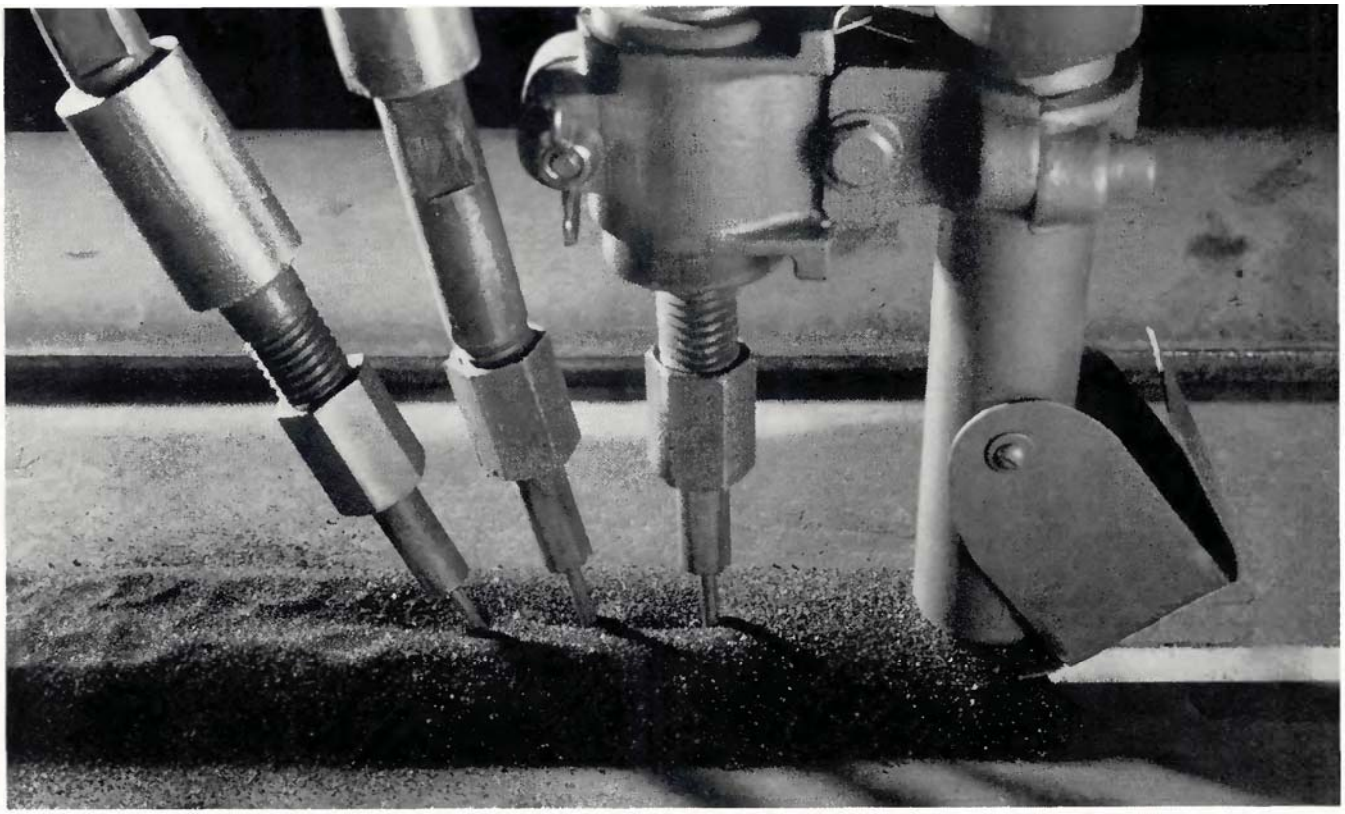

Three-wire submerged-arc welding under way, with motion from left to right

Three-Wire Submerged-Arc Welding of **Line Pipe**

can be carried out at speeds up to 125 ipm on 0.289 in. pipe wall thicknesses using all a-c current instead of d-c current which produces severe arc blow

BY G. D. UTTRACHI AND J. E. MESSINA

Multipower submerged-arc welding has been known for at least 15 years. One of its earliest applications was in the manufacture of carbon steel line pipe from formed plate where high rates of speed are required to economically join the abutting longitudinal edges. A two-pass weld is required for this joint. One weld is made on the inside and the other on the outside of the longitudinal joint. The weld requirements are very stringent. Welds must be free from porosity and cracks as determined by X-ray according to API specifications. Joint penetration must be complete with a minimum amount of reinforcement. The weld surfaces must be free from defects such as undercuts.

Many pipe mills in this country are currently using two-wire submerged arc welding for pipe fabrication. Two wire (or electrode), three phase a-c power systems, connected in the Scott or closed Delta circuitry, provide speed increases of from $2^1/_2$ to 3 times those achievable with a single wire. The Scott and closed Delta systems are also used because of their ability to control arc interactions and arc blow. They provide controlled forward arc deflection of the trail electrode by producing a phase shift between lead and trail electrode currents. A forward deflecting arc is known to allow increased welding speed before undercutting occurs.

