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EFFECT OF OWN MAGNETIC FIELDS ON ELECTRIC ARCS IN TANDEM-ARC WELDING

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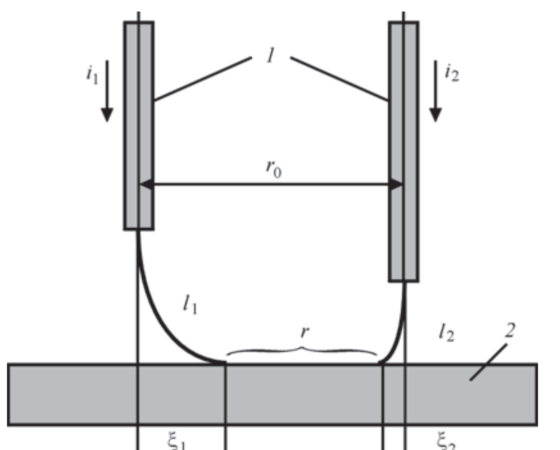
Considered is an effect of own magnetic fields on spatial position of arcs appearing in their deviation from electrode axial lines in automatic tandem-arc welding. The main aim of work is obtaining the dependencies of indicated deviations from arc lengths and welding currents in analytical form. In scope of this problem the conditions were found that limit a relationship between welding currents. Their neglecting can result in «adhesion» of arcs or their extinction in process of welding. In particular, the relationship between height («amplitude») of welding current pulse of one arc and basic current of another one should not exceed specific limit in pulse tandem-arc consumable electrode welding. The work is illustrated by the examples. 9 Ref., 1 Figure.

Keywords: *tandem-arc welding, consumable electrode, electromagnetic interaction of arcs*

Due to recent achievements in the field of design of welding current sources with microprocessor control there is a possibility to realize automatic arc welding with two successive arcs in shielding gas (Tandem Welding). According to work [1] the main advantage of tandem-arc welding in comparison with welding using one arc is significant increase of its efficiency.

From technical point of view the tandem welding is sufficiently complex process requiring coordinated control of welding with both arcs burning in the vicinity to each other. Besides, the undesirable arc deformations can appear due to close positioning of the electrodes. This can result in their «adhesion» or extinction in process of welding. The main reason of the indicated deformations is electromagnetic interaction of parallel arcs with currents. The forces of this interaction, as it is known, are determined by Ampere law



Scheme of magnetic interaction of two arcs: *1* — consumable electrodes; *2* — part being welded

$$F_{12} = \frac{\mu_0\mu}{2\pi}\frac{i_1 i_2}{r} l_2, \quad F_{21} = \frac{\mu_0\mu}{2\pi}\frac{i_1 i_2}{r} l_1. \qquad (1)$$

In formulae (1) F_{12} is the force acting the second arc from the side of the first arc; F_{21} is the force acting the first arc from the side of the second; μ_0 is the magnetic constant; μ is the relative magnetic permeability of the medium; i_1, i_2 are the welding currents of the first and second arcs; l_1, l_2 are the lengths of the first and second arcs; r is the distance between the arcs.

The welding arcs with similarly oriented currents will curve in direction to each other under effect of F_{12} and F_{21} forces, as schematically shown on the Figure.

It is also known [2–6] that curving of the welding arcs provokes so called restorative forces F_1^* and F_2^* preventing indicated curving. At relatively small deviations of arcs ξ_1 and ξ_2 from axial lines of their electrodes, the restorative forces are normal to the deviations, i.e.

$$F_1^* = -G_1\xi_1, \quad F_2^* = -G_2\xi_2. \qquad (2)$$

In the expressions (2) G_1 and G_2 are positive coefficients, titled in work [3] as arc rigidity coefficients; they are related with currents i_1, i_2 and arc lengths l_1, l_2 by relationships

$$G_1 = N\frac{i_1^2}{l_1}, \quad G_2 = N\frac{i_2^2}{l_2}, \qquad (3)$$

where N = const is the coefficient depending mainly on welding conditions.

The following important problems appear, namely how big is effect of own magnetic fields on electric arcs in tandem-arc welding with consumable electrode and what are the limitations necessary to be applied to welding currents i_1, i_2 in order to prevent possible deviations ξ_1 and ξ_2 disturbing stable welding mode?

