Arc welding process control

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In this paper a close loop control system of welding arc and weld pool quality developed at Tsinghua University is introduced. It consists of three parts, namely, adaptive control of pulse MIG/MAG welding, penetration control of the weld bead and automatic seam traking. Principle of operation, special features and experimental results are described.

What is "process control"?

Welding is now used for the fabrication of the most critical industrial products in the world, e.g., nuclear power plants etc. As it is known that slightest leakage of the system will result in catastrophe for humanity, great efforts are being made now a days in the world for automation of the process in order to ensure the quality of the weld and productivity. Among various automatic welding machines the most advanced one is robot welding systems. But from the viewpoint of control engineering the robotic welding is in fact an open loop control system (see Fig.1). The function of the robot is mainly control of the movement of the arc torch according to the predetermined requirement of the trajectory, welding parameters and torch angle. Attempt is now being made in improving the adaptability of the torch movement to the actual seam path of the workpiece, which may be different from piece to piece and deformed due to heat distortion during welding. In the past ten years the author has concentrated his efforts in developing a close loop control system for the quality of arc and weld pool. The idea may be illustrated as Fig. 2. Loop 1 is designed for arc control. Loop 2 is designed for weld pool quality control, specifically, penetration of the bead. Loop 3 is designed for automatic seam tracking, in which the arc itself is being used as a sensor. The close loop control system with the arc and weld pool as the controlled objects is called by the author as "Arc Welding Process Control" or simply "Process Control". Process control will be one of the most important subjects of research in the forthcoming decades for improving quality and automation of arc welding process.

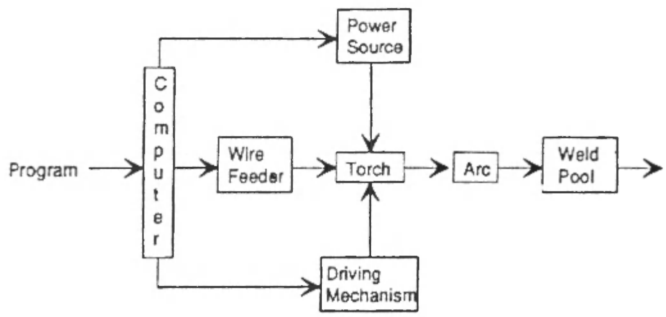

Fig. 1 : Robotic welding system.

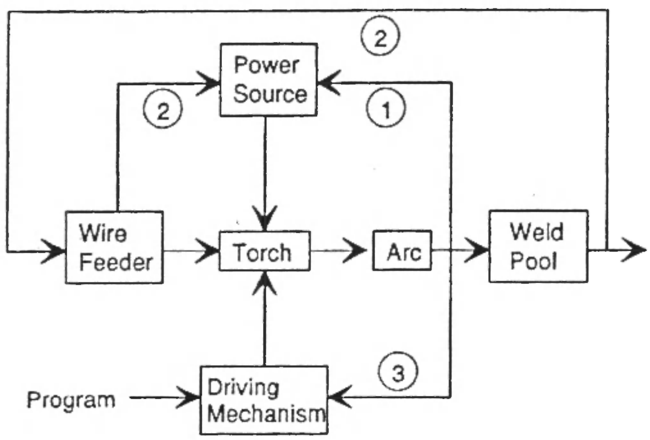

Fig. 2 : Close loop control of arc welding process.

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Adaptive control of pulsed MIG/MAG welding

For many years it has been acknowledged that only the power source with drooping or flat output characteristics can be used for arc welding. The arc should have sufficient capability to adjust itself in case arc length is disturbed by any accidental factors, e.g. unstable handling of welding torch, fluctutation of wire feed rate etc. In this regard flat output characteristic is superior to drooping characteristic. But in view of stability of metal transfer and thus quality of weld the drooping characteristic is more favourable. No compromise can be found and no other type of output characteristic has ever been used. To breakthrough the traditional principle of welding arc control an original concept, named QH-ARC adaptive control, was formed and studied at Tsinghua University [1, 2, 3]. Real time parameters of the arc are feed back to the power source which respond on it and changes the type and shape of output characteristics adaptively so as to achieve the most ideal condition of the arc.

