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ALGORITHM OF JOINT LINE «TRACKING» IN TANDEM ARC WELDING

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The main difficulty, appearing in solution of the problem of automatic «tracking» the line of joint welded in tandem arc welding, is connected with measurement of side deviations from this line of each of electrodes located close to each other in the process of welding. Besides, together with side correction of movement of the electrodes, deviating from the line of joint welded, a need in angular correction of a torch is appeared, which could provide «parallelism» between the line of joint welded and the line, connecting the electrodes. A new approach to the solution of the above-mentioned problem was proposed, based on application of electric arc methods of measurement and application of recurrent procedures of linear and angular correction of the welding torch movement. The results of computer modeling are given in the paper. 8 Ref., 3 Figures.

Keywords: *tandem arc welding, adaptive control, arc sensors, recurrent algorithms of correction*

Among the different welding technologies, used in industrial production, welding with two successive arcs in a shielding gas (Tandem Welding) is considered to be rather challenging, characterized by a higher efficiency and a better quality of welded joints as compared to conventional welding with one arc [1]. The location of electrodes one after another makes a welding pool longer. This, according to [1], provides a more efficient degassing, leading to a decrease in the porosity of a weld, and improves its mechanical characteristics.

At the same time, it is obvious that with all the advantages of tandem arc welding, a good quality of welded joints can be achieved only on the condition that during welding both electrodes move along the line of joint welded. If, for some reason or another, one or both of the electrodes deviate from the indicated line, and if these deviations exceed the admissible value, then, undercuts and other inadmissible defects will be formed in a weld.

In robotic arc welding with one electrode, this problem can be solved using an adaptive control of the movement [2], which refers to the control of a torch movement in a function from the controlled parameters of the outer environment, in particular, from the change in the spatial position of the joint welded. The information about the side deviation of the electrode from the line of joint welded is provided by special sensor devices. Based on this information, the specified movement of the torch is corrected, if necessary. As a result, a kind of «tracking» of the line of joint welded is performed by the welding torch.

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As for the case of tandem arc welding, providing the «tracking» mode encounters certain difficulties associated with the fact that a rather short distance between two electrodes (10–12 mm) complicates a direct measurement of the side deviation of each electrode separately from the line of joint welded using the existing sensor devices. In addition, because of the fixed position of the electrodes relative to each other, in the welding torch certain difficulties appear in providing «parallelism» between the line connecting these electrodes and the line of joint welded under the conditions where the line of the joint welded can deform directly in the process of welding.

Judging from the information, placed on the sites of well-known foreign companies (see, for example, [3]), the interest to the considered problem is constantly growing. In particular, the Company Kobe Steel developed a special «dual arc sensor», used for tracking in tandem arc welding. In the present paper, a slightly different approach to the problem of «tracking» is offered, which consists in using conventional arc sensors and application of recurrent algorithms for correction of the current position of the torch.

1. Determination of deviations. Figure 1 shows the scheme of possible arrangement of the electrodes E_1 and E_2 relative to the axial line of the joint welded (indicated in Figure by the number *1*). ε_1 and ε_2 denote the side deviations of the electrodes from the indicated line. The dashed line shows the section d, connecting the electrodes E_1 and E_2. The location of the electrodes in the welding torch is fixed.

As was mentioned above, the direct measurement of side deviations ε_1 and ε_2 is connected with great technical difficulties. At the same time, it is known

[4–8] that in welding of fillet, tee and overlap joints, as well as joints with V-shaped edge preparation, the information on deviations ε_1 and ε_2 can be obtained indirectly by using arc sensors. A sensitive element of these sensors is the welding arc itself. The theory and principles of designing the arc sensor systems for welding robots are described in the monograph [8].

A peculiar feature of arc sensors is the fact, that they allow determining the present deviation of the electrode end from the line of joint welded on results of the welding current change. Hence, to determine the side deviations of ε_1 and ε_2 by means of arc sensors, it is sufficient to have only sensors of welding currents. If the welding currents i_1 and i_2 (or their deviations $\delta_1 = i_1 - i_{n1}$ and $\delta_2 = i_2 - i_{n2}$ from their nominal values i_{n1}, i_{n2}) are measured in the extreme positions of the torch at its transverse oscillatory movements, then, according to [8], the desired deviations ε_1 and ε_2 can be determined by calculation according to the following formulas:

$$\varepsilon_1 = \frac{\delta_{1R} - \delta_{1L}}{\delta_{1R} + \delta_{1L}} (s - vT_w), \quad (1)$$

$$\varepsilon_2 = \frac{\delta_{2R} - \delta_{2L}}{\delta_{2R} + \delta_{2L}} (s - vT_w). \quad (2)$$

Here the indices R and L denote the values δ_1 and δ_2 in the extreme right and, respectively, in the extreme left positions of electrodes relative to the line of joint welded; s is the half of the distance between the extreme positions of electrodes; v is the absolute value of the speed of the welding torch transverse movement, and the parameter T_w, characterizing the dynamic properties of the processes running in the welding circuit, is determined by the formula

$$T_w = \frac{R_w}{EM},$$

where R_w is the total resistance of welding circuit; E is the electric field intensity in arc column; M is the parameter, which characterizes the electrical, thermophysical and geometric properties of a consumable electrode. (It is assumed that both welding circuits are identical.)