The two wire or electrode systems, however, reach a maximum welding speed beyond which satisfactory welds cannot be produced since weld undercutting occurs and over-all weld shape deteriorates. These weld shape problems are further aggravated by the higher welding currents required to obtain the necessary weld penetration.

A method has been developed which produces high quality welds at speeds beyond the capabilities of two-wire or electrode systems. This was accomplished by adding a third a-c electrode to a conventional two wire or electrode a-c system. The utilization of all a-c power was a prime prerequisite. In a prior development effort a similar system using d-c power for one electrode produced erratic weld results when the system was used near surrounding steel structures.

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Development of Process

To increase welding speeds for a given application, it is necessary to increase the heat applied to the welding zone in some proportion to the speed increase desired. This is normally accomplished by increasing welding currents. With the three-wire system, welding currents can be increased to provide the necessary weld penetration while still providing a satisfactory weld shape. By spacing the electrodes as closely as possible, the total heat liberated from each arc is used to best advantage. This close spacing reduces the heat loss which occurs in the weld puddle between electrodes.[1] However, such close spacing, combined with high welding currents, produces a large amount of arc interaction which, if not controlled, will result in unstable operation and a poor bead shape.

The three-wire or electrode system uses a-c power on each electrode supplied by three single phase a-c transformers. The transformers obtain their primary power from a three-phase, 440 v a-c line. There are many possible ways to connect the welding transformers to the primary power lines. One particular combination was found to provide control of arc interaction at close electrode spacing. A schematic diagram of the electrical hook-up of the three welding transformers used is shown in Fig. 1. The lead and middle electrodes are connected by use of Scott circuitry. The trail electrode transformer is connected in phase with the lead transformer.*

This specific electrical connection provides welding currents which are out of phase with each other. Figure 2 shows a typical welding current trace as seen on an oscilloscope for one cycle. The lead and trail arc current are directly in phase, and the middle arc current lags both by 90 electrical deg.

The electrode arrangement and typical welding conditions are shown in Fig. 3. All three arcs are in the same weld puddle. The electrodes are spaced as close as possible while still providing stable operation. The welding currents used for each electrode are chosen to perform a particular function. The lead arc with its high welding current (1000–1300 amp) provides most of the weld penetration. The lead electrode current is adjusted to obtain the de-

* Patent applied for.

