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INFORMATION-MEASURING SYSTEM FOR ARC WELDING AND SURFACING

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Information-measuring system for arc welding and surfacing was developed. The system allows automatic determination of process state zones, i.e. zone of arc striking, arc running, short-circuiting, open-circuit and arc extinction, thus eliminating any subjectivity in zone identification; and provides an extended set of calculated statistical parameters for each of the states. For this purpose, digitizing of welding current and voltage signals, computer processing by algorithms of automatic recognition and clustering of periodic status zones, using empirical rules, analysis of histograms of distribution of current and voltage signals separately, as well as of histograms of their joint distribution, are used. Built information-measuring system for arc welding and surfacing based on ADC E14-440 and notebook allows calculation of 29 statistical parameters, characterizing the process. Information-measuring system performs automatic identification of the state of welding/surfacing process, thus eliminating the human factor influence on the derived estimates of statistical parameters of the process. 11 Ref., 4 Tables, 8 Figures.

Keywords: *information-measuring system, welding process, welding, surfacing, clustering, welding process state, arc short-circuiting, arc extinction*

Of all the process parameters, the main scope of information about the welding process is provided by the electric parameters, namely welding current I_w and arc voltage U_a. They are also the easiest to measure. Therefore, I_w and U_a are used for studying the processes of welding/surfacing in most cases, and numerous information-measuring systems (IMS) have been created for their measurement, recording, processing and visualization. Measurement and analysis of electric parameters of arc welding/surfacing process is used for quality control, determination of properties, mode selection and regulation of the process.

Composition of all IMS is basically the same: monitored parameter sensors, normalizing signal transducers, analog-digital converter (ADC), data processing and visualization device, and software. In research practice, IMS are mostly assembled from purchased above-mentioned modules. Commercially available IMS are also known, for instance, ADAM III, Arc Guard, Weldcheck [1], Hannover XV (AH XV) [2], DAREG [3], ARCDATA LQ-1N [4], ARCDATA LQ-2 [5], Arcwatch™, APN-1, APN-2 [7].

Analysis of welding current and arc voltage records is usually performed by standard statistical methods, the number of analyzed characteristics being extremely limited.

Several process states during welding can be singled out (Figure 1): open-circuit mode of welding source (OC); arc striking (AS); steady-state arc process with periods of short-circuiting (SC); periods of arc running (AR) and arc extinction (AE). Each of these states is characterized by its statistical indices and threshold binarization levels to determine their beginning and end. Usually, only the steady-state arc process is studied, for which purpose respective fragments of the records have to be manually chosen practically in all IMS. This essentially influences the results of subsequent statistical processing of the data, making them dependent on the specific researcher, conditions of electric signal recording, and record fragment selected for processing. A pleasant exception are works [8, 9], where the problem of automatic identification of the states of consumable-electrode welding process is, apparently, solved, for welding source certification IMS, by clustering current and voltage data.

Described below is arc welding IMS, differing from the known systems by automatic determination of welding process state zones and expanded set of calculated statistical parameters for each process state [10].

Data acquisition. Measurement and recording of arc welding current and voltage is performed using versatile module ADC E14-440 (USB2 bus), which is particularly convenient to create portable measuring systems based on a notebook. Table 1 gives the modes of arc surfacing with 1.6 mm wire in CO_2, and Table 2 — in a mixture of shielding gases (82 % Ar + 18 % CO_2).

For ADC the requirements to quantization level and sampling interval of signals of voltage source U_w and current source I_w are determined by the requirements to accuracy of determination of root mean square (RMS) deviation of SC voltage — $\sigma^{U_{sc}}$ and RMS deviation of SC duration — $\sigma^{T_{sc}}$. Preliminary estimates of $\sigma^{U_{sc}}$ and $\sigma^{T_{sc}}$ showed that $\sigma^{U_{sc}}$ is equal to approximately 2 V, and $\sigma^{T_{sc}}$ is 5 ms. As the accuracy of the order of 1 % is usually sufficient for process parameters, limit measurement error was taken to be $\sigma^{U_{sc}}$ = 0.02 V, and $\sigma^{T_{sc}}$ = = 0.05 ms.

Maximum frequency of ADC E14-440 at digitizing of the two parameters is 200 kHz, and digit capacity is 14 bits, i.e. sampling interval is 0.005 ms, and quantization level is 0.05 %. This more than satisfies the above requirements. To limit the size of obtained records, minimum admissible sampling frequency of 20 kHz was selected.