Principle of Operation

Multi segmental output characteristic

The adaptive control of pulsed MIG/MAG welding arc is realised by means of transistorised power source having multisegmental output characteristic with a scanning slope, see Fig. 3. The function of each segment may be described as follows : a-the open circuit voltage point, and be-the segment for controlling background current amplitude. It is slightly inclined to the vertical axis. This means that the higher the arc voltage or the longer the arc length, the greater the current during the background duration - a factor important for stabilising the arc burning. The cd is the segment for controlling movement of arc operating point and in turn the arc length. Its slope is larger than that of voltage- ampere characteristic of the arc. The arc operating point cannot be kept stable on this segment, but the speed of the movement is not fast enough to perform the prompt jump from point c toward d, or vice versa. Indeed, this segment on the static output characteristic does not appear during the actual welding process because it scans all the time. The function of this segment and its scanning action are discussed next. de is segment for controlling pulse current amplitude; and ef and fg are segments for adjusting the short circuit so as to ensure the reliable ignition of the arc.

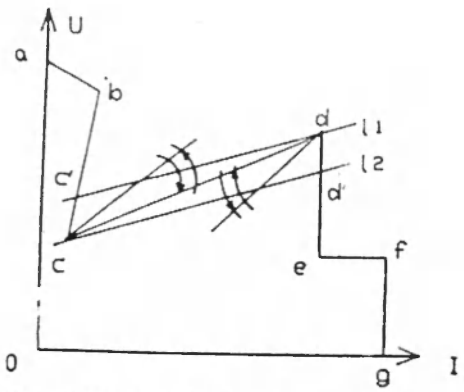


Fig. 3 : Output characteristic of power source - Adaptive control.

Scanning output characteristic

The specified scanning output characteristic (Fig.3) is utilised to direct the arc operating point to leap promptly between the pulse and background current levels. it was proved that the moving speed of the arc operating point depends on the difference between the slope of output characteristic of the power source and that of the voltage ampere characteristic of the arc, in case the former is greater than the latter. The larger the difference, the faster the movement will be. Hence, the segment cd is designed with the capability of scanning around the pivot at either point c or d, i.e., its slope change in a certain way under certain condition.

Assume that the arc operating point c' .goes downward and reaches the intersection of segments bc and cd, i.e., point c. The segment cd scans swiftly around the pivot c in a counter clockwise direction at first to form a large slope, making arc operating point jump off from c. Then it scans back to the static output characteristic position in a clockwise direction and the arc operating point is seized at point d'. Similarly arc operating point goes now upward from d' and touches the transient intersection of segments cd and de, and then it scans around the pivot d swiftly in a counter clockwise direction first and clockwise direction afterward. During this, the arc operating point jumps promptly from d to c'. In such way the process repeats itself automatically durıng welding. Figure 4 shows a trajectory of the arc operating point jumping between pulse and background level taken by cathode oscillograph.

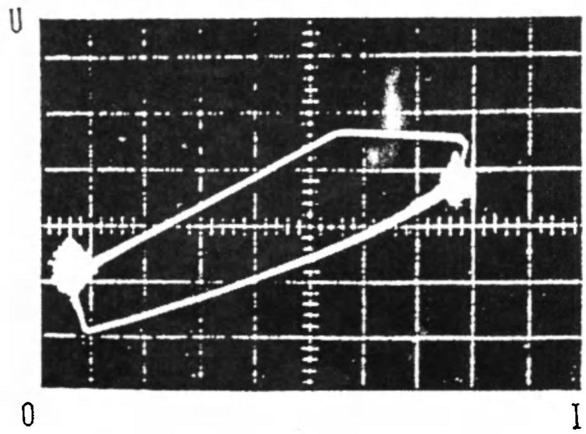


Fig. 4 : The trajectory of arc operating point.

Automatic arc length control

The multisegmental output characteristic itself possesses the effect of automatic control of arc length, see Fig. 3. Suppose that the arc length is l, and the arc operating point is at c'. Since the background current at this stage is very low, the arc keeps on burning without any metal transfer. The arc length and arc voltage tend to decrease meaning the arc operating point c' tends to go downward to c. Once it reaches the intersection bc and cd, i.e., point c, the arc operating point jumps promptly to d' under the scanning action. The welding current now becomes very high, so that spray-mode transfer occurs and the arc length is gradually increased. Upon reaching the intersection of segment cd and de, i.e., point d, the arc operating point jumps promptly back to c' under the scanning action. These processes automatically repeat between pulse and background levels so that the balance of wire feed rate with its melting rate is maintained and thus, the arc length is kept between l_1 and l_2 which has a difference of only a fine droplet diameter.