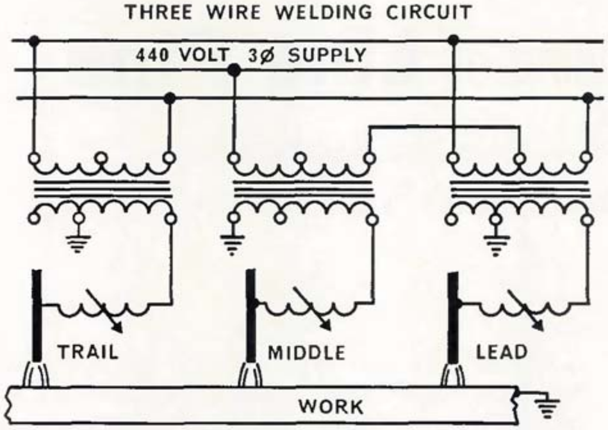

Fig. 1—Wiring schematic of a-c welding transformers used for three wire welding

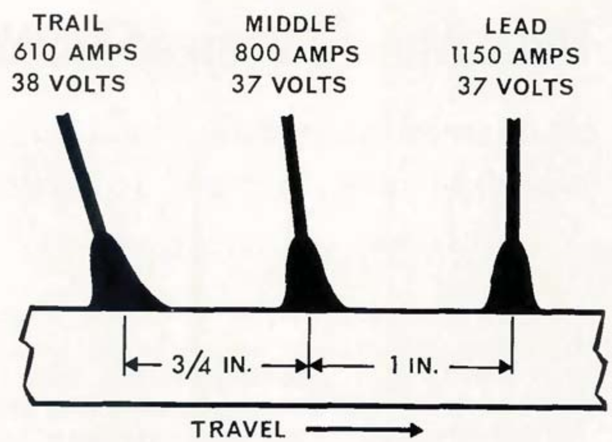

Fig. 3—Typical welding parameters and wire alignment used with three wire system

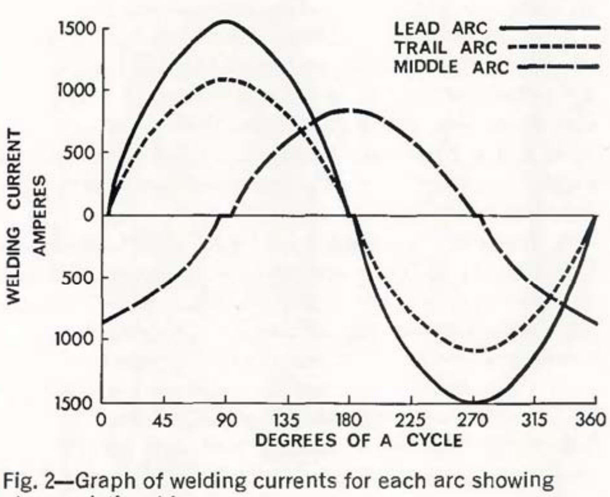

Fig. 2—Graph of welding currents for each arc showing phase relationships

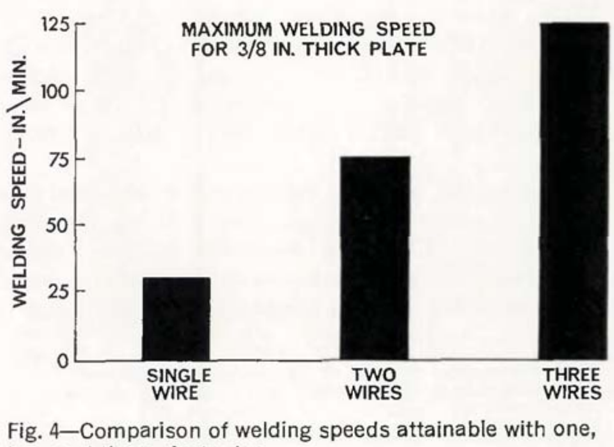

Fig. 4—Comparison of welding speeds attainable with one, two, and three electrodes

