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RESISTOMETRIC METHOD OF WELDING SPEED MEASUREMENT FOR SIMULATING WELDING SYSTEMS

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Some theoretical problems of resistometric method for determination of welding arc spot coordinates and evaluation of speed of electrode movement during realization or simulation of arc welding, as well as the peculiarities of plotting the hardware part and software of simulating welding systems using this method are considered. The examples of application this method in the hardware-software complexes (welding simulators), as well as the basic variants of schematic and technical construction of devices for realization of resistometric method in the simulating welding systems, designed and industrially manufactured at the SE «Scientific and Engineering Center of Welding and Control in the Field of Nuclear Engineering» (SEC WCNE) of the E.O. Paton Electric Welding Institute of the NAS of Ukraine are presented. 17 Ref., 4 Figures.

Keywords: *arc spot coordinates, welding speed, simulating welding systems, simulator of workpiece welded, welding speed control devices, welding current sensors, «current loop»*

In the process of development of works on designing the simulating welding systems (SWS), different methds for welding speed estimation and devices for realizing these methods were proposed [1-3]. In the opinion of many authors, to estimate the welding speed in arc SWS, the technical means applying video sensors [4], devices of acoustic location [5], receivers of optical [6–8] or thermal radiation [1, 9, 10] are most acceptable.

Obviously, the use of video sensors provides the welding speed measurement with a high accuracy, but at the same time today the complexity and cost of hardware and software means of SWS are increasing, which is economically unreasonable in the vast majority of cases.

The use of acoustic location methods in arc SWS (especially in low-amperage ones) is rather complicated due to the low level of useful signals of the arc simulator [11] and, therefore, it is little promising.

For welding speed control devices (WSCD), designed using discrete sensitive elements which perceive optical radiation of visible or infrared range from the moving arc, the dependence on optical state of surrounding medium is characteristic, whereas WSCD on the basis of thermosensors are characterized by dependence on geometric shape of surrounding bodies and distance from them to thermosensors, as well as on the temperature and heat conductivity of the surrounding medium. In addition to a comparatively low accuracy of measurements, among the disadvantages of WSCD produced on receivers of optical or thermal radiation, the need in schematic-design complications of both hardware interface of SWS, as well as the manipulator-positioner and simulators of welding tools or workpiece welded, being in its composition, should be mentioned.

The analysis of capabilities of the known methods of WSCD and increasingly growing technological and didactic requirements to arc SWS shows that the most known and existing WSCD are already far from fully meeting these requirements.

Meanwhile, in arc SWS, quite satisfactory results can be achieved by using a relatively easy realizable resistometric method for determination of moving arc coordinates and estimating the welding speed. This method is based on the method of determining coordinates of a measuring probe in a conductive medium [12, 13], which was developed by V.V. Vasiliev and L.A. Simak at the G.E. Pukhov Institute for Problems of Modeling in Power Engineering of the NAS of Ukraine and later found development at the E.O. Paton Electric Welding Institute (PWI) and SEC WCNE for systems of monitoring the arc welding processes and SWS as-applied to the moving spot of welding arc or its simulator.

The principle of resistometric method is explained by Figure 1.

The simulator of workpiece welded (SWW), typical for SWS, represents a steel plate of rectangular shape, the length of which is l_0, the width is d_0 and the thickness is δ_0, moreover, $\delta_0 << d_0 << l_0$. One of the output poles of the welding power source G is connected to the point of connection of two branches (*ac* and *bc*), each of them is connected to one of two current (*a* or *b*) conductors by the second point, on the opposite end sides of SWW. The second output pole of the welding power source is connected to the current conductors of simulator of the welding tool (electrode holder).

When using the welding source in the mode of the current source (stabilizer), which is characterized by a «bayonet» external volt-ampere characteristic (which is in the most SWS), the welding current I_a does not depend on voltage drops at the arc, in SWW, in the wires and current conductors of the welding circuit.