Special features

- The arc can automatically determine its pulse and background duration in accordance with the realtime value of arc length. Hence, it can quickly respond to any variation of wire feed rate or any kind of arc length disturbance to ensure a stable arc with minimum spatter.
- The arc length is kept at predetermined value, which can be adjusted by changing the parameters or, in other words, the position of point c and slope of cd.
- During the pulse period, metal transfer proceeds under a constant current condition, and the magnitude is determined by pre-setting the parameters of segment de. Therefore, the optimum spray transfer mode can be easily obtained.

Above mentioned points were verified and confirmed by high speed films.

Welding technology

Welding procedures have been conducted with 1.0, 1.2 and 1.6 mm diameter wires in Ar-rich mixed gas or pure Ar gas. The welded metals include mild steel, low-alloy steel, stainless steel, Al and Al-alloy, Cu and Cu-alloy. Experimental results may be summarised as follows :

- Spray transfer arc can be obtained over a wide range of welding current for almost all kind of metals. For example, the usable range of welding current for mild steel is 45-220 Amp. for 1.0 mm diameter, 60-320 Amp. for 1.2 mm diameter and 80-360 Amp. for 1.6 mm diameter wire, respectively.
- As the system automatically regulates the welding parameters, so the system is controlled by operating one knob. It is necessary for the operator only to regulate wire-feed rate, then all the pulse parameters will be automatically optimised.
- To take advantage of the dynamic property of the control system, pulsed wire feed GMAW technique, was developed by the author. The wire feed rate may be programmed according to the needs of the weld quality control and a stable spray metal transfer can always be obtained.

Above mentioned system was patented in USA and China and applied in industry for production and marketing.

Penetration control

Weld pool quality control is the most important but difficult problem in the automation of arc welding. According ot statistics, among all weld quality problems insufficient penetration is one of the most common defect, 80% of the rejects in the petroleum pipe and small diameter pressure vessel production are due to insufficient penetration. The following introduces a close loop penetration control system for GMAW developed at Tsinghua University [4,5].

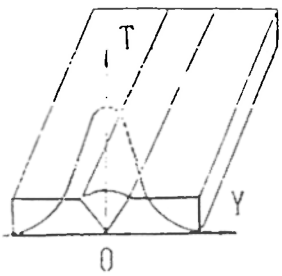
The system consist of three major parts, an adaptive controlled power source, wire feeder and sensing system for weld pool penetration (see Fig. 5). As described in above paragraph, the adaptive control power source has advantage of high dynamic response to arc length disturbance. Taking advantage of this power source to vary the wire feed rate, one can vary the heat input to the weld pool and thus its penetration. In order to obtain high dynamic property of the wire feeder, a special system with torque motor instead of conventional DC servo motor was designed. Experimental results showed that its response to step input is reduced to 10-20 ms, instead of 200-300 ms, so that fast regulation of penetration during welding process can be achieved. The key point of the system is to develop a penetration sensor which is effective and applicable in practice. After study of number of different kinds of sensors, a linear CCD was chosen. During welding a glass fibre with optical system was put under the weld pool, a linear image of the back side of the weld pool, i.e. the temperature distribution across centre of the pool, is taken and outputs to the CCD which is mounted at the other end of the glass fibre. Signals of the CCD are then output to a computer, which processes the data and gives instruction to wire feeder for heat input control of the weld pool.

Principle of temperature distribution detection

Assume that the temperature field of a bead obeys the general rules of heat transmission theory, and the temperature distribution across back of the weld pool centre be expressed as (see Fig. 6a)

$$T(Y) = K.\exp(-\varsigma Y^2) \qquad (1)$$

The CCD image may be expressed as (see Fig. 6b)



A temperature distribution on the back side of the weld pool.

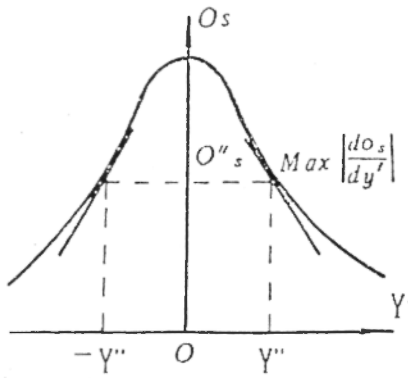


Fig. 6 : Temperature distribution across centre of weld pool and CCD output.