Based on known publications, these questions are without clear answer up to the moment. Mathematical modelling of electromagnetic interaction of two arcs used for casting of metals and alloys in electric furnaces was carried out in work [7]. The results of modelling are presented in form of non-linear integral-differential equations, which are not very convenient for practical application. Simple relationships between deviations ξ_1, ξ_2, welding currents i_1, i_2 and lengths of arc gaps l_{10}, l_{20} were received in the paper of Japanese researches [8]. However, these relationships are not very suitable in the case of consumable electrode welding, which, as it is known, have own peculiarities.

An attempt to get answers to the questions mentioned above is made in the present work. At once it should be noted that action of electromagnetic forces on arcs appear not only in the phenomena of microscopic nature, to which change of shape, dimensions and position of arcs in space are referred. Action of electromagnetic fields inside the arcs provokes appearance of Lorentz force, giving centripetal acceleration to charged particles and resulting in spiral movement of these particles. Obviously that indicated forces as well as other nature forces effect arcs spatial position to significantly less degree than F_{12}, F_{21}, F_1^* and F_2^* forces and they are not taken into account in this problem.

For mathematical description of action of F_{12}, F_{21}, F_1^* and F_2^* forces on welding arcs in tandem-arc welding the following idealization is taken:

- arc column, as in works [2, 3], will be considered as flexible thin current conductor, one end of which is «fixed» close to electrode end and another one, located close to weld pool, is «free», i.e. can move along the weld pool;
- forces F_{12}, F_{21}, F_1^* and F_2^* are collinear and normal to axial electrode lines.

Let's write a balance equation of forces acting on «free» ends of welding arcs in scopes of accepted model

$$F_{21} + F_1^* = 0, \quad F_{12} + F_2^* = 0.$$

Taking into account relationship (1)–(3) these equations will become

$$Pl_1 \frac{i_1 i_2}{r} - N \frac{i_1^2}{l_1} \xi_1 = 0, \quad Pl_2 \frac{i_1 i_2}{r} - N \frac{i_2^2}{l_2} \xi_2 = 0,$$

where $P = \mu_0\mu/(2\pi)$.

Let's re-write the equations in the following way:

$$\xi_1 = \lambda\delta \frac{l_1^2}{r}, \quad \xi_2 = \frac{\lambda}{\delta} \frac{l_2^2}{r}, \tag{4}$$

here $\lambda = P/N$, $\delta = i_2/i_1$ are the dimensionless parameters.

Summing equations (4), we will get

$$\xi_1 + \xi_2 = \frac{\lambda}{r}\left(l_1^2\delta + \frac{l_2^2}{\delta} \right). \tag{5}$$

On the other hand, it follows that

$$\xi_1 + \xi_2 = r_0 - r, \tag{6}$$

where r_0 = const is the distance between axial lines of the electrodes.

Equating the right parts of the equations (5) and (6), we will get a quadric equalities relatively to distance between the arc ends r:

$$r^2 - r_0 r + a = 0.$$

A free element of this equation

$$a = \lambda\left(l_1^2\delta + \frac{l_2^2}{\delta} \right) = \text{const}, \tag{7}$$

and its roots equal

$$r_* = \frac{r_0}{2} + \sqrt{\frac{r_0^2}{4} - a}, \quad r_{**} = \frac{r_0}{2} - \sqrt{\frac{r_0^2}{4} - a}. \tag{8}$$

The roots (8) are real if the condition is fulfilled

$$a \le \frac{r_0^2}{4}. \tag{9}$$

Obviously that physical meaning has only root r_* (increase of distance r_0 rises r_* distance).

