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SOME PROBLEMS OF ROBOTIZATION OF GAS-SHIELDED CONSUMABLE ELECTRODE ARC WELDING

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Robotization of gas-shielded consumable electrode arc welding provokes a series of problems. They are caused by necessity to equip welding robots with special sensing devices, which could communicate information on real process of arc welding to control system in very complicated for observation conditions. This work considers the possibilities of practical application of arc sensors, which in contrast to other sensing devices do not need special protection from light and heat flows, spattering of molten metal and intensive emission of fumes in measurement zone itself. Given are analytical relationships for numerical evaluation of welding tool deviation from joint line on the results of current measurements coming from the arc sensor. These relationships can be used for construction of algorithms of automatic correction of welding tool movement directly in process of arc welding. 29 Ref., 3 Figures.

Keywords: *robotization of arc welding, consumable electrode, electric-arc adaptive systems*

Application of robots for resistance spot welding started back in the 70^{th} of the last century by «General Motors» Company in manufacture of automotive bodies [1] and with time got a widespread use in all countries with advanced economies. It was possible due to the fact that resistance spot welding operation can be easily robotized.

Situation with arc welding was completely different. Its performance using the robot with fixed program control requires very high accuracy of welded parts manufacture and assembly, which will keep constant form, area of groove preparation, gap between the parts being welded and their spatial position. However, these rigid requirements are not always fulfilled under real conditions of welding production. Therefore, deviations of a welding tool being moved on real welded joints by robot at previously set program are unavoidable. When indicated deviations come out of allowance limits, welded joint quality can become unacceptably low. There can be another reasons of mismatch of required and program set movement trajectory of welding tool, for example, temperature deformations of the thin parts in process of welding such called magnetic blowing etc.

Necessary quality of welded joint under conditions of not completely determined and partially varying «technological medium» is provided using adaptive control, which is realized as control of a welding robot in a function from controlled parameters of this medium. Adaptive welding robots are capable to «adjust» to varying arc welding conditions and, in particular, change spatial position of welded joints. However, realizing the adaptive control requires the welding robot to be equipped with special sensing devices (probes) which will provide control system with information on real current position of electrode tip relative to welded joint line.

The problem of sensor fitting-out of welding robot is still relevant. The matter is that gas-shielded consumable arc welding is accompanied by powerful light, electromagnetic and heat radiation, spattering of molten metal, intensive emission of fumes and dust directly in measurement zone. Functioning reliability of optical, inductive or acoustic sensing devices is not high under such conditions. In this connection, following from many publications [2–20], particular attention is given to electric arc sensors, i.e. sensors in which welding arc itself is an information source. They are called Arc Sensors in the literature. Intense interest to them is caused also by the fact that determination of electrode tip position relative to welded joint line is carried out directly in welding point at complete absence of any measurement devices close to it. However, arc sensors are capable to function only under specific conditions.

Aim of this work is to consider the conditions of application of the arc sensors in the systems of adaptive control of welding robots and get analytical relationships for evaluation of consumable electrode tip deviation from joint line of parts being welded on the results of current measurements coming from the arc sensor.

Conditions of application of arc sensors. One of the main conditions lies in the fact that cross-section line of the surfaces being welded $F = F(y)$ has an extreme nature (Figure 1) and the extremum itself was on the axial line of welded joint. Majority of welded joints fulfill this condition according to works [21, 22]. Fillet, tee, lap as well as butt joints with V-groove can be referred to them.

One more indispensable condition is permissibility (from point of view of welding technology) of electrode oscillations across welded joint line directly in welding process. According to work [22] application of transverse oscillations in majority of cases is quite permissible and even results in positive effect, i.e. weld width rises, penetration depth reduces, weld metal overheating and its chemical inhomogeneity reduce. Therefore, arc welding in the most of the cases is performed using transverse oscillations following technical reasons.

And finally, it is important that frequency of transverse oscillations does not come in a frequency band, where welding current oscillations caused by another reasons, for example, voltage fluctuations on welding current source input or globular metal transfer can be present. Fulfillment of these conditions can transform the arc in a source of information on current state of electrode tip relative to welded joint line and become a sort of sensing element of some virtual sensing device [23].

