the welding circuit. The heating duration in welding is no more than 3 s, and power consumed from mains of the electric drive is 230–420 kW. Application of high-rate high-concentration heating at current densities of 50–60 A/mm^2 made it possible to produce the high-quality joints on 80–320 mm diameter pipes with wall thickness of 8–12 mm, made from X65 type steels and steels of the austenitic and martensitic grades belonging to the hard-to-weld ones. Along with high strength values, the joints exhibited the high properties in impact toughness tests.

Further improvement of this type of energy storages creates conditions for widening of the application fields for the FBW technologies, especially for hard-to-weld materials.

As noted for the machines for FBW of 114–320 mm diameter pipes, utilisation of a power supply with square wave pulses and frequency of 50 Hz provides a 25 % reduction in the welding time [6].

1. Kuchuk-Yatsenko, S.I. (1992) *Flash butt welding*. Kiev: Naukova Dumka.
2. Paton, B.E., Lebedev, V.K. (1969) *Electric equipment for flash butt welding. Moscow*: Mashinostroenie.
3. Smirnov, V.V. (2000) *Equipment for flash butt welding*. St.-Petersburg: Energoatomizdat.
4. Podola, N.V., Kuchuk-Yatsenko, S.I. (1957) Low-frequency current flash butt welding. *Avtomatich. Svarka*, **1**, 63–72.
5. (1985) *Catalogue of Schlatter Company*. Prosp. 2. Schlatter AG.
6. Khomenko, V.I., Pankov, O.G., Sergeev, S.K. et al. (1991) Application of inverter power supplies for flash butt welding in construction of pipelines. *Svarochn. Proizvodstvo*, **9**, 16–17.
7. Bertinov, A.I., Alievsky, B.L., Troitsky, S.R. (1966) *Unipolar electric machines with liquid metal current pickup*. Ed. by A.I. Bertinov. Moscow; Leningrad: Energiya.
8. Haase, P.W., Carries, R.W., Hudson, R.S. (1995) The University of Texas at Austin, Center for Electromechanics. Homopolar pulsed welding for offshore deep water pipelines. *Welding J.*, **5**, 35–39.
9. Shurygina, V. (2003) Supercapacitors. *Elektronika, Nauka, Tekhnologiya, Biznes*, **3**.
10. Despotuli, A.L., Andreeva, A.V. (2006) Supercapacitors for electronics. *Sovrem. Elektronika*, **5**, 10–14.
11. James, C., Wright, P.E. (1999) *Homopolar pulsed welding for pipeline application*: Report of Int. Symp. on Exploiting Solid State Joining. Cambridge.

PORTABLE SYSTEM OF MONITORING AND CONTROL OF RESISTANCE SPOT WELDING PROCESS

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The paper presents the schematic diagram and operative algorithm of system of quality control of welded joints made by resistance spot welding, based on a pocket PC. In addition to real-time quality control, the system also implements functions of expert system for technology selection and production analysis.

Keywords: *resistance spot welding, welded joints, quality control, process control, weld spot nugget diameter, expert system, pocket PC*

The quality of resistance spot welding depends on many factors, mainly on the selected technology, applied equipment and automatic control of process in real time.

A lot of stationary and pocket devices, systems, based on the office and industrial PCs and laptops, designed for control of process of resistance spot and seam welding is known.

These devices and systems allow investigation of process of welding the new and well-known materials and structures, automation of selection of welding condition and its optimization, presetting and verification of acceptable limits of variables of condition parameters, welding quality control in real time. With their use it is possible to perform accumulation, statistical processing and analysis of data, certification of production, calibration of sensors, to realize the technical maintenance of welding machines and electrodes.

As an example of resistance spot welding control systems it is possible to mention the wide nomenclature of devices of Miyachi Uniteck [1], monitors of WeldComputer Corp., ATek Resistance Welding and Dengensha America (USA), pocket tester of TECNA (Italy) [2], measuring systems of VNIIESO (Russia) [3].

The E.O. Paton Electric Welding Institute has also developed the series of devices for monitoring and diagnostics of process (UDK-01 -02, -05) [4] and welding condition control systems with wide package of functions on control of condition parameters and quality of a welded joint (RVK-100, KSU KS-02) [5, 6].

The above-mentioned devices on controllable parameters are differed negligibly. This is in general the welding current or current in primary winding of welding transformer, voltage between electrodes, pressure or compression force of electrodes, movement of electrodes and time of optimizing operations in cyclogram. However they can considerably differ in technical realization. For instance, the series of Miyachi Uniteck includes stationary MG3, MM-370 (of 5 kg weight) with a graphical display, more compact MM-122A (1.9 kg) with possibility of connection to outer PC (e.g. laptop) and printing device, so-called palm MM-380 (0.9 kg) and, finally, pocket devices for measuring of current parameters (MM-315A) and compression forces (MM-601A). At the same time the monitors WeldComputer Corp. are similar to industrial working stations with a full-scale graphical screen with options of working as a local, remote or net device, controlling several welding machines.