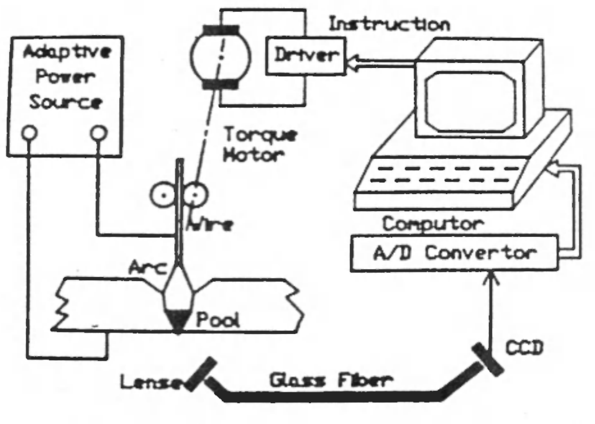


Fig. 5 : Block diagram of penetration control

$$T(Y') = K.\exp[-\varsigma(Y'.R/\beta)^2]$$

where

T - temperature
Y - abscissa on work piece
Y'- abscissa on CCD
ς,K - coefficient
R - distance between CCD and weld pool
β - magnification of optical system, which can be measured by experiment.

Actually the CCD does not receive the signals of the temperature itself, but heat or light emission of the weld pool. The relation between CCD output O_s and the temperature may be derived as

$$O_s = K_c . \exp[-C_2/\lambda_o . T]/R^2 + D$$

K_c - constant, which may be derived from experiments

C - constant, from Stenfen-Bolzamn equation

λ_o - average wave length of optical filter

D - noise signal due to background light

Therefore in order to obtain information about temperature field, mathematical derivation has to be made. Assume that the relation of CCD outputs O_s and its abscissa Y' be expressed as shown in Fig. 6b. It can be proved that there are two, and the only two, symmetrical points $\pm$ Y' on the abscissa Y' where O_s/Y') take maximum value. Then the following relations may be found

$$F = / O_s/Y'/_{max.}/Y''/O'_s \qquad (4)$$

$$F = 1 + 2\varsigma(Y''R/\beta)^2 \qquad (5)$$

$$T'' = C2(F-1)/lo.F) \qquad (6)$$

where O_s" is CCD output at $\pm$ Y". From these equations one can derive K, ς, R and the full picture of temperature distribution across the weld pool. Direct measurements with theremocouples were conducted in order to compare with the results obtained from computer. Coincidence of them proved correctness of the theoretical analysis of the sensing system.

Control system

Degree of penetration is then assessed by the computer according to the width of the bead where temperature is above melting point. According to experimental results the penetration responds to welding current as a first order lag process plus dead

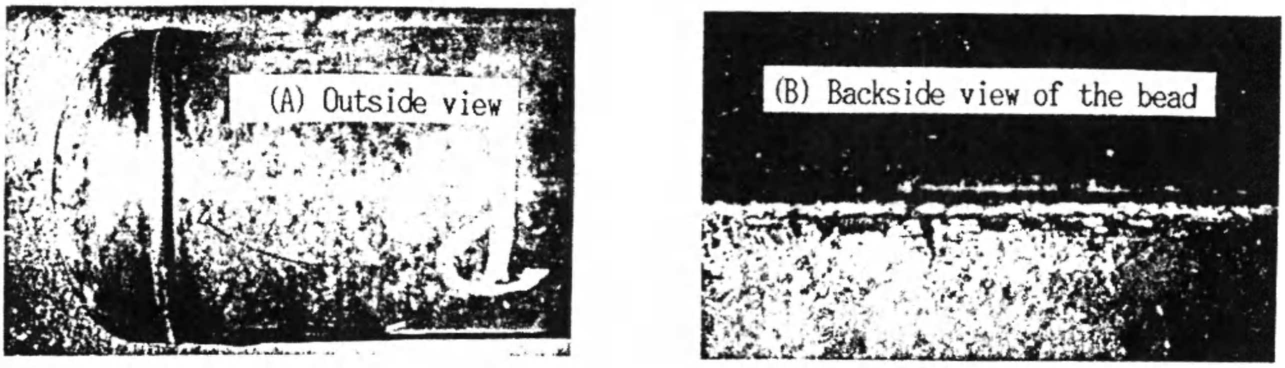


Fig. 7 : Product welded with penetration control system

time process. Therefore a feedback control system with non-linear controller of on-off relay type was designed to achieve the best result. Welding was then carried out in practice. Percentage of insufficient penetration was reduced to almost zero, see Fig. 7.