From the obvious equality $R_0 = R_1 + R_2$ (where R_0 is the electrical resistance of SWW, R_1, R_2 are the resistances of its regions *ax* and *bx*, respectively) and from the assumption about inalterability of SWW section along its entire length l_0 it comes out that the coordinate *x* of the arc spot on SWW is determined by the relation:

$$x = l_0R_1/R_0 = l_0(1 - R_2/R_0). \quad (1)$$

In accordance with the laws of Kirchhoff and assumptions that the electrical resistances of SWW and its individual regions remain unchanged in the process of welding, and the electrical resistances of branches *ac* and *bc* are equal between each other and are negligibly small as compared to the resistance of SWW, for regions *cax* and *cbx* the following system of equations is justible:

$$\begin{cases} I_1 + I_2 = I_a \\ I_1R_1 = I_2R_2 \end{cases}, \quad (2)$$

where I_1, I_2 are the currents passing through the regions *cax* and *cbx*, respectively.

The solution of the system of equations (2), taking into account the expression (1) is the following relations:

$$I_1 = I_a(1 - x/l_0), \quad (3)$$

$$I_2 = I_ax/l_0, \quad (4)$$

from which we obtain the expression for the arc spot coordinate *x*:

$$x = l_0(1 - I_1/I_a) = l_0I_2/I_a, \quad (5)$$

and from it the expression for the speed of arc movement (welding speed) V_w is obtained:

$$V_w = dx/dt = l_0/I_a(- dI_1/dt) = l_0/I_adI_2/dt. \quad (6)$$

Thus, the solution of the problem on estimation of welding speed in SWS is reduced to determining the changes in time of currents in the branches, by which SWW is connected to one of the output poles of the welding power source.

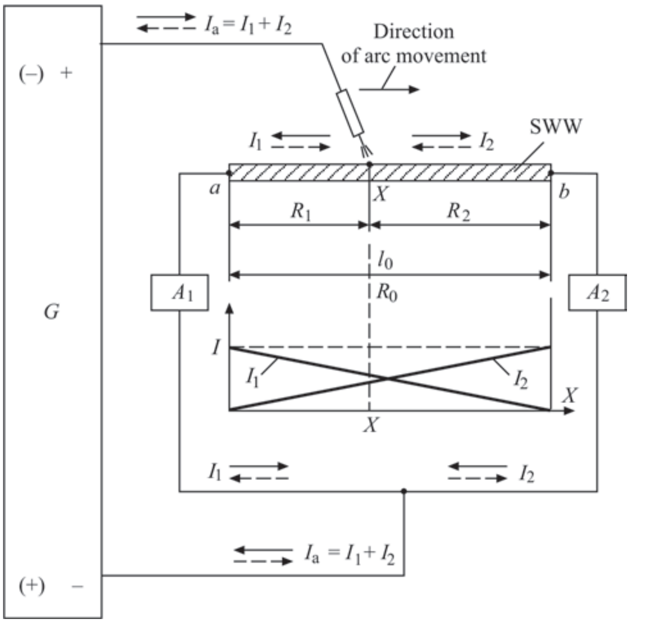

Figure 1. Scheme of resistometric method for determining welding arc spot coordinate and measuring welding speed in SWS (description see in the text: A_1, A_2 are the current sensors in the branches *cax* and *cbx* of the welding circuit)

The real connections of SWW with a welding circuit are carried out by conductors having a finite length and a certain section, and, consequently, having an ohmic resistance.

Figure 2 shows an equivalent diagram of welding circuit in which resistors R_1^* and R_2^* imply the active resistances of branches *ac* and *bc*. Obviously, taking into account R_1^* and R_2^*, the system of equations for the regions *cax* and *cbx* has the following form:

$$\begin{cases} I_1^* = I_2^* = I_a \\ I_1^*(R_1 + R_1^*) = I_2^*(R_2 + R_2^*) \end{cases}, \quad (7)$$

where I_1^*, I_2^* are the currents through the real regions *cax* and *cbx*.