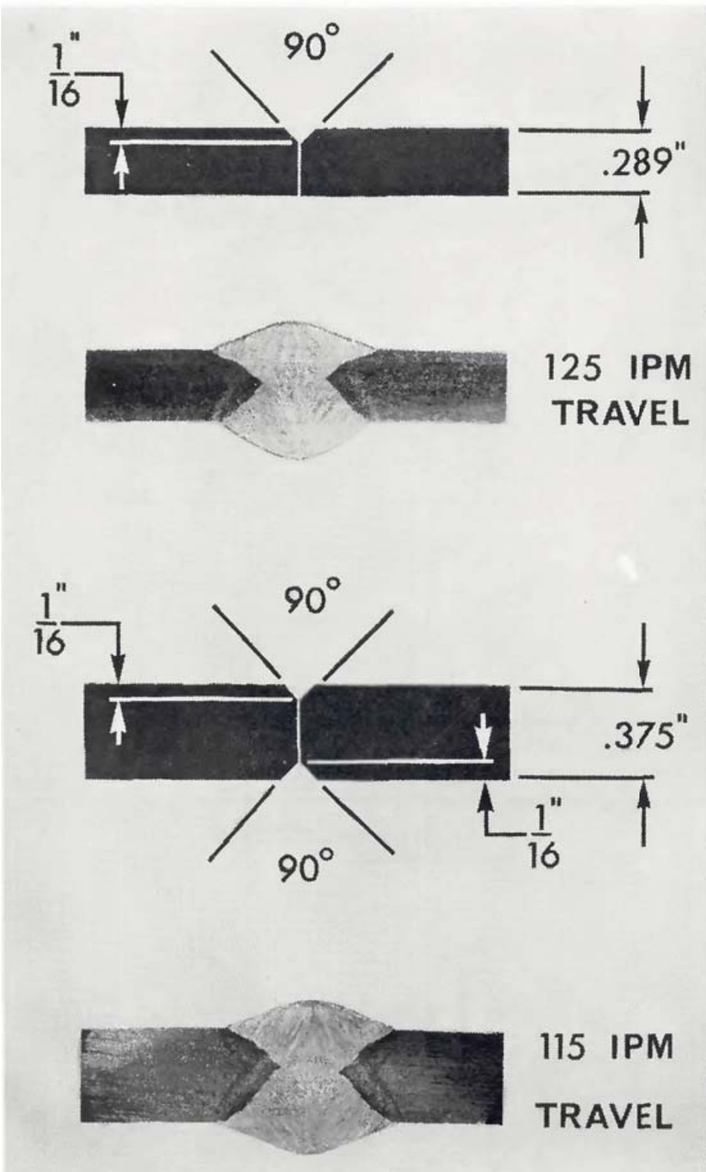

Fig. 5—Joint designs and weld cross sections for 0.289 and 0.375 in. thick plate

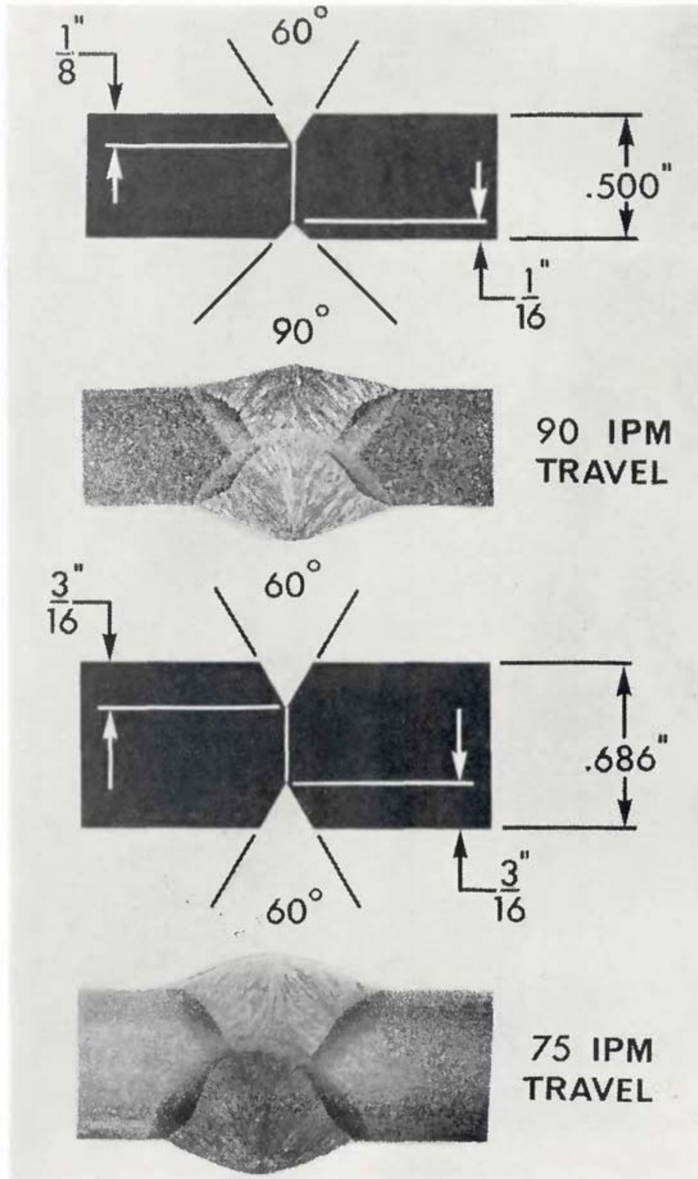

Fig. 6—Joint designs and weld cross sections for 0.500 and 0.686 in. thick plate

sired weld penetration. The middle arc adds about 15% to the penetration with its 800 amp, but its main function is to begin forming the weld bead. After the middle arc has performed its function, the weld will still be severly undercut. The function of the trail arc is to provide the final required weld shape. The third arc, operating at 400–600 amp, flattens the weld bead and eliminates undercuts. The weld shape can be altered by varying the trail electrode current.

The welding materials used are those presently employed for two wire welding. However, it has been found that the standard grade welding flux provides superior operation if it is ground to a finer sizing. The resulting weld mechanical properties are similar to those obtained in two-wire welding.

Advantages of Process

One of the most important advantages of the three wire (or electrode) welding system is to provide increased welding speeds. An example of the speed advantage derived from the use of the system on $^3/_8$ in. thick plate is shown in Fig. 4. The welding speed for the three wire system is 125 ipm; this is a fivefold increase in speed when compared with single electrode welding and a 75% increase over two wire (or electrode) Scott welds made using a standard two-wire Scott system.

It has been found that one welding condition can be used for a wide range of plate thickness by changing only the speed of welding. Welds were made in four plate thicknesses ranging from 0.289 to 0.686