Data processing. Algorithms of automatic recognition of OC, AS, SC, AR and arc extinction AE periods have been developed for computer processing of I_w and U_w signals, recorded using E14-440 module and PowerGraph software. The algorithms use empirical rules, analysis of distribution histograms of I_w and U_w signals separately, and analysis of histograms of joint distribution of I_w and U_w.

Obvious features of I_w and U_w signals, which can be used at data clustering to single out welding process periods, are as follows:

● increased rate of variation of I_w and U_w signal at the moment of SC appearance;

● «zero» or close to zero I_w value and higher U_w value in OC or AE periods;

● increased I_w value and lower U_w value in SC period;

● relatively mean values of I_w and U_w in AR period;

● OC period is characteristic only for beginning and/or end of signal records;

● AE period appears only after AR or SC periods;

● AE period, which exceeds a certain time limit, is a OC;

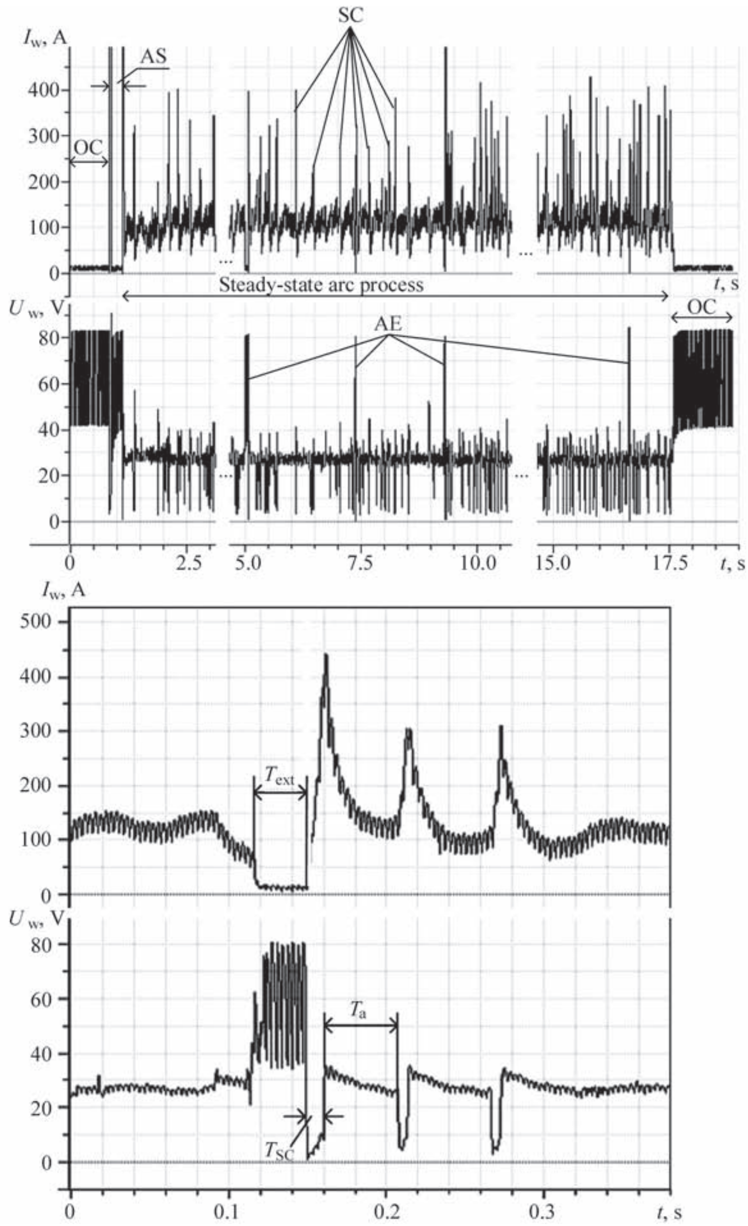

Figure 1. Record of CO_2 welding process

● AS period starts at first SC, and ends at first appearance of the period of AR steady-state process;

● steady-state welding process is observed from the beginning of first AR period and up to the moment of the beginning of OC period at the end of recording;

Table 1. Modes of CO_2 arc surfacing with 1.6 mm wire

Number of arc surfacing mode	Wire feed rate, m/h	Source voltage, U_w, V	Source current, I_w, A
1	160	26	120
2	330	28–29	220
3	220	27–28	150
4	420	30	260
5	460	60	270–280

Table 2. Modes of arc surfacing in a mixture of gases of 82 % Ar + 13 % CO_2

Number of arc surfacing mode	Wire feed rate, m/h	Source voltage, U_w, V	Source current, I_w, A
1	220	28	170–180
2	25	18–20	40–50
3	155	28	120
4	225	30	150
5	325	30	200
6	520	30	250
7	450	40	250

