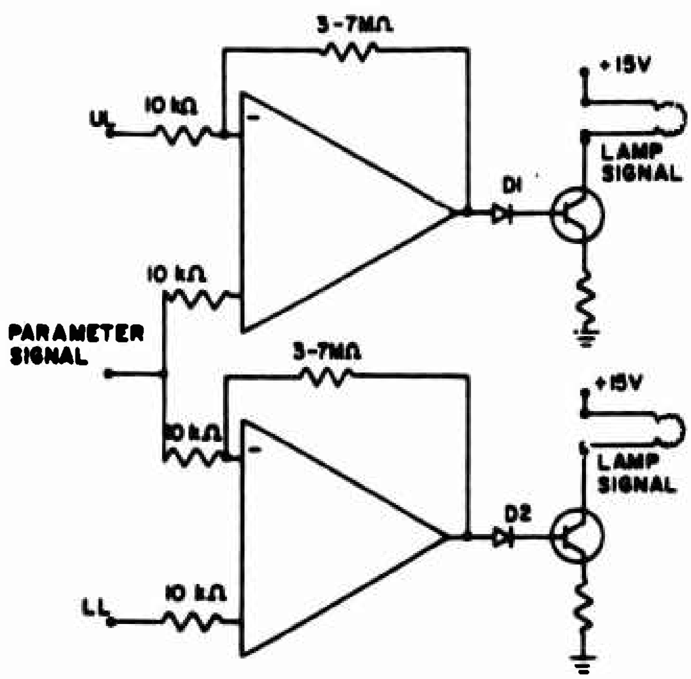

Figure 7. One channel of the comparator module.

Control Limit Preprogramming Module

The control limit preprogramming module provides the limits for the comparator module. It consists of an array of 12 variable resistors (potentiometers) grouped into six pairs of preset potentiometers (Figure 8). The control limits are set by adjusting the potentiometers while monitoring the set points with a voltmeter; potentiometer VR_L is adjusted for the lower limit and VR_H for the upper limit.

One of the most important features of the signal-sensing assembly is that the upper and lower limit settings are totally independent of each other and can be set at any value between 0 and 15 V, thus providing a high degree of flexibility.