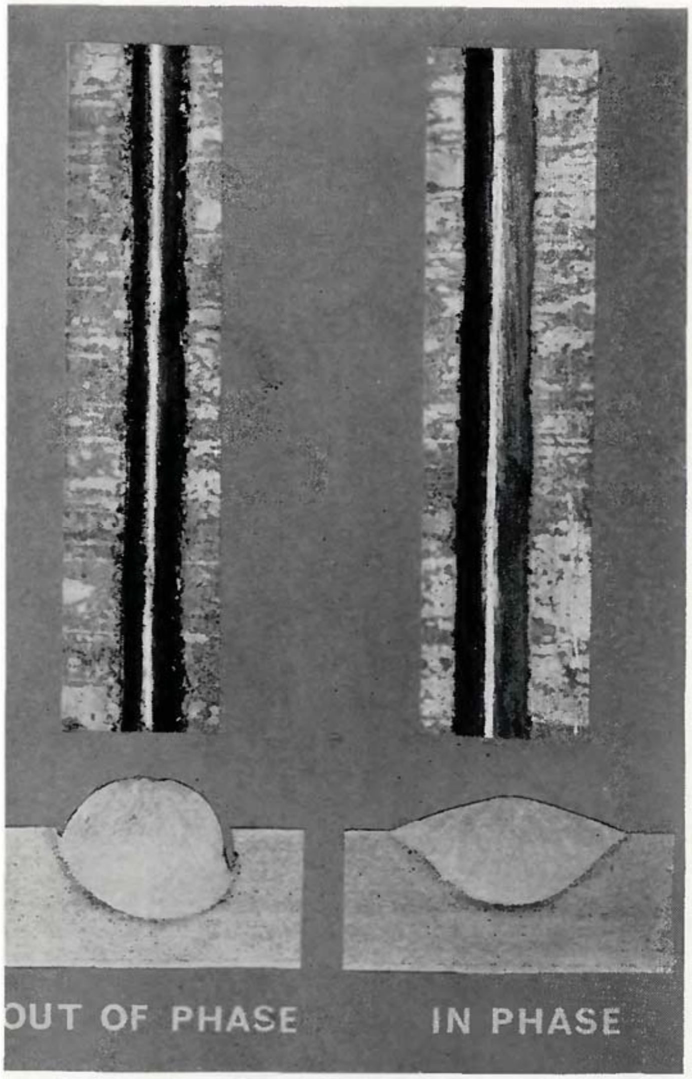

Fig. 7—Welds demonstrating the importance of transformer phasing on obtaining good weld results

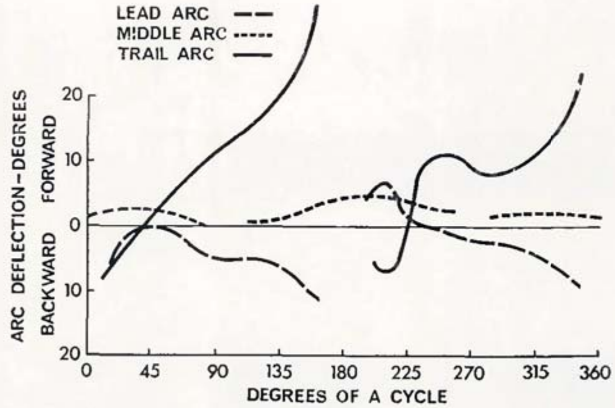

Fig. 8—Plot of observed arc deflections made from high speed motion picture analysis

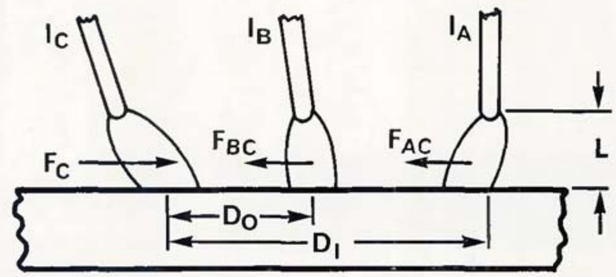

Fig. 9—Forces acting on trail arc caused by interaction of magnetic fields surrounding each arc

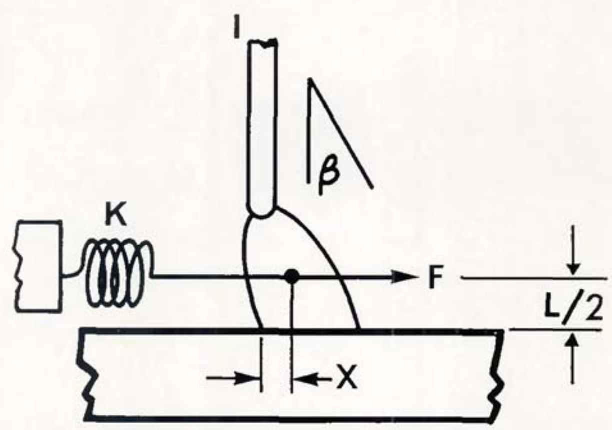

Fig. 10—Resulting effect of forces acting on an arc using spring analogy

in. The welding conditions were identical for all welds being: 1150 amp, 35 v lead arc; 800 amp, 35 v middle arc; 600 amp, 37 v trail arc. The welding speed was the only variable change and ranged from 75 ipm for the 0.686 in. thick plate to 125 ipm for the 0.289 in. thick plate. Cross sections of the four welds and the joint design used for each are shown in Figs. 5 and 6.

A bevel is used on the thinner plates to provide a means of automatically guiding the welding electrodes in the joint by using a V wheel which rides in the groove. On the thicker plates the bevel serves an additional function by providing an area for the weld metal to flow so that weld reinforcement is kept less than that allowed by specification, which is usually $^1/_8$ in.

All of the welds are completely penetrated with sufficient depth and fusion to produce clear X-rays. The weld surface is free of undercuts and reinforcement is at a minimum. In recent months this system has been used on several pipe mills with satisfying results.

Importance of Phasing

It is important to have the welding transformers phased in a particular manner to obtain the desired weld results. To illustrate the effect of improper phasing, two welds were made using identical welding conditions except for a difference in transformer phasing. Cross sections and surface condition of each are shown in Fig. 7.

The weld labeled "in phase" was made using the phasing sequence just described, with the trail arc current in phase with the lead arc current. For the weld labeled "out of phase" the trail electrode transformer was connected 180 deg out of phase with the lead electrode transformer. In other words, when the lead arc current was at a maximum positive value the trail arc current was at a maximum negative value. A drastic difference in weld shape is obvious. When properly phased, the resulting weld is flat and free of undercuts. With improper phasing, the weld becomes narrow and peaked with severe undercutting occurring.