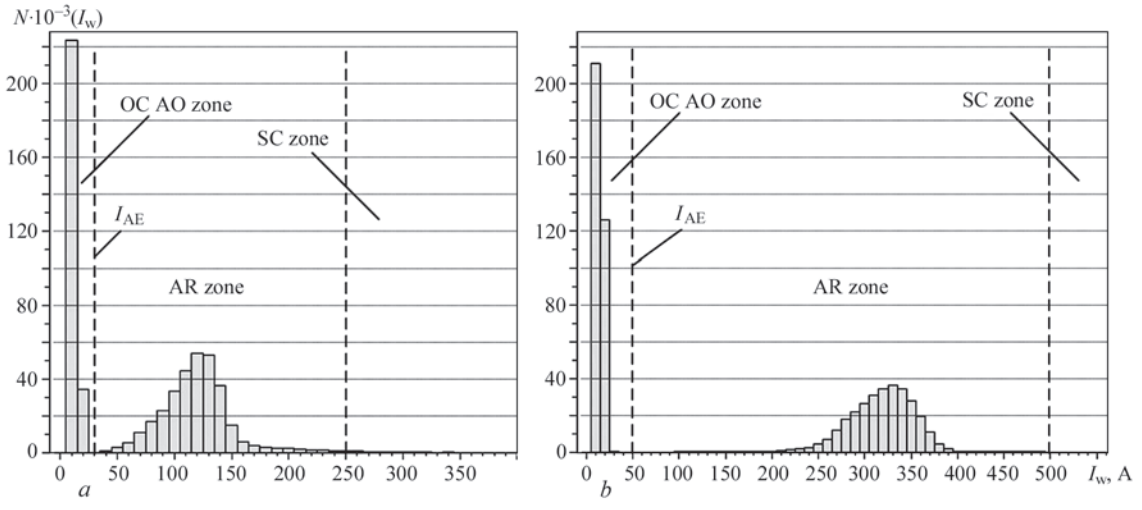

Figure 2. Histogram of distribution density N of I_w values for processes of CO_2 welding 1 (*a*) and 5 (*b*) (see Table 1)

- «zero» I_w and U_w values are indicative of a switched off source.

Considering that U_w in OC period can vary within a wide range and with sufficiently high rate in some cases (300 Hz frequency of change), beginning of AS period t_n is determined not by the first «abrupt» exceeding a certain limit change of I_w and/or U_w signals, but by the change of I_w level in keeping with the following algorithm:

$$t_n = \begin{cases} \dfrac{\overline{I}_i}{\overline{I}_{i-1}} > (\text{at } t \geq t_k) \\ \dfrac{\overline{I}_i}{\overline{I}_{i-1}} \leq (\text{at } t < t_k) \end{cases}, \qquad (1)$$

where $\overline{I}_i = \overline{I}_{i-1} + \dfrac{I_i}{N} - \dfrac{I_{i-N}}{N}$; I_i is the *i*-th value of I_w; I_i is the *i*-th value of averaged I_w value; ∞ is the constant value, determined experimentally (∞ = 2 is assumed); N is the number of samples, determining the interval of moving averaging (N = 100 is assumed).

A similar algorithm was used to determine the moment of the end of steady-state welding process t_k, and the moment of OC beginning at the end of observation with the only difference that the moving averaging should be implemented in the opposite direction: from the end to the beginning.

Preliminary identification of SC, AR and AE states of the process is based on analysis of histograms of distribution of probability density of I_w and U_w signals.

To be specific, let us consider two processes in CO_2: 1 and 5. Process 1 (Figure 1) is characterized by a large number of arc extinctions and quite fast striking, while 5 differs by rather long AS period and long record of OC period at the end of the process.

As one can see from Figure 2, *a*, *b* the histograms differ strongly by the ranges of current variations and modes, but have the same nature of distribution density. In both the cases, three characteristic regions are present, which kind of divide the entire range of current variation into three zones. For process 1 these are ranges of 0–30, 30–250 and 250–860 A. For process 5 these are ranges of 0–50, 50–500 and 500–1060 A.

The same can be said also about voltage histograms for process 1 (Figure 3) and 5 (Figure 4). For 1 these are ranges of 0–17, 17–40, and 40–90 V, and for 5 these are 0–43, 43–65 and 65–107 V.