Automatic Seam Tracking [6,7]

Principle of operation

The system was developed on the basis of welding arc sensor. As it is known that the the torch to workpiece distance of two parts, i.e. wire extension and arc length, when the torch to workpiece is varied the arc length changes according to characteristics of the welding system. Therefore to oscillate the torch across the groove of the weld, arc length varies in relation with the groove shape. To record the parameters of the arc during oscillation of the torch, one can obtain the information of the relative position of the torch with the centre line of the weld path and thus realise the feedback control of movement of the torch during welding.

Welding arc sensor

The welding torch is hung on a ball bearing and driven by a motor via a pair of gears, see Fig. 8. in the centre of the gear there is an eccentric hole which the welding torch passes through. Therefore the torch performs a conic rotation while the gear rotates. Eccentricity of the hole is designed to be adjustable, so that the angle of the cone or the diameter of the rotation of the arc may be regulated according to the requirement of welding technology. Together with the gear an encoder is mounted, on which a single hole is made on the inner circle, for detection of the relative position of the torch with the axis of groove line, 90 holes are made on the outer circle evently for detection of the angle of rotation. Two pairs of infrared ray emission and receiving devices are mounted above and under the holes, so that the angle and relative position of the torch tip with regards to the groove line can be determined while parameters of the arc are detected. A F/V converter device is connected with the photoelectric circuit in order to obtain the signal of the real time rotating speed of the torch. In present design the rotating speed of the arc may be regulated from 0-3000 RPM. Rotation diameter of wire tip may be regulated from 2-8 mm.

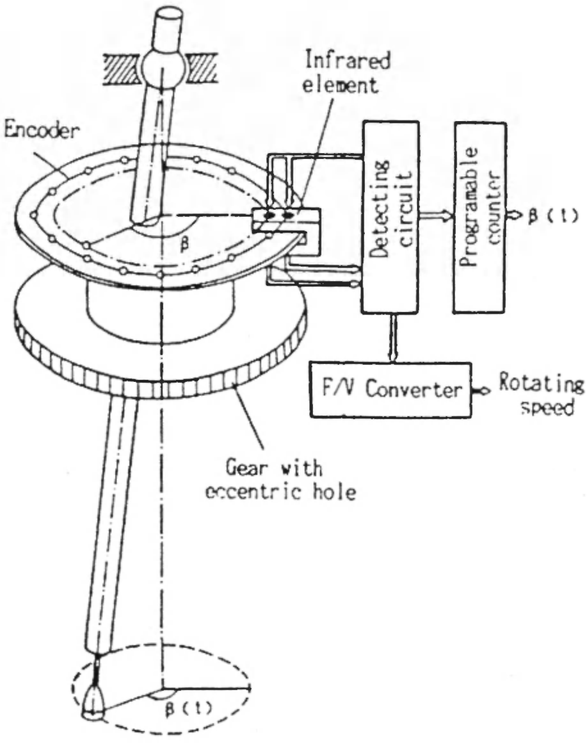


Fig. 8 : Structure of arc sensor.

Physical-mathematical model of arc sensor

The physical model of the welding arc sensor may be presented as shown in Fig. 9 where H is torch to work distance, L_s is wire extension, L_a is arc length, U_s is voltage drop on wire extension, U_a is voltage of the arc, U is voltage drop across H, V_f is wire feed rate and *I* is welding current. Obviously, the input signal of the system under discussion is H and output signal of the systems I. In order to derive the mathematical model of the system, state equations of the system should be eatablished. Assume the welding power source has a straight but dropping output voltage of power source can be written as

$$U_p = U_o - K_d I$$

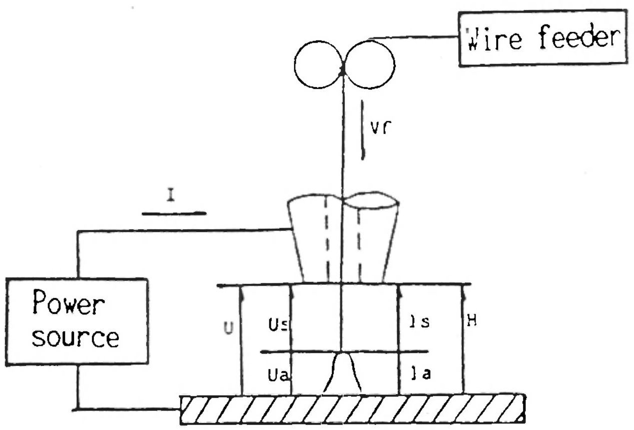


Fig. 9 : Physical model of arc sensor.