In order to develop an explanation for this phenomenon, it was decided to study the arc action. When this was done with two wire or electrode submerged-arc systems, it was found that, when properly phased, the trail arc is deflected forward and produces superior welds.[2] To study the arc action directly (the arc normally being completely blanketed from view by the granular welding composition), the system was allowed to operate out of the welding composition in air. The welding conditions used for these tests were: 1100 amp, 35 v lead arc; 780 amp, 35 v middle arc; 600 amp, 37 v trail arc.

There was a 1 in. spacing between the lead and middle and $^3/_4$ in. between the middle and trail electrodes. The lead electrode was perpendicular to the plate, the middle electrode was inclined 7 deg and the trail electrode 14 deg in the direction of travel. Because these current and voltage values and electrode positions are equal to those normally used with welding composition, magnetic interactions would be the same as when welding composition is used. The arcs were photographed with a high speed movie camera with film speed chosen to provide approximately 5000 frames/sec or 80 frames/cycle. Examination of the films, one frame at a time, provided data on the deflection angle (from the vertical) of each arc vs. time; a plot of the deflection data indicates the amount of time spent forward or backward by each arc and the direction of sweep of the arcs.

Figure 8 shows plots of the deflection of the lead, middle, and trail arc in the three wire (or electrode) system for one complete cycle or from 0 to 360 electrical degrees. The vertical scale shows the angle through which the arcs deflect measured in degrees from the vertical both forward and backward.

Each arc extinguishes as the arc current approaches and goes through zero; therefore, the deflection is not plotted in this area. This occurs twice each cycle for each arc. For the lead and trail arc since they are in phase, outages occur at 0 and 180 deg; the middle arc, which is out of phase, extinguishes at 90 and 270 deg.

The lead arc deflects predominantly backward, reaching a maximum rearward deflection of 11 deg. The middle arc deflects only slightly with a maximum deflection of 5 deg forward. The trail arc deflects predominently forward reaching a maximum of over 25 deg. The trail arc deflection is the one which is of most concern, since this arc determines the final weld shape.

It has been shown by Hicken and Jackson[3] that a forward deflecting arc (in the direction of travel) can provide greatly increased welding speeds by eliminating undercutting. The trail arc, deflects predominently in a forward direction for approximately 75% of the cycle. It also sweeps in a forward direction starting backward and deflecting forward. It is this forward deflection and sweep which allow the use of high welding speeds before encountering undercutting.

Theory of Arc Deflection

To better understand the variables that affect arc deflection, an attempt was made to develop an equation to predict arc deflection. The equation developed provides a close approximation of the actual results.

To develop the equation the forces acting on the arc were considered. The most important force acting on the arc is the interaction of magnetic fields between the arc under consideration and adjacent arcs.

For two current carrying conductors (in this case the arcs) the force acting on the conductor caused by the interactions of the magnetic fields surrounding each is given by the equation:

$$F = B\frac{(I_A L_A)(I_B L_B)}{D^2}$$

Where I_A and I_B are the currents in the wires, L_A and L_B are the length of the conductors (arc length), D is the distance separating them, and B is a constant.

For the three wire system, as shown in Fig. 9, the force created by two adjacent arcs must be considered. Assuming all arcs are of equal length the force acting on the third arc can be written:

$$F_c = F_{BC} + F_{AC}$$

$$F_c = BI_cL^2\left[\frac{I_A}{D_1^2} + \frac{I_B}{D_0^2}\right] \quad (1)$$

where I_A, I_B and I_C are the welding currents in the lead, middle and trail arcs, respectively. The distance between the lead and trail arcs is labeled D_1 and D_0 is the distance between the middle and trail arcs.

To determine what effect this force will have on the arc the analogy developed by I. A. Bachelis[4] was used. The arc is assumed to behave as a spring, as shown in Fig. 10, and the standard spring equation is then applicable:

$$F = KX \quad (2)$$

Converting to an angle:

$$\tan\beta = \frac{X}{L/2}$$

$$\tan\beta = \frac{2F}{LK} \quad (3)$$

Bachelis has found that the spring constant K is a

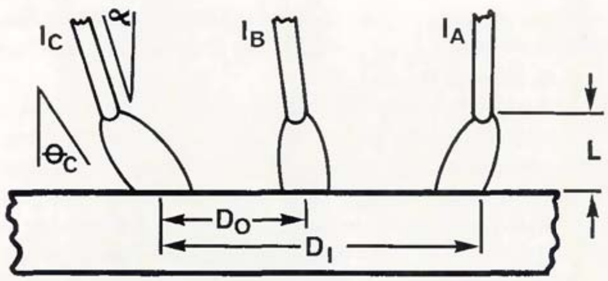

Fig. 11—Variables effecting the trail arc deflection in the three wire system

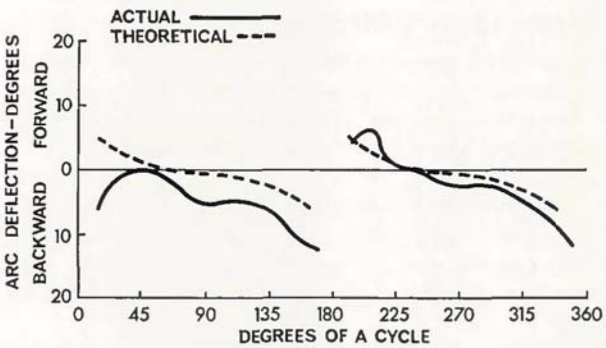

Fig. 12—Comparison of observed and theoretically computed deflection of lead arc

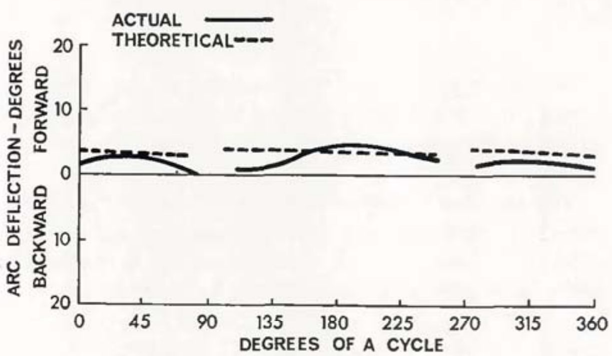

Fig. 13—Comparison of observed and theoretically computed deflection of middle arc

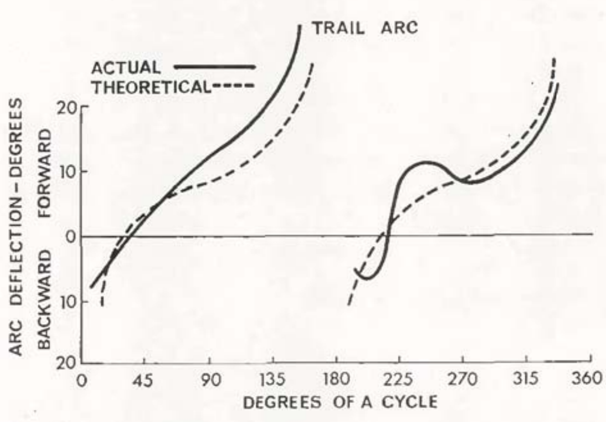

Fig. 14—Comparison of observed and theoretically computed deflection of trail arc

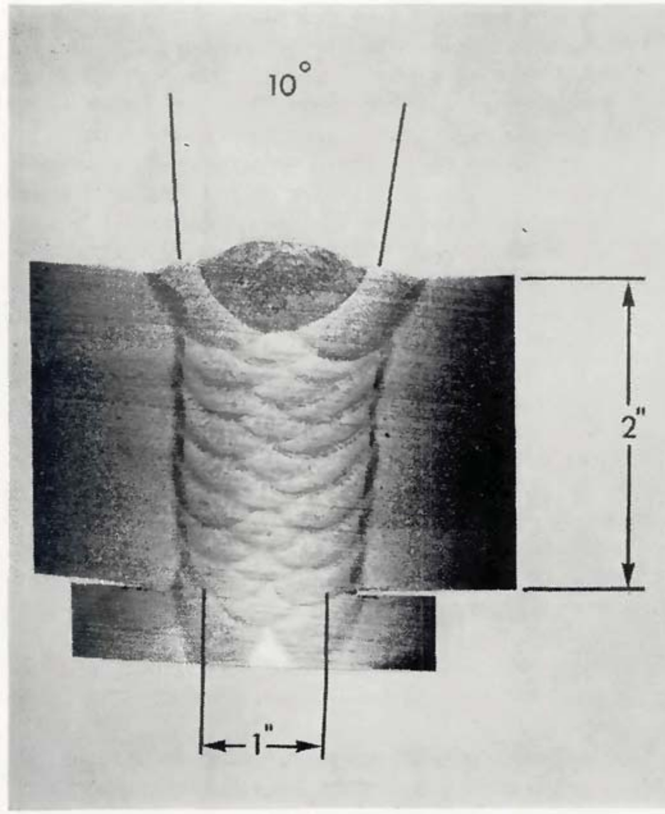

Fig. 15—Cross section of multipass weld made with three wire system. Total deposition rate—75 lb/hr; total heat input—80,000 joules/in.: travel speed—60 ipm

function of the arc length and current and can be written:

$$K = C_1 \frac{I^2}{L} \tag{4}$$

Therefore, the arc stiffness is proportional to the current in the wire squared divided by the arc length.

Substituting eqs 1 and 4 into eq 3, we obtain for the trail arc:

$$\beta_C = \arctan C_0 \frac{L^2}{I_C} \left[\frac{I_B}{D_0^2} + \frac{I_A}{D_1^2} \right] \tag{5}$$

All constants are combined into a general constant C_0.