Solving the system of equations (7), we obtain the expressions:
for currents I_1^*, I_2^*:

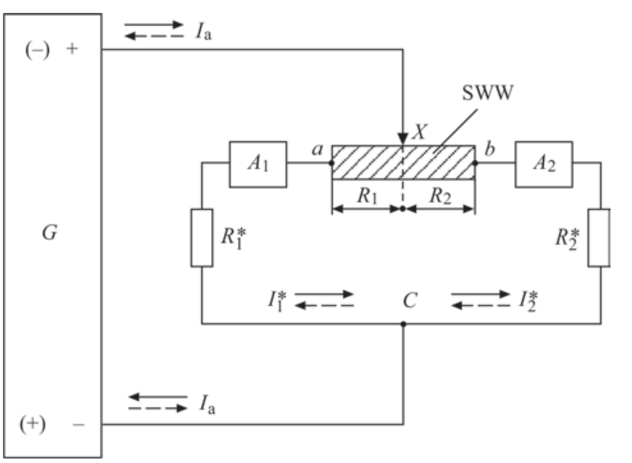

Figure 2. Equivalent electric diagram of SWS welding circuit (description see in the text)

$$I_1^* = \frac{I_a(R_2 + R_2^*)}{R_0 + R_1^* + R_2^*}, \quad (8)$$

$$I_2^* = \frac{I_a(R_1 + R_1^*)}{R_0 + R_1^* + R_2^*}; \quad (9)$$

for arc spot coordinate:

$$x^* = l_0\left[\left(1 + \frac{R_2^*}{R_0}\right) - \frac{I_1^*}{I_a}\left(1 + \left(R_1^* + \frac{R_2^*}{R_0}\right)\right)\right] = = l_0\left[\frac{I_2^*}{I_a}\left(1 + \left(R_1^* + \frac{R_2^*}{R_0}\right) - \frac{R_1^*}{R_0}\right)\right]; \quad (10)$$

for welding speed:

$$V_w^* = \frac{l_0}{I_a}\left(1 + \frac{R_1^* + R_2^*}{R_0}\right)\left(-\frac{dI_1^*}{dt}\right) = = \frac{l_0}{I_a}\left(1 + \frac{R_1^* + R_2^*}{R_0}\right)\frac{dI_2^*}{dt}. \quad (11)$$

Here:

$$\frac{dI_1^*}{dt} = \left(\frac{1}{1 + \frac{R_1^* + R_2^*}{R_0}}\right)\frac{dI_1}{dt}, \quad (12)$$

$$\frac{dI_2^*}{dt} = \left(\frac{1}{1 + \frac{R_1^* + R_2^*}{R_0}}\right)\frac{dI_2}{dt}, \quad (13)$$

By making simple transformations with the substitution of expressions (8) and (9) into (10), and expressions (12) and (13) into (11), it is easy to be sure that $x^* = x$, and $V_w^* = V_w$, and, consequently, the active resistances R_1^* and R_2^* of branches *ac* and *bc* of the welding circuit do not influence the determination of arc spot coordinate and welding speed. At the same time, it follows from the expressions (8), (9), (12) and (13) that on the values of relation $(R_1^* + R_2^*)/R_0$ the values of currents I_1^*, I_2^* and their derivatives dI_1^*/dt and dI_2^*/dt depend.

On the relation $(R_1^* + R_2^*)/R_0$, the characteristic largely depends, which is important for realization of resistometric method, which can be called the sensitivity by the current E_i, and determined through the values of currents I_1^*, I_2^* per unit of length of SWW according to the expression

$$E_i = \frac{I_a}{l_0}\left(\frac{1}{1 + \frac{R_1^* + R_2^*}{R_0}}\right). \quad (14)$$

In the process of experimental and technological investigations carried out at the PWI and SEC WCNE, the dependence $E_{rel} = f(k_R)$ was investigated, here the relative sensitivity E_{rel} implies the relation E_i/E_{i0}, where E_{i0} is the sensitivity at $R_1^* = R_2^* = 0$, and $k_R = 1 + (R_1^* + R_2^*)/R_0$. Moreover, it was established that the dependence $E_{rel} = f(k_R)$ has a hyperbolic character and is the most sharply expressed at $k_R < 1.2$.

In real SWS, as a rule, $k_R > 1.2$, which predetermines the possibility of rational selection of sections and weight of the wires of branches of welding circuit. Thus, for example, in the low-ampere arc welder simulator MDTS-05M1, a low-carbon steel plate (in particular, St3) is applied as SWW, whose operating length is l_0 = 360 mm, and R_0 = 0.45 mOhm. The length of the conductor of each of the branches *ac* and *bc* of the welding circuit is 0.45 m. At a 30 mm^2 cross-section of the copper conductor of each branch, the active resistance $R_1^* = R_2^*$ = 0.17 mOhm, k_R = 1.46 and (at welding current I_a = 4.5 A) E_i = 6.84 mA/mm.