where U_o is open circuit voltage of the power source and K_d is drooping slope of the output characteristics. Voltage U across H is

$$U = U_a + U_s \quad (8)$$

and voltage drop on wire extension U_s is

$$U_s = K_s \cdot L_s \cdot I \quad (9)$$

where K_s is specified linear resistance of the wire. Arc voltage can be written as

$$U_a = K_a L_a + K_p I + U_c \quad (10)$$

Where K_a is gradient of voltage drop in arc, K_p is equivalent resistance of the arc on cathode and anode and U_c is constant. The melting rate of the wire V_m may be expressed as

$$V_m = K_m I + K_n I^2 L_s + C_m \quad (11)$$

where K_m, K_n, C_m are constants. For the stability of the arc length, the following condition should be satisfied $\quad V_m = V_f \quad (12)$

Take Laplace transform of above equations and simplify them, the transfer function representation of the system may be expressed as

$$G(s) = I(s)/H(s) = \frac{K_a(s + K_r).P(s)}{[1 - K_n P(s)]s + K_q \cdot P(s) + K_r} \quad (13)$$

where K_r, K_n, K_q are constants. P(s) is transfer function of dynamic property of the power source. Experiments were conducted to verify the theoritical analysis with a transistorised power source having the transfer function

$$P(s) = I(s)/U(s) = \frac{P_o}{[1 = T_p S]} \quad (14)$$

where P_o is constant and T_p is time constant. The experimental results together with the theoretical curve are plotted in Bode diagram as illustrated in Fig. 10 which shows excellent consistency between them. The derivation of the physical- mathematical model of the arc sensor will be of great significance for further development of the arc sensor.

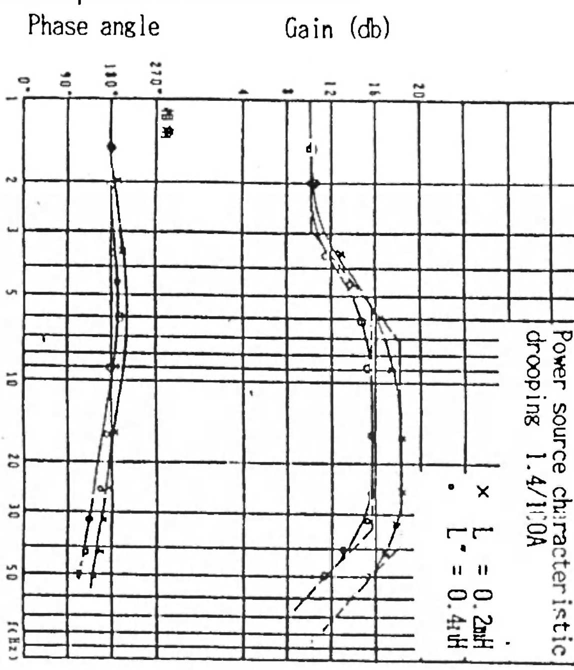


Fig. 10 . Bode diagram for arc sensor. Wire diameter 1.0 mm, shielding gas Ar + 10% CO_2.

Control system

The block diagram of the seam tracking machine is illustrated in Fig. 11. Two servo motors are used to drive the welding torch or arc the sensor along horizontal and vertical axes to adjust its position. A single microcomputer 8031 of MCS-51 series is used for control of the system, see Fig. 12.