Therefore, in many practical cases, the side deviation of each electrode separately in tandem arc welding can be determined from the measurements of welding currents passing through these electrodes, followed by calculation using formulas (1) and (2).

2. Correction of welding torch movement. The task of side correction of the welding torch movement consists in eliminating the outlined deviations ε_1 and ε_2 (directly in the welding process). In other words, the task is to provide the movement of the electrodes E_1 and E_2 inside the «band» of a given width $2\varepsilon_0$ (Figure 1), the axial line of which is the line of joint welded.

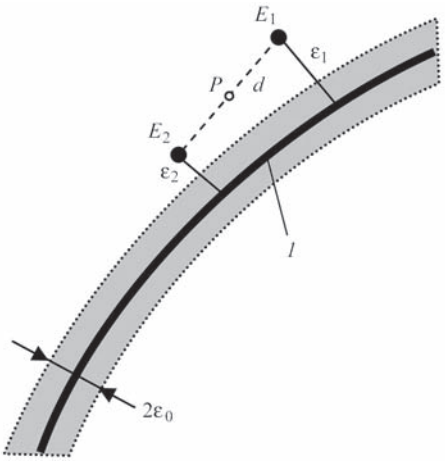

Figure 1. Scheme of arrangement of electrodes relative to the joint welded (see indications in the text)

Here it is necessary to pay attention to the fact that, unlike welding with one arc, it is necessary to correct not only the position of the electrodes E_1 and E_2 but also the orientation of the line connecting these electrodes with respect to the line of joint welded.

Mathematically, let us formulate the task of correction in the form of the following requirements:

$$\frac{|\varepsilon_1 + \varepsilon_2|}{2} \le \varepsilon_0,$$

$$\frac{\varepsilon_1 - \varepsilon_2}{d} \le \sin\varphi_0,$$

where φ_0 is the admissible value of the angle between the section d and the tangent to the line of joint welded.

The formulated problem can be interpreted as the problem of stabilizing the movement of electrodes E_1 and E_2 rigidly interconnected within a preset «band». With this formulation of the problem, the stabilization algorithms are conveniently constructed in the form of recurrent relations

$$u(k+1) = u(k) + \Delta u(k+1), \quad (3)$$

$$q(k+1) = q(k) + \Delta q(k+1), \quad k = 0, 1, 2, ..., . \quad (4)$$

In these relations, $u(k)$ is the position of the point P located in the middle of the section d (see Figure 1), relative to the line of joint welded; $q(k) = \text{tg}\varphi(k)$, where $\varphi(k)$ is the angle between the section d and the tangent to the line of joint welded; k is the index indicating the moment of time kT_0, where T_0 is the step of time sampling;

$$\Delta u(k+1) = \begin{cases} -\varepsilon_0, & (\varepsilon(k) > \varepsilon_0), \\ \varepsilon_0, & (\varepsilon(k) < -\varepsilon_0), \\ 0, & (|\varepsilon(k)| \le \varepsilon_0), \end{cases} \quad (5)$$

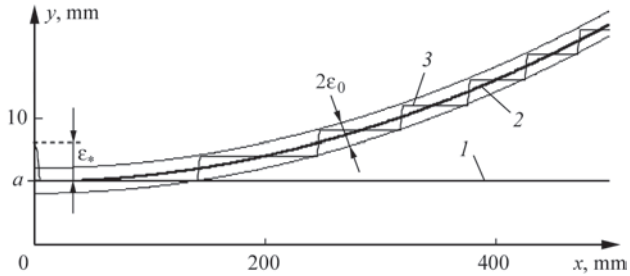

Figure 2. Results of modeling the correction of electrodes position (point *P*) relative to the line of joint welded (see indications in the text)

$$\Delta q(k+1)=\begin{cases}-\mu_0, & (\mu(k)>\mu_0),\\ \mu_0, & (\mu(k)<-\mu_0),\\ 0, & (|\mu(k)|\le\mu_0).\end{cases} \qquad (6)$$

In (5) and (6) the following designations are introduced: μ_0 is a preset number characterizing the admissible degree of «non-parallelism» between the section *d* and the tangent to the line of joint welded;

$$\varepsilon(k)=\frac{|\varepsilon_1(k)+\varepsilon_2(k)|}{2},$$

$$\mu(k)=\mathrm{tg}\varphi(k)\text{-}y'(k),$$

where $y' = dy/dx$ is the angular coefficient of tangent to the line of joint welded, described by the expression $y = y(x)$.