Thus, presence of extremal characteristic in the control object and application of search oscillations as a mean for receiving information on virtual position of the system relative to extremum are as it is well known [24–27] the main indices showing attachment of the system with the arc sensors in feedback circuit to a class of adaptive systems of extremal type. A series of sufficiently effective methods of extremum searching were developed in theory of extremal control, the complete understanding on which can be found in special literature, for example, in work [24]. Two methods, i.e. difference method and method of modulating action are the most appropriate according to work [20] for solution of the tasks of welded joint line tracking.

Herein, we in short words will describe only the difference method. The idea of difference (or, as it is sometimes called, differential) method lies in the following. A trajectory of movement of welding tool in a working space of welding robot is set in a form of «zigzag» curve $y = y(x)$, having symmetrical location relative to axial line, which ideally should match the axial line of welded joint. Value of $F = F(y)$ function is measured in the process of movement on curve $y = y(x)$ in its left and right extreme points and calculate the difference ΔF of measured values. If axial line of $y = y(x)$ curve matches the axial line of welded joint, then difference ΔF will equal zero. Variation of this difference from zero directly indicates deviation of axial curve line $y = y(x)$ from desired line. A signal corresponding to ΔF difference is used for correction of current position of welding tool.

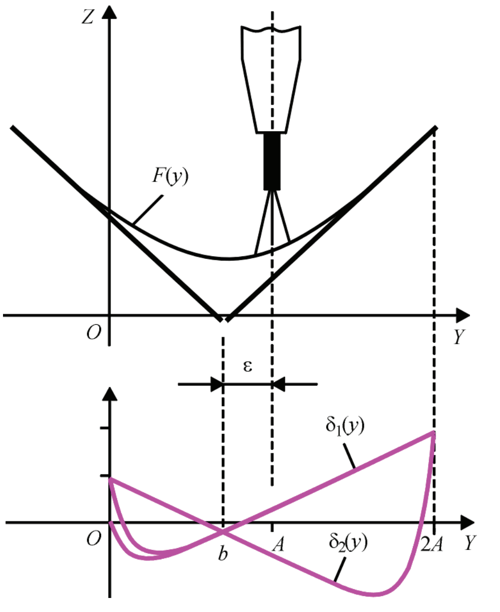

Figure 1. Scheme of movement of welding tool across joint line of welded being parts and diagrams of $\delta_1 = \delta_1(y)$ and $\delta_2 = \delta_2(y)$ functions

Construction of electric arc adaptive system based on difference method requires only welding current probe i. Measurement of welding current i or its deviation $\delta = i - i_n$ from nominal value i_n is carried out in the extreme points of torch transverse oscillations. The task is to find the analytical relationships, which based on measurement results, allow getting current numerical evaluation of side deviation $\varepsilon(t)$ of medium position of oscillating electrode from the welded joint line.

Numerical evaluations of ε (*t*) deviation. Let's assume that the welding tool in process of welding is moved across the fillet joint line (along axis Y in Figure 1) from point O to some point $2A$ and back with constant speed v_y = const. At that it is supposed that a rate of torch movement along axis X (directed up on normal to drawing plane) is preserved constant. i.e. v_x = const.

Line $F = F(y)$, following work [7], is approximated by parabola

$$F(y) = a(y - b)^2 + c, \quad (1)$$

where a, b, c are the positive coefficients, characterizing form and position of curve $F(y)$ in coordinate system OYZ.

It is assumed that these coefficients in small interval of time $\theta = 2A/v_y$ do not vary significantly. The distance between point b and point A (Figure 1) being equal:

$$\varepsilon = A - b, \quad (2)$$

characterizes desired deviation of middle position of the torch from joint line of elements being welded.

The relationship between the functions $\delta(y) = i(y) - i_n$ and $F(y)$ according to work [20] can be described by differential equation

$$\frac{d\delta}{dy}+\frac{1}{v_yT_w}\delta=\frac{1}{MT_w}\frac{dF}{dy},\qquad(3)$$

where

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

where M is the parameter characterizing electric, thermal and physical and geometry properties of consumable electrode; E is the intensity of electric field in arc column; R_w is the total resistance of welding circuit, and dF/dy is the slope of curve in current point of welding.