The estimation of accuracy of welding speed measurement applying resistometric method, taking into account the influence of R_1^* and R_2^*, can be carried out by determining the root-mean-square error σ_{rel} according to the expression

$$\sigma_{rel} = \frac{dV_w^*}{V_w} = = \sqrt{\left(\frac{dl_0}{l_0}\right)^2 + \left(\frac{dR_1^*}{R_0 + R_1^* + R_2^*}\right)^2 + \left(\frac{R_1^* + R_2^*}{R_0 + R_1^* + R_2^*}\right)^2 + \left(\frac{dR_0}{R_0}\right)^2 + \left(\frac{dI_a^*}{I_a}\right) + \left(\frac{di}{i}\right)^2}, \quad (15)$$

where dV_w^* is the differential of the function V_w^*; $i = dI_1^*/dt$ or $i = dI_2^*/dt$; $di = d(dI_1^*\,\mathrm{d}t)$ or $di = d(dI_2^*/dt)$.

Since in the expression (15) the summands, containing R_0, R_1^*, R_2^*, as is shown by numerical analysis, are negligibly low, then the formula for determining σ_{rel}, can be represented with a sufficiently accurate approximation, in the form as:

$$\sigma_{rel} = \sqrt{\left(\frac{dl_0}{l_0}\right)^2 + \left(\frac{d(I_1^* + I_2^*)}{I_1^* + I_2^*}\right)^2 + \left(\frac{di}{i}\right)^2}. \quad (16)$$

The expression (16) allows making the conclusion that the error of measurement V_w is determined by the errors in the measurements of l_0, I_1^*, I_2^*, dI_1^*/dt or dI_2^*/dt, which, in their turn, depend on accurate characteristics of respective tools and measuring devices.

The resistometric method can be realized using analog or digital WSCD.

To the advantages of analog WSCD the comparative simplicity of circuit solutions and algorithms for their operation, high quick response, possibility of using an elementary base of mass application, relatively low cost should be attributed, and among the drawbacks: the limited accuracy of differentiating signals reflecting changes in the arc spot coordinate and the need in periodic readjustments to compensate the drift of zero values of output signals of operational ampli-

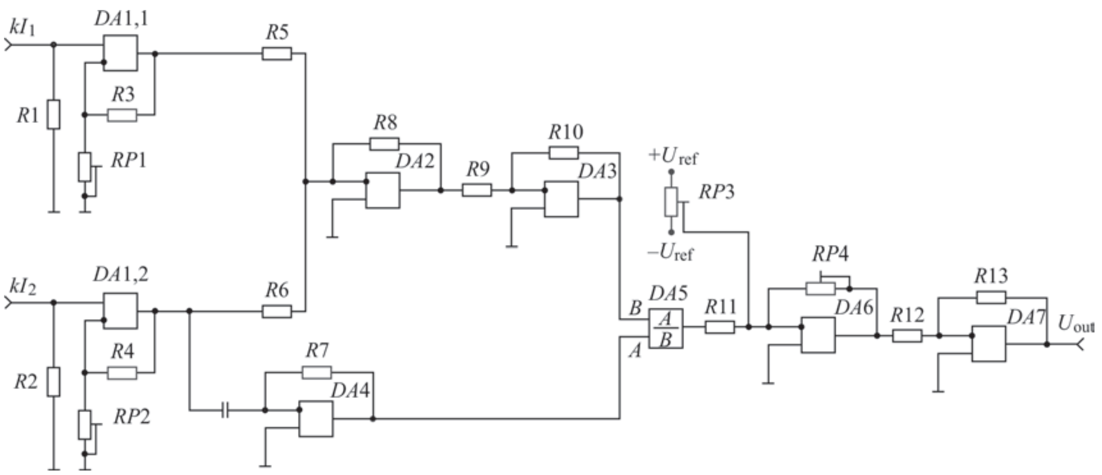

Figure 3. Simplified elementary electric diagram of one of the variants of plotting analogue WSCD

fiers and instrumental recalibrations when changing the initial conditions (SWW dimensions, arc current values I_a, etc.) should be mentioned.