If condition (9) is written in expanded form

$$\delta^2 - \frac{r_0^2}{4\lambda l_1^2}\delta + \frac{l_2^2}{l_1^2} \le 0, \tag{10}$$

then solution of inequality (10) determine area of allowable values of δ relationship:

$$\delta_m \le \delta \le \delta_M, \tag{11}$$

where

$$\delta_m = \frac{r_0^2}{8\lambda l_1^2} - \sqrt{\left(\frac{r_0^2}{8\lambda l_1^2} \right)^2 - \frac{l_2^2}{l_1^2}},$$

$$\delta_M = \frac{r_0^2}{8\lambda l_1^2} + \sqrt{\left(\frac{r_0^2}{8\lambda l_1^2} \right)^2 - \frac{l_2^2}{l_1^2}}.$$

Let's come back to expressions (4) and insert r_* value found in (8) instead of variable r. As a result new desired estimations ξ_1 and ξ_2 are received.

$$\xi_1 = \lambda\delta \frac{l_1^2}{r_*}, \quad \xi_2 = \frac{\lambda}{\delta} \frac{l_2^2}{r_*}. \tag{12}$$

Estimations (12) have approximate nature since parameter λ, rather coefficient N, included in $\lambda = P/N$ relationship is not known exactly and can be determined only in experimental way. Paper [3] provides approximate value $N \approx 5.6\mu_0\mu/(4\pi)$ (in our designations) received as a result of experimental investigation, in which arc rigidity G was determined on measurements of deviations of arc «free» end ξ on axial line of the electrode under effect on the arc of specially developed transverse magnetic field.

If this result is used, then parameter λ will get the following numerical value:

$$\lambda = \frac{P}{N} = \frac{\mu_0\mu 4\pi}{2\pi 5.6\mu_0\mu} \approx 0.35,$$

and desired estimations (12) will take on form of calculation formulae

$$\xi_1 = 0.35\delta\frac{l_1^2}{r_*},\quad \xi_2 = \frac{0.35}{\delta}\frac{l_2^2}{r_*}. \qquad (13)$$

Comparing formulae (13) with formulae

$$\xi_1 = 0.5\delta\frac{l_{10}^2}{r_0},\quad \xi_2 = \frac{0.5}{\delta}\frac{l_{20}^2}{r_0}, \qquad (14)$$

received in work [8] in a more complex way, we can see that they are similar on shape, but differ in parameters included in them. First of all, arc lengths l_1 and l_2 appearing in formulae (13) in consumable electrode welding do not equal the initial values l_{10} and l_{20} and depend on welding currents in the next way [9]:

$$l_1 = \frac{u_x - u_0}{E} - Tv_{e1},\quad l_2 = \frac{u_x - u_0}{E} - Tv_{e2}. \qquad (15)$$

In these expressions u_x is the open circuit voltage of welding current sources; u_0 is the sum of near-electrode voltage drops; E is the electric field intensity in welding arcs; v_{e1} and v_{e2} are the rates of feed of the first and second electrodes, respectively; $T = R/(EM)$, where R is the resistance of welding circuits, M is the parameter characterizing electric, thermal-physical and geometry properties of consumable electrodes (it is assumed that both welding circuits are identical).

Secondly, formulae (13) in contrast to (14) contain no distance between the electrodes $r_0 = \text{const}$, but distance between arc ends r_*, which according to expressions (8) and (7) depends on arc lengths l_1 and l_2, and on relationship between welding currents δ.

Work [8, Figure 3] shows the diagrams representing arc shapes, received as a result of modelling of arc end deviations from axial lines of the own electrodes under the next parameters: $i_1 = i_2 = 9\cdot 10^3$ A, ($\delta = 1$), $r_0 = 800$ mm, $l_1 = l_2 = 400$ mm. It follows from a diagram, plotted for the case when the arc shapes are approximated by polynomial of the second degree, that at indicated parameters

$$\xi_1 = \xi_2 \approx 80 \text{ mm}. \qquad (16)$$

Now let's make calculation of deviations ξ_1 and ξ_2 on formula (13). For this at the beginning on formula (7) find parameter $a = 11.2\cdot 10^4$ mm^2. The condition is fulfilled. Then using formula (8) calculate $r_* = 619$ mm and by formulae (13) the next is received

$$\xi_1 = \xi_2 = 0.35\frac{(400\text{ mm})^2}{619\text{ mm}} \approx 90\text{ mm}. \qquad (17)$$

Comparison of estimations (16) and (17) allows concluding that their numerical values are sufficiently close, however, the estimations themselves are received using different methods. It should only be noted that no complex calculation procedures and graphical plotting necessary in order to get the estimation (17).