Under the influence of $\Delta u(k + 1)$, the electrodes E_1 and E_2 are «displaced» (as a one whole) along the normal to the line of joint welded, and under the action of $\Delta q(k + 1)$, the welding torch is rotated relative to point *P*, providing «parallelism» between the section *d* and the tangent to the line of joint welded.

It is seen from expressions (1)–(6), that the stabilization of the welding torch movement in a preset «band» occurs quite simple. First, the side deviations $\varepsilon_1(k)$ and $\varepsilon_2(k)$ are calculated according to formulas (1) and (2) based on the results of measurements δ_{1R}, δ_{1L}, δ_{2R}, δ_{2L} at each cycle *k*. Then, in accordance with the logical functions (5) and (6), the correcting actions Δu and Δq are determined. After this, the correction of the welding torch position is performed according to the laws (3) and (4) at the cycle $(k + 1)$.

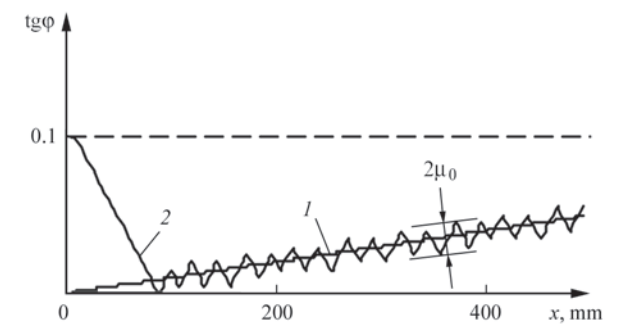

Figure 3. Results of modeling the correction of the section *d* slope relative to the tangent to the line of joint welded

3. Results of computer modeling. Let us illustrate the effectiveness of automatic correction algorithms (3) and (4) on a certain example (Figure 2). Let the line of joint welded, along which it is planned to move the electrodes in the process of welding, be preset in Cartesian coordinates by equations in a parametric form $x = v_w t$, $y_1 = a$, $t = \{0, t_*\}$. Here v_w = = const is the speed of welding torch movement along the joint welded; *a* is the constant; $t_* = l/v_w$, where *l* is the length of the preset line (in Figure 2 this line is indicated by the number 1).

Let us suppose that the line 1 in the process of welding is deformed for one reason or another and takes the form of a line marked with the number 2. Let us approximate this line by the equations $x = v_w t$, $y_2 = a + bx^2$, in which *b* is a positive coefficient. Moreover, let us assume that the point *P* located in the middle of the section *d* (see Figure 1) before start of welding was at a distance ε_* from the line of joint welded, and the angle between the section *d* and the tangent to the curve $y_2 = a + bx^2$ was equal to φ_*.

The number 3 in Figure 2 denotes the curve $u(x)$ representing the «trace» of the moving welding torch (point *P*) as a result of the correction of its movement on the basis of the algorithm (3). When modeling the correcting control, the following parameter values were used: v_w = 12 mm/s; *l* = 500 mm; *d* = 10 mm; *a* = = 5 mm; Δl = 1 mm; $b = 4\cdot10^{-5}$/mm; ε_0 = 1 mm; ε_* = = 7 mm; $\mathrm{tg}\varphi_* = 0.1$, $T_0 = \Delta l/v_w = 0.08$s.

From Figure 2 it is seen that although the line of the joint *2* does not substantially coincide with the line *1*, preset by the program, nevertheless, due to the correcting control, the movement of the characteristic point *P* in the steady state occurs near the line *2*, i.e., inside the «band» at a given width $2\varepsilon_0$.

Simultaneously with the correction of the position of welding torch relative to the line of joint welded, its angular correction occurs by turning around the point *P* in accordance with the algorithm (4). Figure 3 presents the results of modeling the angular correction. As the angular coefficient $\mathrm{tg}\varphi_*$, which characterizes the slope of the section *d* to the welded joint line before the start of welding, the number 0.1 (dashed line) was taken.

The line denoted by the number 1 represents a diagram of functional dependence $y_2'(x) = 2bx$, and the curve *2* obtained as a result of the angular correction of the torch movement is nothing else than a graphic image of the variation of angular coefficient $\mathrm{tg}\varphi(x)$, which tends to the line $y_2'(x)$.

From the analysis of these curves it follows that corrective control of the rotation of welding torch leads to the fact that the deviation of angular coefficient $\mathrm{tg}\varphi(x)$ of the section *d* from the angular coeffi-

cient of the tangent to the welded joint line $y_2'(x)$ in the steady state does not exceed the preset value.

Therefore, the general conclusion follows that due to the use of arc sensors as a source of present information about the deviations of electrodes from the line of joint welded and the application of recurrent procedures for correcting the movement of welding torch, control of tandem arc welding acquires adaptive properties. Its peculiarity consists in the fact that not only the positions of electrodes (as a one whole) are corrected in the welding process, but also their orientation relative to the line of joint welded, which provides a high accuracy of electrodes movement along the joint welded. This creates prerequisites for the provision of sufficiently high technological indicators inherent in tandem arc welding.

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