Using equation (3) and taking into account (1) and (2), write down separately two equations, corresponding to movement of electrode from point O to point $2A$ and back:

$$\left.\begin{aligned}\frac{d\delta_1}{dy}+\frac{1}{v_yT_w}\delta_1&=\frac{2a}{MT_w}(y-b),\\ \frac{d\delta_2}{dy}+\frac{1}{v_yT_w}\delta_2&=\frac{2a}{MT_w}(2A-y-b).\end{aligned}\right\}\qquad(4)$$

In these equations the deviation of welding current, appearing in movement of the torch from point O to point $2A$, is presented through $\delta_1=\delta_1(y)$ and deviation of welding current in torch movement in back direction $2A\to O$ through $\delta_2=\delta_2(y)$

Solutions of equations (4) have the following form

$$\delta_1(y)=\frac{2av_y}{M}(y-b-v_yT_w)+C_1\exp\left(-\frac{y}{v_yT_w}\right),\qquad(5)$$

$$\delta_2(y)=-\frac{2av_y}{M}(2A-y-b+v_yT_w)+\\ +C_2\exp\left(-\frac{2A-y}{v_yT_w}\right),\qquad(6)$$

where C_1 and C_2 are some constants. Since we are interested in deviations of welding current only in the extreme points of transverse oscillation of the electrode, then, the following relationships taking into account (2) are received assuming in equation (5) $y=2A$ and in (6) $y=0$ and introducing designations $\delta_R=\delta_1(2A)$, $\delta_L=\delta_2(0)$:

$$\left.\begin{aligned}\delta_R&=\frac{2av_y}{M}(A-v_yT_w+\varepsilon),\\ \delta_L&=\frac{2av_y}{M}(A-v_yT_w-\varepsilon).\end{aligned}\right\}\qquad(7)$$

From here

$$\delta_R-\delta_L=\frac{4av_y}{M}\varepsilon.\qquad(8)$$

The latter equation shows that if coefficient value a was known in process of measurement of δ_R and δ_L together with values of parameters v_y and M, then sufficiently accurate evaluation could be received on $(\delta_R-\delta_L)$ difference

$$\varepsilon=(\delta_R-\delta_L)\frac{M}{4av_y}\qquad(9)$$

of interesting for us lateral deviation of the welding torch from axial line of the welded joint. Such type of evaluation, namely $\varepsilon=K_1(\delta_R-\delta_L)$, where K_1 is some constant was used in works [3, 11, 12].

Unfortunately, coefficient a, included in formula (9), can be considered as one with small variation only in not large time interval. In process of arc welding due to non-stationary movement of free surface of liquid pool, a is changed in unpredictable way and virtually can not be identified at present moment. Respectively, evaluation ε, received based on $(\delta_R-\delta_L)$ difference, reflects real deviation, in the best variant with accuracy up to one sign.

The natural question arises, is it possible to eliminate effect of uncontrolled variations of parameter a on evaluation ε, received based on the results of δ_R and δ_L measurement. It appears that such a possibility really exists. In fact, if we consider sum of $(\delta_R+\delta_L)$, which according to equation (7) equals

$$\delta_R+\delta_L=\frac{4av_y}{M}(A-v_yT_w),\qquad(10)$$

then it is difficult not to see that multiplier $4av_y/M$ in the right part of this expression, containing unknown coefficient a, is the same as in the right part of the expression (8). This fact, for the first time, was outlined in work [28].

Let's divide relationship (8) by (10) and write the results as

$$\varepsilon=\frac{\delta_R-\delta_L}{\delta_R+\delta_L}(A-v_yT_w).\qquad(11)$$

Now coefficient a is not involved in (11). This means that lateral deviation ε, determined by this formula, is completely independent on this coefficient. Expression (11) in contrast to (9) includes only measured values δ_R, δ_L and earlier known values of parameters A, v_y and T_w. In other words, evaluation of lateral deviation, calculated on formula (11), has a robustness property in relation to current change of form of pool free surface.