It is obvious that these zones represent three different states of the welding process: SC; AR, OC or AE. We will define the boundaries of the zones as follows:

- U_{SA} is the boundary of SC and AR zones;
- U_{AE} is the boundary of zones AR and OC or AE;
- I_{AO} is the boundary of zone AR and OC or AE.

To determine the boundaries of U_{SA} and U_{AE} zones, it is logical to move to the left and to the right from AR zone mode up to the first minimums of voltage density distribution. As the arcing process is the most probable state of the arc in arc welding, the mode of the entire range of distribution density can be taken as the approximation of AR zone mode. However, in research practice OC duration can sometimes be greater than AR duration, which results in the entire implementation mode being in OC and AE zones (Figure 5). Therefore, before computer processing the observation record should be «cleaned» from excessive OC periods. It is sufficient for OC periods at the beginning and end of the record not to exceed 1 s at more than 10 s total duration of the record.

To «clean» the record from excessive OC periods, all the entries made 1 s before t_n, and 1 s after t_k are automatically removed. Figure 5 shows the histogram of distribution density of voltage after «cleaning».

Figure 6 gives the histogram of distribution density of current after «cleaning» for process 5. As we can see, compared to the histogram, shown in Figure 3, *b*, the frequency of current values appearing in OC and AE zones was greatly reduced, but not to the point when the entire record mode can be considered an AR zone mode. This is related to the fact that current in OC and AE periods has small scatter of values that increases distribution density of current in this zone.

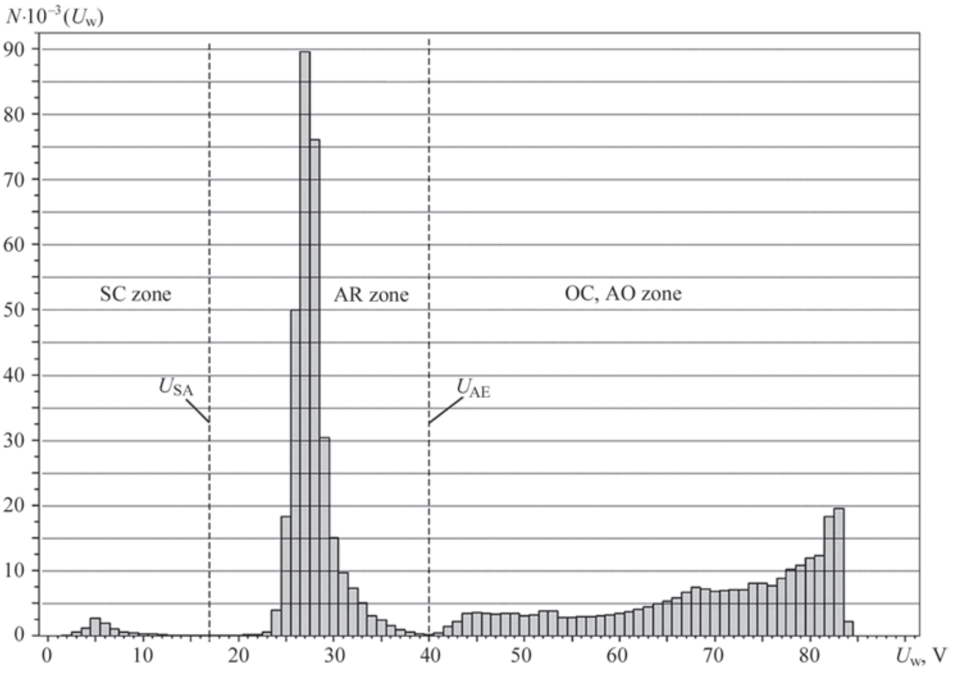

Figure 3. Histogram of distribution density N of U_w values for CO_2 welding process 1

The above-mentioned circumstance does not allow applying a similar algorithm of searching for zone boundaries for currents, as the one for voltages. In this case, it is proposed to use the feature of current histogram by which it differs from voltage histogram, namely OC and AE zones in the current histogram are much narrower than SC and AR zones. Assuming that OC and AE zone is in the range from 0 up to 40 A, and narrowing the search for I_{AE} boundary to these limits, it will be reduced to searching for a mode and gradient descent to the right of the mode to reach a minimum. Searching for boundary of AR and SC zones in the current histogram becomes senseless, because of «blurred» boundaries.

Boundaries of the three zones determined by current and voltage histograms are very inaccurate, as the zones overlap with each other and a signal with the value level, approximately corresponding to the zone boundary, can belong to either of them. The accuracy of determination of zone boundary can be enhanced by analysis of joint density of I_w and U_w distribution (Figure 7).