Efficiency of received results is shown by the example of robotic gas-shielded tandem-arc welding using consumable electrode, performed at the next values of parameters: $u_x = 30$ V, $u_0 = 16$ V, $E = 2$ V/mm, $M = 0.37$ mm/(s·A), $R = 0.04$ Ohm, $r_0 = 10$ mm, $H = 17$ mm (H is the distance between torch edge and part being welded).

Let's consider separately three cases.

1. Rates of electrode feeding v_{e1} and v_{e2} are small. Let's $v_{e1} = v_{e2} = 35$ mm/s. In this case $i_1 = i_2 = v_{e1}/M = 35/0.37 = 95$ A, ($\delta = 1$). Using formula (15) find $l_1 = l_2 = 5.1$ mm and on formula (7) calculate $a = 18.2$ mm^2. According to (9) $a \le r_0^2/4 = 25$ mm^2 condition shall be fulfilled. The condition is fulfilled. Further on formula (8) determine the distance between arc ends $r_* = 7.6$ mm and on formulae (13) calculate deviations

$$\xi_1 = \xi_2 = 0.35\frac{(5.1\text{ mm})^2}{7.6\text{ mm}} = 1.2\text{ mm}.$$

2. Increase the rates v_{e1} and v_{e2}. Let's $v_{e1} = v_{e2} = 80$ mm/s. Then $i_1 = i_2 = 216$ A, ($\delta = 1$), $l_1 = l_2 = 2.7$ mm, $a = 5.1$ mm^2, $r_* = 9.5$ mm. Respectively,

$$\xi_1 = \xi_2 = 0.35\frac{(2.7\text{ mm})^2}{9.5\text{ mm}} = 0.3\text{ mm}.$$

3. Now we consider the case when v_{e1} and v_{e2} rates are different. Let's $v_{e1} = 35$ mm/s and $v_{e2} = 80$ mm/s. In this case $i_1 = 95$ A, $i_2 = 216$ A, ($\delta = 2.3$), $l_1 = 5.1$ mm, $l_2 = 2.7$ мм, $a = 22.0$ mm^2, $r_* = 6.7$ mm. On formulae (13), find

$$\xi_1 = 0.35\cdot 2.3\frac{(5.1\text{ mm})^2}{6.7\text{ mm}} = 3.1\text{ mm},$$

$$\xi_2 = \frac{0.35}{2.3}\frac{(2.7\text{ mm})^2}{6.7\text{ mm}} = 0.2\text{ mm}.$$

Analysis of received results allows making several important conclusions, which, in general, are not obvious.

Conclusions

1. If welding currents of both arcs are equal then they decrease, not rise with increase of arc deviation currents ξ as it may seem from the first sight. This fact in a physical way is explained by the phenomenon that increase of welding currents (by means of rise of feed rate of consumable electrodes v_e at $H = \text{const}$) results in reduction of arc lengths. At that attractive forces F_{12} and F_{21} normal to arc lengths reduce and restor-

ative forces F_1^* and F_2^* reciprocally proportional to arc lengths rise. As a result the points characterizing position of arc ends in relation to axial lines of the own electrodes, are shifted to the side of axial lines, reducing thus arc deviations ξ from indicated lines.

2. If welding currents are different then deviation ξ will be larger in the arc with lower welding current. It is also caused by the fact that arc with lower current has larger length. Therefore, attractive force, acting on longer arc, exceeds attractive force acting on shorter one. Besides, rigidity of longer arc, and, respectively, its restorative force are significantly lower than rigidity and restorative force of shorter arc.

3. Arc deviations ξ significantly depend on relationship between welding currents δ, moreover rise of δ, as can be seen from expressions (12), promotes rapid increase of deviation ξ of longer arc and decrease of that in shorter one. It follows from this that relationship δ can not be taken randomly; it shall be taken in accordance with limitation (11). This is a moment important for practice.

In the conclusion it should be noted that estimations of arc deviations (12) under effect of own magnetic fields were received by us, based on simplified mathematical model, describing these actions. Nevertheless, their comparison with the results given in works [7, 8] brings out clearly that estimations (12) sufficiently well discover functional dependencies between arc deviations, their lengths, welding currents and distance between the arcs and more convenient for practical application. The necessity in such simple estimations has already appeared at a stage of development of special welding equipment (in particular, welding torch with two isolated electrodes) and the technologies of automated tandem-arc welding using consumable electrode.

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