Figure 2 presents the results of computer modelling of process of consumable arc welding with transverse oscillations of torch at constant lateral deviation $\varepsilon_0=1$ mm and at two different values of parameter a, i.e. $a=0.1$ mm^{-1} and $a=0.25$ mm^{-1}. The values of other parameters, used in modelling, are typical for robotic arc welding: $v_x=5$ mm/s; $v_y=12$ mm/s; $A=3$ mm; voltage of welding current source $u=30$ V; electrode feed rate $v_e=45$ mm/s; $i=145$ A; $E=2$ V/mm; $M=0.31$ mm (s·A); $L=0.4$ mH; $R_w=0.04$ Ohm.

It can be seen from Figure 2 that $\delta=\delta(t,a)$ to significant extend depends on coefficient a. Substituting the results of δ_R and δ_L measurements in formula (11):

$\delta_R=19.96$ A, $\delta_L=5.94$ A (at $a=0.10$ mm^{-1}),
$\delta_R=55.07$ A, $\delta_L=17$ A (at $a=0.25$ mm^{-1}),

the following is received

$$\varepsilon_1 = \frac{19.96 - 5.94}{19.96 + 5.94}(3 - 12\cdot 0.1) = 0.97 \text{ mm}$$

(at a = 0.10 mm^{-1}),

$$\varepsilon_2 = \frac{55.17 - 16.80}{55.17 + 16.80}(3 - 12\cdot 0.1) = 0.96 \text{ mm}$$

(at a = 0.25 mm^{-1}).

Comparison of ε_1 and ε_2 between themselves and with ε_0 proves that coefficient a does not have noticeable effect on the results of ε calculation on formula (11) and calculation values ε_1 and ε_2 virtually match the real ε_0 deviation. This means that evaluation of lateral deviation ε, made on formula (11), is sufficiently effective.

We are not going to give in this article the details of noise resistance of differential arc sensor. It should only be noted that in the cases when the noises at input of welding current probe are significant, i.e. when signal-to-noise relationship is not enough for guaranteed evaluation of ε, one of the most efficient methods of noise suppression, so called accumulation method can be used [29]. For this not one reading, but several should be taken and averaged in process of $\delta_R(t)$ and $\delta_L(t)$ measurement. At that useful signals as well as instantaneous values of noises are averaged, but relationship of signal-to-noise as a result of averaging, as it is shown in work [29], will be n times (n — number of readings) higher than in one-shot measurement. Thus, evaluation reliability significantly increased with storage method application.

As for time of measurement accumulation τ, then its selection is regulated with Kotelnikov theorem, according to which $\tau = n/v$ condition should be fulfilled, where v is the half of spectrum of measurement signal. It should be noted that if movement of welding torch across the welded joint line takes place without stops in the extreme points, then measurement accumulation should be started somewhere before welding torch coming the extreme point, i.e. at moment of time $t_m = 2A/v_y - \tau$. At that is assumed that the start of the time reading is the moment when welding torch is located in a previous extreme point.

Thus, lateral deviation ε can be calculated on the next formula using accumulation method

$$\varepsilon = \frac{\bar{\delta}_R - \bar{\delta}_L}{\bar{\delta}_R + \bar{\delta}_L}(A - v_y T_w), \qquad (12)$$

similar to formula (11), but which instead of instantaneous values $\delta_R(t)$ and $\delta_L(t)$ used average values $\bar{\delta}_R$, and $\bar{\delta}_L$ received as a result of accumulation of n readings and their averaging in time interval τ.

In the conclusion it should be noted that a task of welding robot adapting to varying conditions of arc welding can be only partially solved with the help of the arc sensors, since these sensors function only

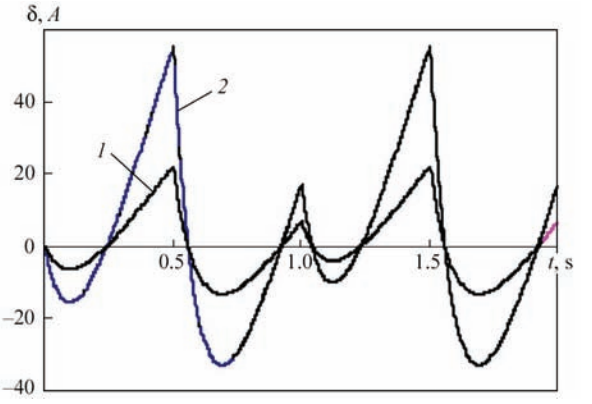

Figure 2. Curves of transition processes $\delta = \delta(t, a)$: *1* — at a = 0.10 mm^{-1}; *2* — at a = 0.25 mm^{-1}

in process of arc welding. Obviously, that additional adapting means are necessary at «free» movement of welding tool from one welded joint to another. A solution of a difficulty can be recently discussed idea on development of multisensor systems.