The graph clearly shows the zones of arc running and SC. Open circuit zone is less clearly visible, as there are no arc extinctions in process 3 (see Table 3), and open circuit periods here have been «cleaned». The surface between the zones is practically even that is indicative of the rarity of appearance of I_w and U_w combination in these locations.

$L_{AR\text{-}SC}$ boundary between SC and AR zones is defined as a projection on a plane (I_w, U_w) of the trajectory of movement of a certain point in a 3D space, mov-

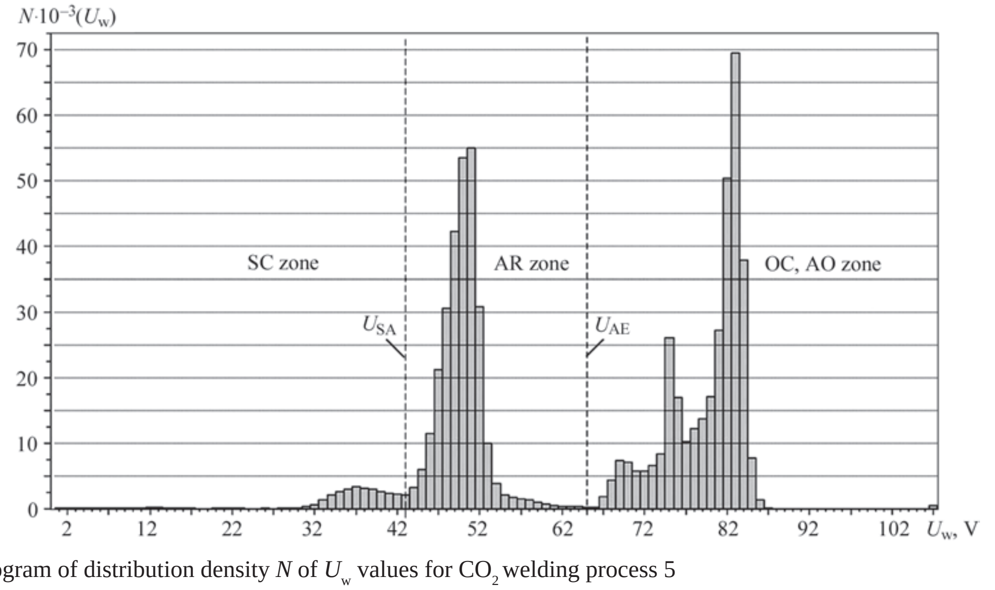

Figure 4. Histogram of distribution density N of U_w values for CO_2 welding process 5

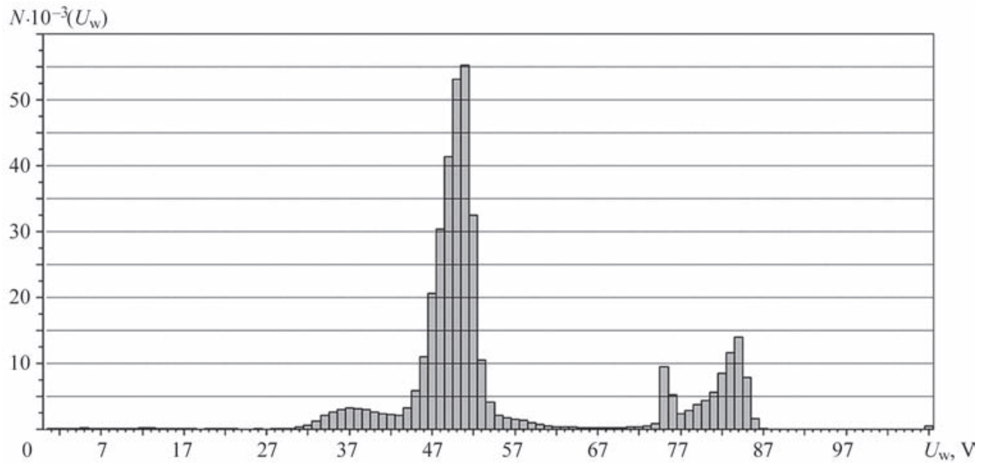

Figure 5. Histogram of distribution density N of U_w values for CO_2 welding process 5 after «cleaning»