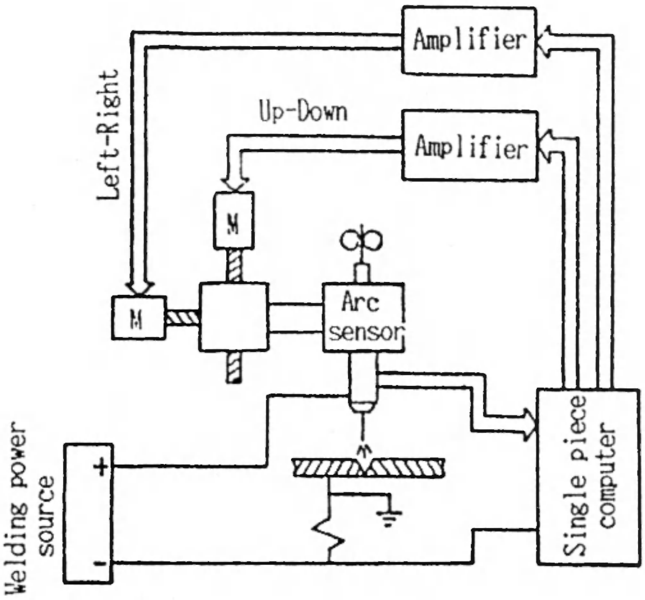


Fig. 11 Seam tracking system with arc sensor

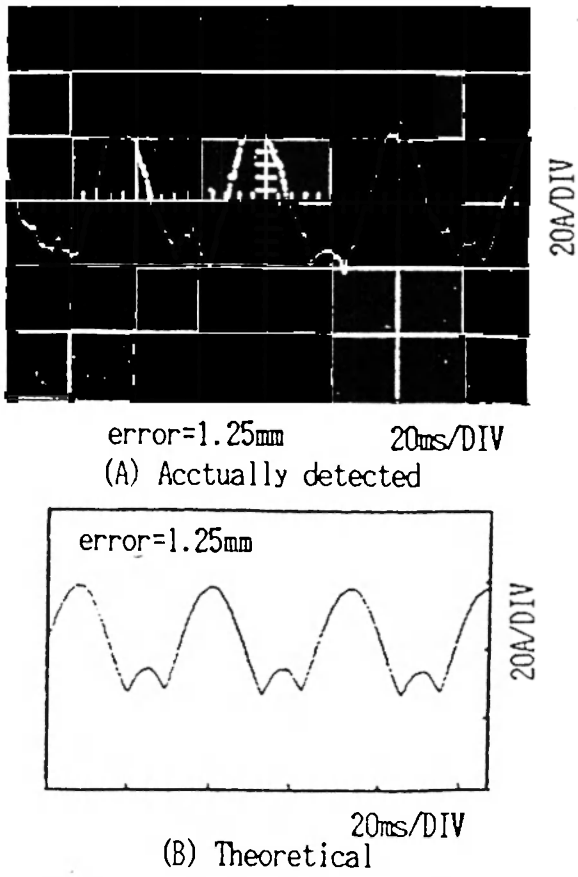


Fig. 13. Waveform of welding current detected by arc sensor.

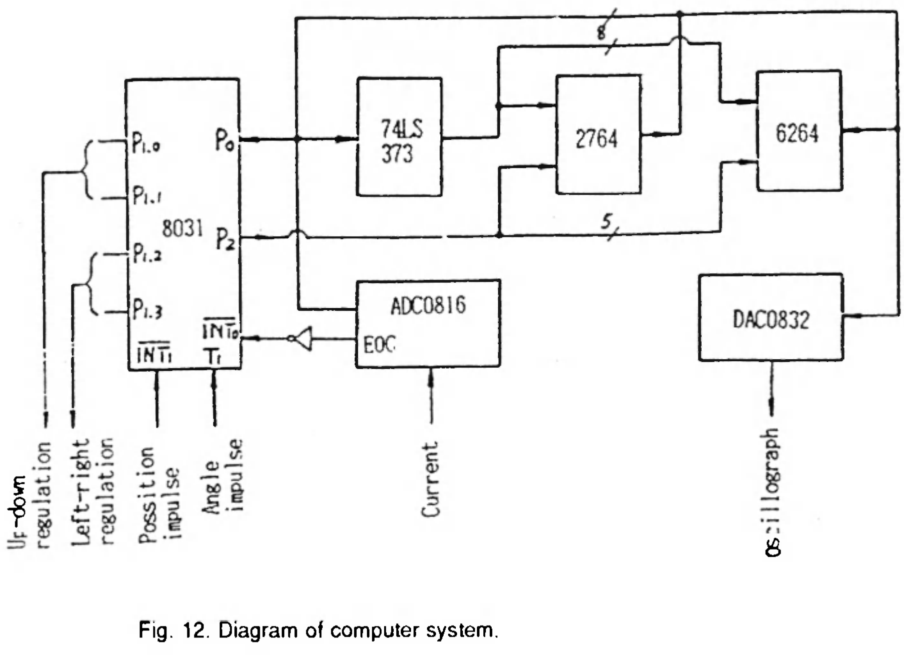


Fig. 12. Diagram of computer system.