In particular, the welding robot equipped with the sensing system, consisting of two devices, i.e. arc sensor and video camera, can be used for consumable electrode arc welding of fillet joints and joints with groove preparation. The video camera allows on-line evaluation of a difference of geometry characteristics of welded joint on the characteristics set by program. Based on this information the welding robot control system automatically corrects a welding tool movement program before arc welding start and at transfer from one welded joint to another. The video camera is not used in process of welding and current information on welding tool position relative to welded joint

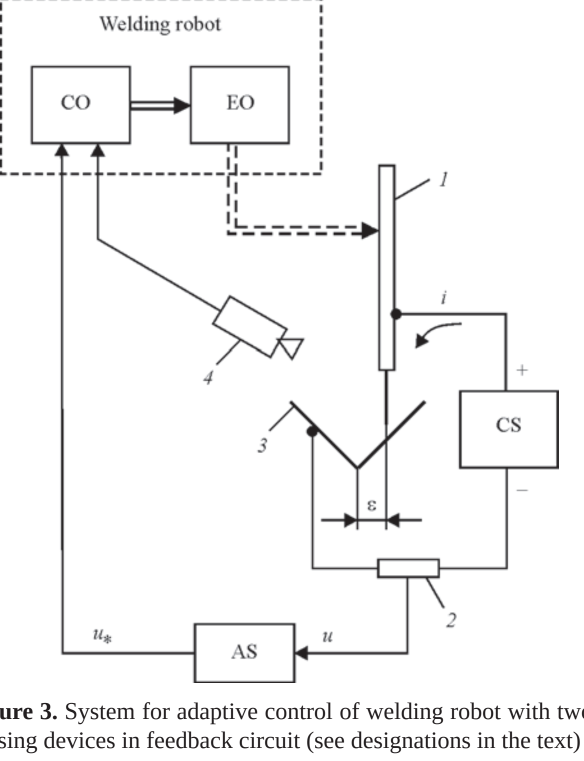

Figure 3. System for adaptive control of welding robot with two sensing devices in feedback circuit (see designations in the text)

line comes from other sensor. This information is used for correction of welding tool movement directly in process of arc welding.

Figure 3 shows one of the possible variants of system for adaptive control of welding robot with two sensor devices in feedback circuit, where the following designations are taken: CD — control device; ED — executive devices; CS — welding current source; AS — arc sensor; *1* — welding tool; *2* — current probe; *3* — part being welded; *4* — video camera. Signal $u = K_2 i$, where K_2 = const, comes to input of AS. Signal $u_* = u_*(u)$, corresponding the requirements of interface of specific welding robot, is formed at AS output. Evaluation of ε deviation, appearing in process of arc welding, is calculated in CD on formulae (11) or (12) and used for automatic correction of welding tool movement directly in process of arc welding. Correction of spatial position of welding tool before and after arc welding operation is carried out based on information coming from video camera *4*.

Conclusions

1. Application of robots for gas-shielded consumable electrode arc welding provokes a series of problems related with necessity to equip the robots with special sensing devices, which would provide a system for control of current information in course of welding process in very complicated for observation conditions.

2. Possibility was considered for partial solution of this problem using the arc sensing devices, which in contrast to optical, induction or acoustic sensors are not effected by light, electromagnetic or heat radiation, turbulent flows of gas, spattering of molten metal, intensive emission of fumes and dust directly in the measurement zone.

3. The formulae are given for numerical evaluation of the welding tool deviation from the joint line based on the results of current measurements coming from the arc sensor. These formulae can be used for construction of the algorithms of automatic correction of welding tool movement directly in arc welding process.

4. Application of the arc sensor together with the video sensor systems is perspective for widening the adapting capabilities of the welding robot.

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