One additional factor which must be considered is the initial wire inclination. Muller, *et al.*,[5] show that an arc will tend to follow the projected axis of a wire when the electrode is inclined from the vertical. The amount that the arc will deviate from this axis is dependent on electrode size, welding current, and arc length. Empirically, it has been found for the electrode sizes and currents being used for this work that the arc will deflect through an angle approximately one-half of the electrode inclination angle. Using this information and eq 5, we can write a general equation for the arc deflection measured in degrees of the third electrode in a three wire system. An explanation of symbols can be seen from Fig. 11:

$$\theta_C = \frac{\alpha}{2} + \arctan C_0 \frac{L^2}{I_C} \left[\frac{I_B}{D_0^2} + \frac{I_A}{D_1^2} \right] \tag{6}$$

The general dimensionless constant C_0 must be determined empirically. This can be done by determining the deflection of one arc at one point in time through experimentation. The constant was determined in these tests to be equal to 0.65.

For an a-c system the welding current is not a constant value; it changes from positive to negative following a sine curve. However, at any instant in time, a value of current can be obtained for each arc being careful to determine both direction and magnitude of current. The values can then be inserted in the equation, and the deflection angle can be obtained for that instant.

The equation can also be written in terms of degrees of a cycle by replacing the currents with their respective sinusoidal functions. The peak current values are obtained by multiplying the meter reading by $\sqrt{2}$. The calculated deflection of the electrode arc can be determined by substituting in eq 6 the parameters used for the highspeed motion picture analysis; thus the equation becomes:

$$\theta_C = 7^\circ + \arctan 0.65 \left(\frac{(0.25)^2}{805 \sin \phi}\right) \times \left[\frac{1100 \sin (\phi - 90)}{(0.75)^2} + \frac{1560 \sin \phi}{(1.75)^2}\right] \quad (7)$$

The arc length was measured as 0.25 in. for all three arcs.

One then can substitute values of ϕ from 0 to 360 deg. From equation 7, it can be seen that the phasing of each arc will affect the arc deflection. Changing the phasing can make an arc which normally deflects forward, deflect backward.

Equation 7 can be written for the lead and middle arc in the same manner, if the proper signs are observed.

A comparison of the actual arc deflections as determined by high speed pictures with calculated values plotted from equation 7 is given in Figs. 12–14. From these graphs it can be seen that the calculated curves closely predict the actual arc deflection for each arc. The slight differences in the actual deflection between half cycles is not predicted by the theoretical analysis. This phenomena is probably caused by the difference in arc behavior between straight and reverse polarity which was not considered in the theoretical model.

One phenomenon, which was difficult to explain prior to the development of the theoretical equation, was the occurrence of the maximum deflection in the lead and trail electrodes at a point just before their arcs extinguish. When the derived equations are used, the explanation for this occurrence is apparent. As the arc currents decrease, their stiffness decreases allowing them to be readily deflected by the magnetic field surrounding the middle electrode which, at this instance, is at its maximum.

When the theoretical deflection for the middle arc is plotted, it can be seen that the two adjacent arcs create opposing and almost equal forces on the middle arc effectively canceling each other. Thus the middle arc deflects only slightly. This small deflection of the middle arc aids in producing stable operation by eliminating interference from adjacent arcs.

From the plot of actual and theoretical deflection curves it can be seen that the equation developed provides a good first order approximation of the actual deflection pattern. Although other factors such as ground current and polarity of the electrode may influence arc deflection, the significant factors determined by the theoretical analysis are arc current, electrical phasing, electrode inclination, electrode spacing, and arc length. The equation can be expanded to include any number of electrodes. Any combination of a-c or d-c arcs can be analyzed.

Other Applications

While the three wire (or electrode) welding system was developed for use in line pipe fabrication, other applications should be considered. One such application is the multipass welding of heavy plate. Today all major fabrication shops are using two electrode systems for this work. By using the three wire (or electrode) system weld metal deposition rates up to 75 lb/hr are possible.

Figure 15 shows a cross section of a three wire multipass weld made in 2 in. thick plate. The flux was removed easily, even down at the bottom. In three wire welding, the thickness of each weld pass was held the same as with one or two wire welding. This was achieved by using a weld travel speed of 60 ipm. The over-all weld heat input was 80,000 joules/in.

The significant increase in weld metal deposition rate achieved with the three wire system, with no change in joint design, would appreciably reduce the time required to weld heavy sections.

Summary

1. A new system has been developed which uses three a-c powered submerged-arc electrodes for producing high speed, high quality welds.

2. The system utilizes high a-c welding currents in areas where equivalent d-c power produces severe arc blow.

3. A specific electrical connection is used which provides control over arc deflections at close electrode spacings.

4. Welding speeds of 125 ipm can be used for line pipe fabrication; this represents at least a 75% increase over present two wire welding methods.

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