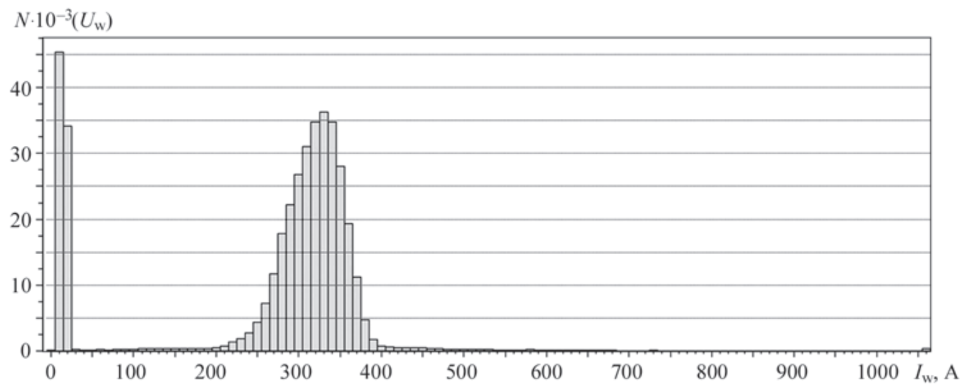

Figure 6. Histogram of distribution density N of I_w values for CO_2 welding process 5 after «cleaning»

ing in a certain direction from the assigned location by the algorithm of «search for least resistance path». Surface in space (I_w, U_w, $N(I_w, U_w)$), where $N(I_w, U_w)$ is the value of density of joint distribution of I_w, U_w, is assigned in the tabulated form. Taken as the initial point for searching for the boundary, are the coordinates of point A (see Figure 7) with the above derived U_{SA} value and «zero» current, i.e. $A(0, U_{SA}, N(0, U_{SA}))$. L_{AR-SC} path is drawn so that at movement from point A towards increase of current value in each step i value $N(I_w(i), U_w(j))$ was the smallest of the neighbouring values $N(I_w(i), U_w(j-1))$ and $N(I_w(i), U_w(j+1))$.

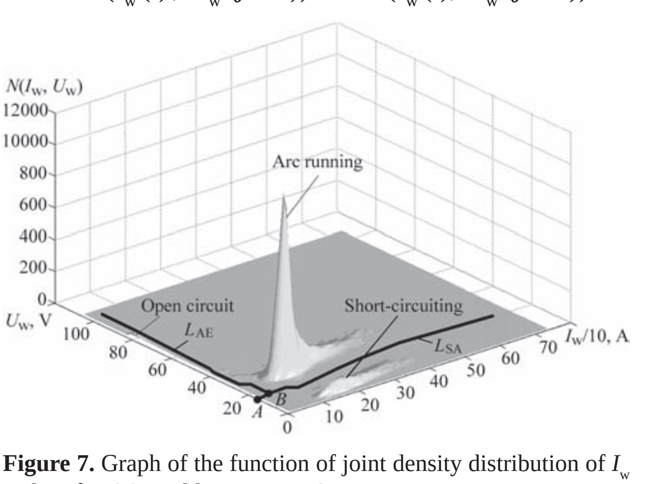

Figure 7. Graph of the function of joint density distribution of I_w and U_w for CO_2 welding process 3

Boundary of AE and AR zones is found in a similar way. Point $B(I_{AE}, U_{SA}, N(I_{AE}, U_{SA}))$ is taken as the initial point for searching for the boundary. L_{AR-OC} trajectory from point B towards increase of voltage value is drawn so that in each step j, value $N(I_w(i), U_w(j))$ was the smallest of the neighbouring values $N(I_w(i-1), U_w(j))$ and $N(I_w(i+1), U_w(j))$ (see Figure 7).

IMS of welding process parameters. A program of processing a binary file of 2-channel recording of welding current and voltage, created with PowerGraph software, was developed. The main format of the program is given in Figure 8.

The procedure for calculating the welding process parameters is as follows:

1. Signal filtering is performed:

● eliminating transient spikes (up to 0.1 ms) for I_w;

● filtering both the signals, using a non-linear filter with variable structure [11], which completely repeats the signal without delay, if the speed of its change does not exceed a certain assigned value ε, determined experimentally (in our case for current ε = 15 A, and for voltage ε = 5 V);

$$\overline{I_w(i)} = I_w(i-1) + \frac{\Delta I_w(i)}{|\Delta I_w(i)|}\varepsilon$$

provided $|\Delta I_w(i)| > \varepsilon$, otherwise $\overline{I_w(i)} = I_w(i)$. Similarly, for expression:

Table 3. Parameters of CO_2 welding process

CO_2 welding process parameters	Process number				
	1	2	3	4	5
Welding process duration, s	16.8	19.9	14.0	16.6	17.7
AS duration, s	0.31	0.31	0.34	0.23	2.68
Number of SC during AS period	2	2	3	2	15
Average current of arc process, A	121	231	167	283	317
Average voltage of arc process, V	27.5	28.9	26.8	30.8	48.7
RMS value of arc process current, A	40.7	62	55.6	84.9	42.9
RMS value of arc process voltage, V	5.7	7.1	7.3	7.8	5.6
Average arc current, A	120	226	162	274	318
RMS value of arc current, A	35.2	53.8	48.8	69	37.6
Average arc voltage, V	27.8	30.7	28.8	32.9	48.7
RMS value of arc voltage, V	2.4	2.9	2.7	3.8	4.8
Average SC current, A	196	287	218	362	308
Average SC voltage, V	6.2	10.1	7.1	12.9	12.4
RMS value of SC voltage, V	2.6	3.2	2.6	4.1	4.3
Average SC duration, ms	4.29	4.01	4.61	3.69	3.11
RMS value of SC duration, ms	2.1	1.4	1.3	2.3	1.3
Average arcing time, s	0.14	0.0	0.05	0.03	0.87
RMS value of arcing, s	0.119	0.033	0.026	0.0217	2.545
Average SC frequency, Hz	6.75	21.7	19.3	27.5	1.1
Average number of AE per min	15	0	0	0	12

$$\overline{U_w(i)} = U_w(i-1) + \frac{\Delta U_w(i)}{|\Delta U_w(i)|}\varepsilon$$

provided $|\Delta U_w(i)| > \varepsilon$, otherwise $\overline{U_w(i)} = U_w(i)$.

2. Record cleaning from excessive OC periods is performed. As a result of «cleaning», sections of OC periods of not more than 1 s duration remain at the beginning and end of the records.

3. Calculation of distribution density of voltage is performed with 5 V increment, U_{SA} and U_{AE} are calculated.

4. Current distribution density is calculated with 5 A increments in the section from 0 up to 31 A. The mode in this region is determined, then the location of density minimum (I_{AO} position) to the right of the mode in 0–31 A region is determined.