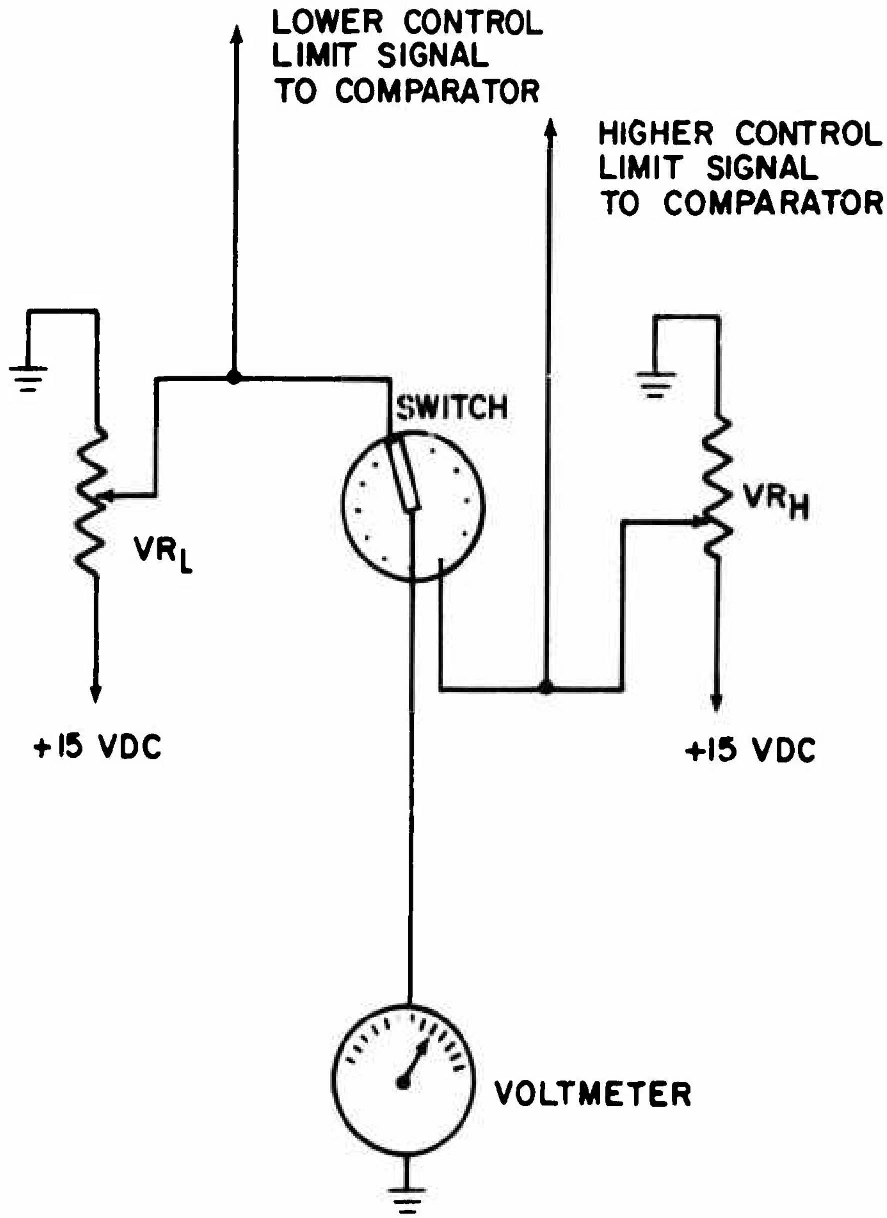

Figure 8. Diagram of one preprogrammed upper and lower limit signal circuit.

4 PRELIMINARY TESTING

Procedure

After assembly of the monitor, each channel was individually tested with a simulated signal similar in current and voltage level to the primary signal from the welding machine. The limits for each channel were set, and the test voltages were varied to simulate changes in the primary signals. When the lights indicated that the limits had been exceeded, the test voltage was compared to the limit to check the accuracy of the comparator circuit.

After each channel had successfully been tested individually, the three simulated primary signals were fed into the monitor simultaneously. The limits were again set and the input voltages varied. All circuits were checked for accuracy and proper functioning.

The monitor was then connected to the welding machine voltage output to test the circuitry with an actual voltage signal. After the limits were set, a welding arc was established on a test plate. During the weld pass, the arc voltage was varied to exceed the preset limits.

Results

Results of the preliminary testing using simulated primary signals showed that all channels performed satisfactorily, both independently and in conjunction with the other channels. The warning lights were triggered when the input signal exceeded the limits set by the reference signal, and no difficulties were encountered when the reference signals were increased or decreased.

Preliminary testing of the monitor on the automatic welding machine using the arc voltage channel was satisfactory. The arc voltage was raised and lowered to the limits, and the proper warning lights were triggered.

While investigating the outputs of the three parameters, it was found that the voltage and amperage signals were not smooth and contained many spurious signals. The amperage signal contained more spurious signals, which appeared to be directly related to the shunt. The two approaches to removing these signals are (1) to incorporate filters on the lines to remove the peaks and smooth out the signals, thus reducing the chance of damage to components, and (2) to replace the shunt as the amperage signal source with a Hall effect device. The advantage of this device is that it is not directly connected to the welding cable as the shunt is; instead, it fits around the cable and measures the magnetic field generated by the current passing through the cable. This device, which will be incorporated in the monitor, should minimize all amperage transient signal problems.

5 SUMMARY AND FUTURE WORK

An operational prototype weld quality monitor was fabricated and tested with simulated input signals and actual arc voltage signals from an automatic welding machine. The results of the testing were satisfactory, with all channels functioning properly.

The next step in the testing of the monitor will be to tie in the amperage and travel speed signals, and test these channels and the analog computation module with actual signals from a welding machine. A method of measuring the travel speed in a manual operation will be developed concurrently.

At the conclusion of the preliminary testing, the improvements suggested by the testing program will be incorporated in the monitor in preparation for field testing. Results of current research on the weldability of construction materials will be used to set the parameter limits for the various steels before field testing.

REFERENCES

Dorschu, K. E., "Control of Cooling Rates in Steel Weld Metal," *Welding Research Supplement* (February 1968).

Shultz, B. L. and C. E. Jackson, "Influence of Weld Bead Area on Weld Metal Mechanical Properties," *Welding Research Supplement* (January 1973).

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