There are three inputs to the microcomputer. The first is "position impulse" from encoder of the arc sensor which tells the computer relative angle position of the arc to the weld pool, one impulse is generated for one rotation of the sensor. The second is "angle impulse" which tells the microcomputer the real time rotating angle of the sensor.

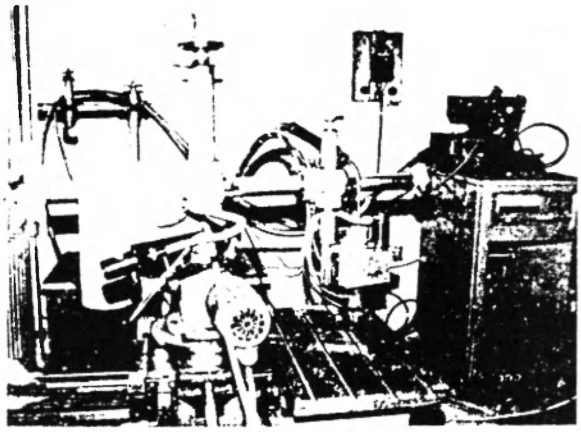


Fig. 14. Outside view of welding machine

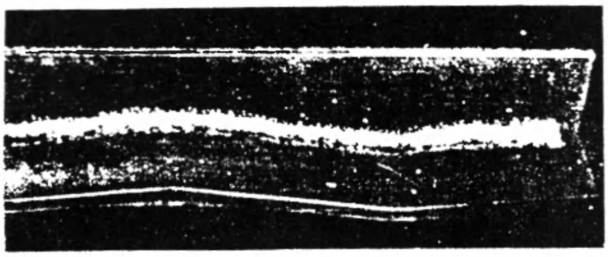


Fig. 15. Zig zag seam welded with automatic tracking system.

90 impulses are generated per one rotation of the arc. These two signals are used in the computer for triggering of the sampling of the welding current and measuring the rotation speed of the arc. The latter is used for feedback control of the arc sensor motor. The third input is the welding current. There are four outputs from the computer. The first is form $P_{1.0}$, $P_{1.1}$, for control of three verticle movement of the torch. The second is from $P_{1.2}$, $P_{1.3}$, for control of the horizontal movement of the torch. The third is the measured rotating speed of the sensor used for feed back control of its servo motor. The fourth is data calculated by the computer which may be used for the purpose to display them on the cathode oscillograph.

Waveforms of the welding current recorded during rotation of the arc are different from each other for different weld groove shape and depends on many technological factors. Large amount of experiments were conducted by the author in order to set up recognition models of the groove shape and its position. Figure 13 shows actually recorded and theoritical current waveform for V-groove butt joint when the error is 1.25 mm. For different groove shapes, different arithmetic and logic methods should be adapted. For example, for V-groove joint integration of the welding current data is carried out separately for both sides of the arc while it swings along the front half circle. The difference of these two integration values is used for control of the horizontal movement of the arc and some of them is used for control of the vertical movement of the arc. Filtering of the digital data of the welding current should be processed first for increasing the signal-noise ratio. The outside view of the machine is shown in Fig. 14. The experimental results of the system is shown in Fig.15, the seam has a zigzag path of $\pm$ 15^{o} inclination in both vertical and horizontal plane. It can be seen that quality of the system is excellent.

CONCLUSION

The idea of segmental and scanning output characteristics is not only a way for realisation of pulse GMAW process, but more significant, it broke through the traditional principle of welding arc control and provided a broad way for developing various new welding arc control methods in the future.

Quality control of the weld pool is an important but difficult task in the future for furthering automation of arc welding process. Penetration control is an achievement in this field which is very useful in industries.

Welding arc sensor is one of the most prospective sensor for seam tracking of automatic welding machines. Design of the welding arc sensor and theoretical analyses of its dynamic properties presented in this paper are original which is helpful for further advancing this technique.

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