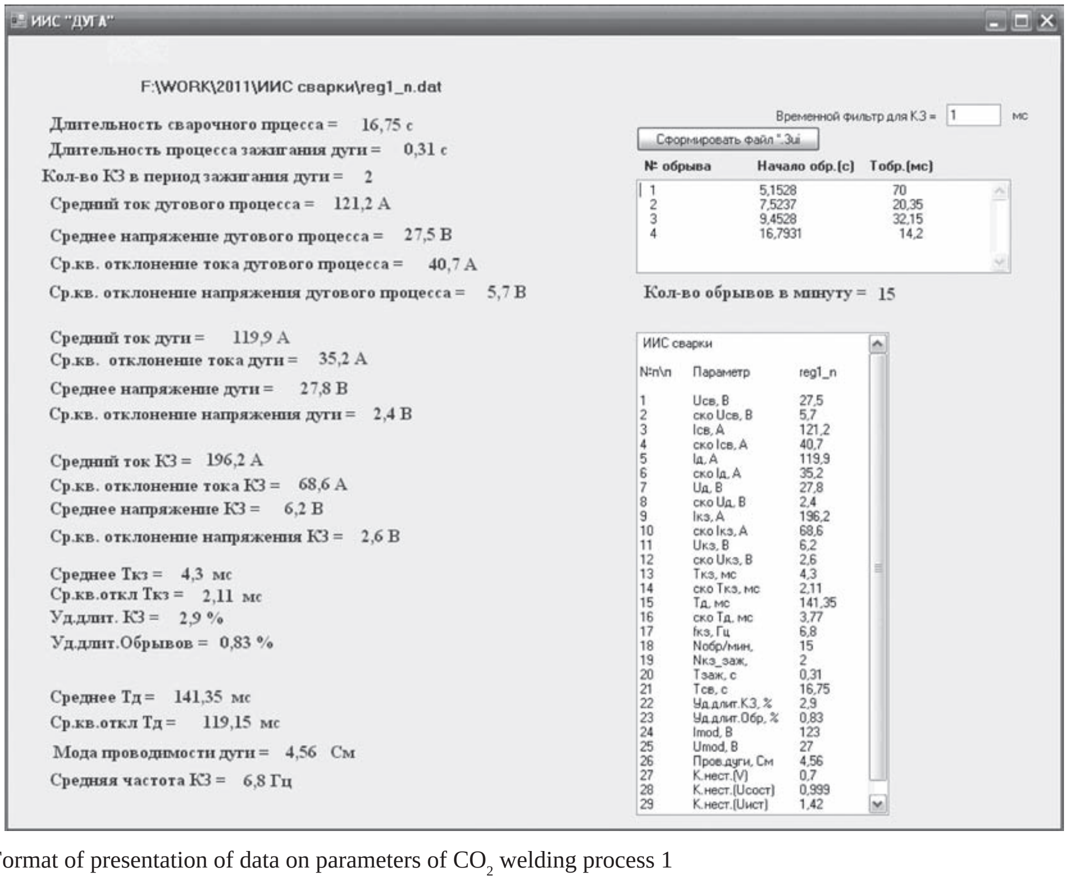

Figure 8. Format of presentation of data on parameters of CO_2 welding process 1

Table 4. Parameters of the process of welding in a mixture of CO_2 with argon

CO_2 welding process parameters	Process number						
	1	2	3	4	5	6	7
Welding process duration, s	16.9	19.8	16.5	14.9	12.0	13.3	21.9
AS duration, s	0.45	2.02	0.39	0.0	0.0	0.22	3.09
Number of SC during AS period	2	7	2	1	1	2	10
Average current of arc process, A	166	55	141	171	219	251	267
Average voltage of arc process, V	30.1	17.1	29.3	30.7	31.6	31.5	41.9
RMS value of arc process current, A	20.4	40.4	26.6	27.5	23.3	27.1	28.2
RMS value of arc process voltage, V	1.8	4.7	2	1.6	1.7	2.5	2.6
Average arc current, A	166	49	141	170	219	251	267
RMS value of arc current, A	19.6	30.5	25.9	21.8	23.3	27	28.2
Average arc voltage, V	30.1	18.1	29.4	30.7	31.6	31.5	41.9
RMS value of arc voltage, V	1.3	1.8	1.6	1.4	1.7	2.4	2.6
Average SC current, A	246	127	226	423	No SC	278	No SC
Average SC voltage, V	9.4	4	6.9	14.3	Same	14.4	Same
RMS value of SC voltage, V	2.7	1.6	2.2	8.4	»	5.9	»
Average SC duration, ms	3.89	9.07	4.79	5.01	»	1.58	»
RMS value of SC duration, ms	1.2	4.2	1.4	3.2	»	0.2	»
Average arcing time, s	1.096	0.111	1.46	1.855	11.975	1.302	18
RMS value of arcing, s	1.852	0.202	1.748	3.266	0	2.138	0
Average SC frequency, Hz	0.85	8.26	0.62	0.47	No SC	0.69	No SC
Average number of AE per min	0	3	0	4	0	0	0

5. The function of joint density distribution of I_w and U_w is calculated for current with 10 A increment, and for voltage with 1 V increment.

6. Boundaries of AR and SC zones — $L_{AR\text{-}SC}$ and boundary of AR and OC (AO) zones — $L_{AR\text{-}OC}$ are calculated, as well as $L_{AR\text{-}SC}$ and $L_{AR\text{-}OC}$ projections on plane $[U_{w,} I_w]$, i.e. $U_w = Tri(I_w)$ and $I_w = Tru(U_w)$, respectively.

7. Welding process clustering is performed.

Process state array $Kdd(i)$ is formed for its subsequent analysis. Each process state in $Kdd(i)$ array is encoded by a certain value of signal level:

• $Kdd(i)_{OC,\,AO}$ when the following condition is satisfied:

$$U_w(i) > [Tri(I_w(i) Or (U_w(i) \le U_{SA} \text{ And } I_w(i) \le U_{AO})] \text{ And } I_w(i) \le Tru(U_w(i));$$

• $Kdd(i)_{SC}$ when the following condition is satisfied:

$$U_w(i) \le [Tri(I_w(i) Or (U_w(i) \le U_{SA} \text{ And } I_w(i) \le I_{AO})];$$

• $Kdd(i)_{AR}$ when the following condition is satisfied:

$$U_w(i) > [Tri(I_w(i) Or (U_w(i) > U_{SA} \text{ And } I_w(i) > U_{AO})] \text{ And } I_w(i) > Tru(U_w(i)).$$

Tables 3 and 4 give the results of IMS operation for welding modes, given in Tables 1 and 2.

Conclusions

1. Presented IMS enables obtaining a wide range of statistical indices of the process electrical parameters for analysis of all the stages, namely source switching on, arc striking, steady-state arc process and completion of welding.

2. IMS performs automatic identification of the welding process state, thus eliminating the human factor influence on the derived assessments of statistical parameters of the process.

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