Figure 3 shows a simplified electrical diagram of one of the possible variants for plotting the analog WSCD. The device contains input scaling amplifier *DA*1, adder *DA*2, which also performs the scaling function, functional divider *DA*5, inverting amplifier *DA*3, differentiating amplifier *DA*4 and realizing the function $U_{out} = k(AU_{in})$, where *k* and *A* are proportionality and scaling factors, respectively, output amplifiers *DA*6 and *DA*7. The setting-up resistors *RP*1 and *RP*2 serve for readjusting the device, and the resistors *RP*3 and *RP*4 serve for its calibration. The levels of output signals of the device displaying the arc spot coordinate x^* and welding speed V_w^* are selected based on the required range of standard signals, for example, ± (0–5) V or ± (0–10) V.

As compared to analogue ones, the digital WSCD provide a significantly higher interference immunity and measurement accuracy, possibility of in-process changing in operation and performance of calibrations and readjustments, stability of parameters in the acceptable range of changes of influencing climatic factors of the outer environment using the algorithm programming means. Moreover, as the digital WSCD include such a functional unit as an analog-to-digital converter (ADC), which is complicated as to its internal structure and a relatively expensive one, the cost of digital WSCD significantly exceeds the cost of analog devices.

The block diagram of the variant of a digital WSCD is shown in Figure 4. The device is composed of normalizing amplifiers *DA*1.1, *DA*1.2 and ADC *DA*4. To improve the interference immunity of ADC, the active low-pass filters with a single amplifying by *DA*2 and *DA*3 are introduced into the device. The normalizing amplifiers *DA*1.1 and *DA*1.2 provide the input of signals in the regulated range of levels, for example, ± (0–1.25) V or ± (0–2.5) V to the analog inputs of ADC. The type of ADC is selected from the conditions of its compatibility with a personal computer (PC), including the levels of output signals of ADC and software. At the same time, it should be noted that since almost every ADC, intended for input of information into PC, has at least eight analog input channels, it can be used not only to enter the information about the arc spot coordinate and welding speed, but also about the voltage (length) of the arc, angular positions of electrode of the welding tool simulator and other parameters characterizing the process of training or testing.

Both analogue and digital WSCD should provide their calibration, taking into account the initial conditions: geometrical dimensions of SWW, active resistances of wires and transient resistances of contact connections of branches of welding circuit, influence of factor k_R, sensitivity E_i. The calibration of analog WSCD is more labor-consuming and requires the use

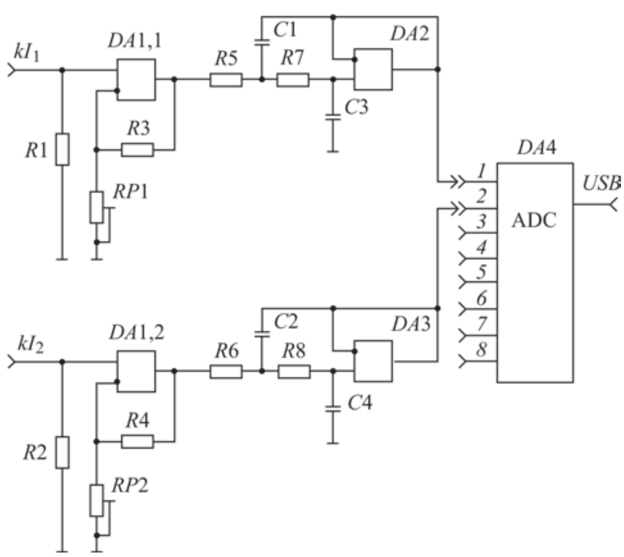

Figure 4. Simplified electric principal circuit of one of the variants of digital WSCD construction

of additional measuring equipment, for calibration of digital WSCD it is enough to have the software means.

The obligatory sensor components of both analog and digital WSCDs are two identical current sensors, which should have a linear transmission characteristic (nonlinearity coefficient of ≤ 0.5 %) in the whole range of possible changes of welding current, independently of its shape and polarity, high accuracy (the given error is not more than ± 1 %), wide dynamic and frequency range (transmission band of not less than 50 kHz), resistance to effect of inductions and interferences, always occurring during arc welding. In addition, the sensors should provide galvanic isolation of input and output circuits and should not introduce the significant additional resistances into the welding circuit. As-applied to arc SWS, the sensors based on the Hall effect the best comply with these requirements, including current sensors serially produced by a number of companies, including LEM (Switzerland) and OJSC «LEM Rossia» (RF), for example, the current sensors LAH25-NP with current measurement error of ± 0.3 %, PJSC «CHEZARA» (Ukraine), for example, the current sensors DIT-50M, DST-250, DST-500 with the measurement error of ± 0.1 %. Such current sensors have a potential or current output. The latter allows forming a link between the information output of the sensor and the WSCD input amplifier in the form of a «current loop», and thus, significantly improving the interference immunity of the device, but in this case the input stages of WSCD should be performed using the «current-voltage» converter scheme.

At the PWI together with SEC WCNE the experiments were carried out for checking the accuracy of digital WSCD, included into the computerized low-ampere arc welder simulator MDTS-05M1 and the arc welder simulator TSDS-06M. For movement of non-consumable electrode along the fixed SWW at the preset speed, the installation mechanism was used, assembled on the base of the automatic machine ADSV-6 for argon-arc welding. The source for arc supply in the case of MDTS-05M1 was the welding power module MSS-05 of this simulator, operating in the mode of a current source and providing welding current (4.5 ± 0.3) A throughout the whole technologically grounded range of the arc length, and in the case of TSDS-06M the power module based on the universal welding inverter «PROFI TIG 200», operating also in the mode of current source and providing the welding current of 80, 100, 120, 140, 160 and 180 A with the accuracy of ± 5 was used. As the SWW, in case of using MDTS-05M1 a plate of St3 was used, the total length of which was 440 mm (working length l_0 = 360 mm), width 40 mm, thickness 2 mm, and in case of using TSDS-06M a plate of the same steel, the total length of which was 470 mm (working length l_0 = 390 mm), width 60 mm, thickness 10 mm was used. The welding was performed at a constant speed of movement of non-consumable electrode (rated diameter was 2.0 mm in case of MDTS-05M1 and 3.0 mm in case of TSDS-06M) of 2, 5 and 8 mm/s, at each fixed value of welding speed, after each pass (of 360 and 390 mm length, respectively), the arc passing was performed in the opposite direction. Each experiment was repeated at least five times. The values of welding speed obtained with the help of the system WSCD — PC of the simulators MDTS-05M1 and TSDS-06M, were compared with the values of the speed of electrode movement, controlled by the devices (in particular, by ammeters of M42100 type) of the experimental installation mentioned above at the error, not exceeding ± 1.5 %. It was established by the statistical processing of experiments results that the relative error in measuring welding speed with the help of digital WSCD in case of MDTS-05M1 did not exceed ± 2.0 %, and in case of TSDS-06M ± 2.5 %.

It should be emphasized that resistometric method for determining the linear coordinate of welding arc spot and measuring welding speed, as well as digital WSCDs for its realization, were successfully applied in the hardware-software simulating complexes (welding simulators) MDTS-05M1, TSDS-06M and TSDS-06M1, designed at the PWI together with SEC WCNE [14–17]. They are widely represented and operate in Ukraine and in a number of countries of near and far abroad (for example, in Kazakhstan, Belarus, RF, Macedonia, China and other countries). Only in Russia, more than 1200 such hardware-software simulating complexes are in operation. Moreover, in a number of their educational institutions, training and certification centers, the whole simulating classes and laboratories were created on the base of these simulators to train operators in MAW, TIG and MIG/MAG welding. The experience in applying these means of technical training confirms their high operation reliability, economical efficiency and effectiveness both in the professional selection and in the initial professional training of welders, as well as for improvement of welding personnel skills, industrial training and testing, and in some cases for admittance control.

Conclusions

1. Resistometric method of measuring welding speed provides the possibility of determining linear coordinate of welding arc spot and speed of its movement in arc SWS applying a comparatively simple method with acceptable validity.

2. Taking into account the trends of development of SWS, the most challenging devices providing realization of resistometric method for determining linear coordinate of welding arc spot and measuring welding speed are digital WSCD.

3. In some cases, the resistometric method of measuring welding speed can also be used to solve the problems of monitoring real arc welding processes.

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