The E.O. Paton Electric Welding Institute has developed an expert system for resistance spot welding [7] which, basing on databases and experience, gives recommendations on technology of welding of products with a preset thickness of parts, condition of their surface, peculiarities of design and grade of material. To increase competitiveness it is desirable to develop control devices with functions of expert system. Besides the work of reference system there is also option of the most efficient method of evaluation of quality for considered product and automatic switching of a device to a required monitoring mode.

The UDK devices were developed on the basis of the industrial controllers. The realization of algorithms in them, similar to expert systems is impossible due to a limited memory capacity for storage of software and data. The data output displays have limited possibilities as to volume of produced textual and graphic information. Nevertheless, the full output of information is very important and its absence results in limitation of possibilities of expert systems. Meantime, the devices of monitoring and control are complex computer devices and their small-batch production leads to a high cost.

Nowadays, the mobile computer computing means with screens from 3–4 inches to represent textual and graphic information, such as the pocket PCs, smartphones, communicators, netbooks and laptops find a wide application in everyday life (entertainment, organizing of working day, text translation, GPS, health control and other). Their technical characteristics in providing output of information about welding process parameters from the welding machine can successfully replace the above-mentioned devices and, moreover, obtain additional advantages by realizing required functions of expert system.

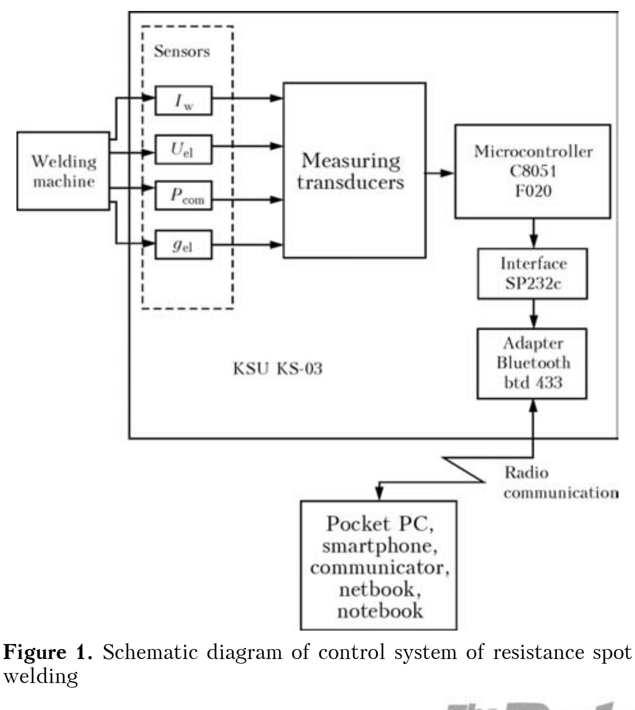

Figure 1. Schematic diagram of control system of resistance spot welding

The purpose of the work is the development of a portable computer system where functions of expert system and those of welding process monitoring, typical of specialized devices, are realised simultaneously. Moreover, the system should maximum apply the widely spread serial equipment of high reliability, low cost and can be adopted for the application under the conditions of welding shop.

One of the basic tasks at the design of such system is the development of equipment and software to interface the mobile computers with sensors of process parameters.

To interface the resistance spot machine with universal mobile computer devices, the E.O. Paton Electric Welding Institute has developed a system KSU KS-03 of monitoring the spot welding process parameters, designed for measuring process parameters and transfer of these data to the computer of upper level. The unit is developed on the basis of a single-crystal controller C8051 F020 of company «Silicon Laboratory», the main advantage of which is presence of necessary resources for design of measuring system: 12-charge 8-channel ADC of efficiency of up to 100 K measurements per 1 s and input amplifier with a programmable amplification factor at high productivity as to calculations and control. The schematic diagram of the system is given in Figure 1.

Technical characteristics of measuring unit

Range of welding current measurement, kA	2–25 4–50
Range of voltage measurement between electrodes, V	0–5
Range of measurement of compression force of electrodes, kN	0–10; 0–20
Range of measurement of acceleration of electrodes movement, *g*	±1.7
Given error in parameters measurement, %	not more than 3
Speed of data transfer on the radio channel, Kbit/s	19.2–115.2
Mains voltage, V	220–380
Dimensions, mm	260 × 220 × 160

The main distinction of the unit from control devices is the presence of one of two communication channels, which are available practically in all portable computers, USB and Bluetooth. In the first case exchange speed is 921.6 Kbit/s, in the second Bluetooth the adapter operates in the mode of series channel RS232 and maximal speed of transfer is 115.2 Kbit/s. Although radiochannel has a lower speed, its application can be more preferable as it does not need the wire communication between the devices, the distance between receiver and transmitter can be up to 100 m excluding high voltages at the input of computer system, the connection is simple.

In capacity of base package the unit consists of the following sensors: a Rogowski belt of a split type of manufacture of the Engineering Pressure Welding Centre of the E.O. Paton Electric Welding Institute; sensor of compression force MEGATRON KMB 31K 10KN 0000D; acceleration sensor ANALOG DEVICE ADXL 103.

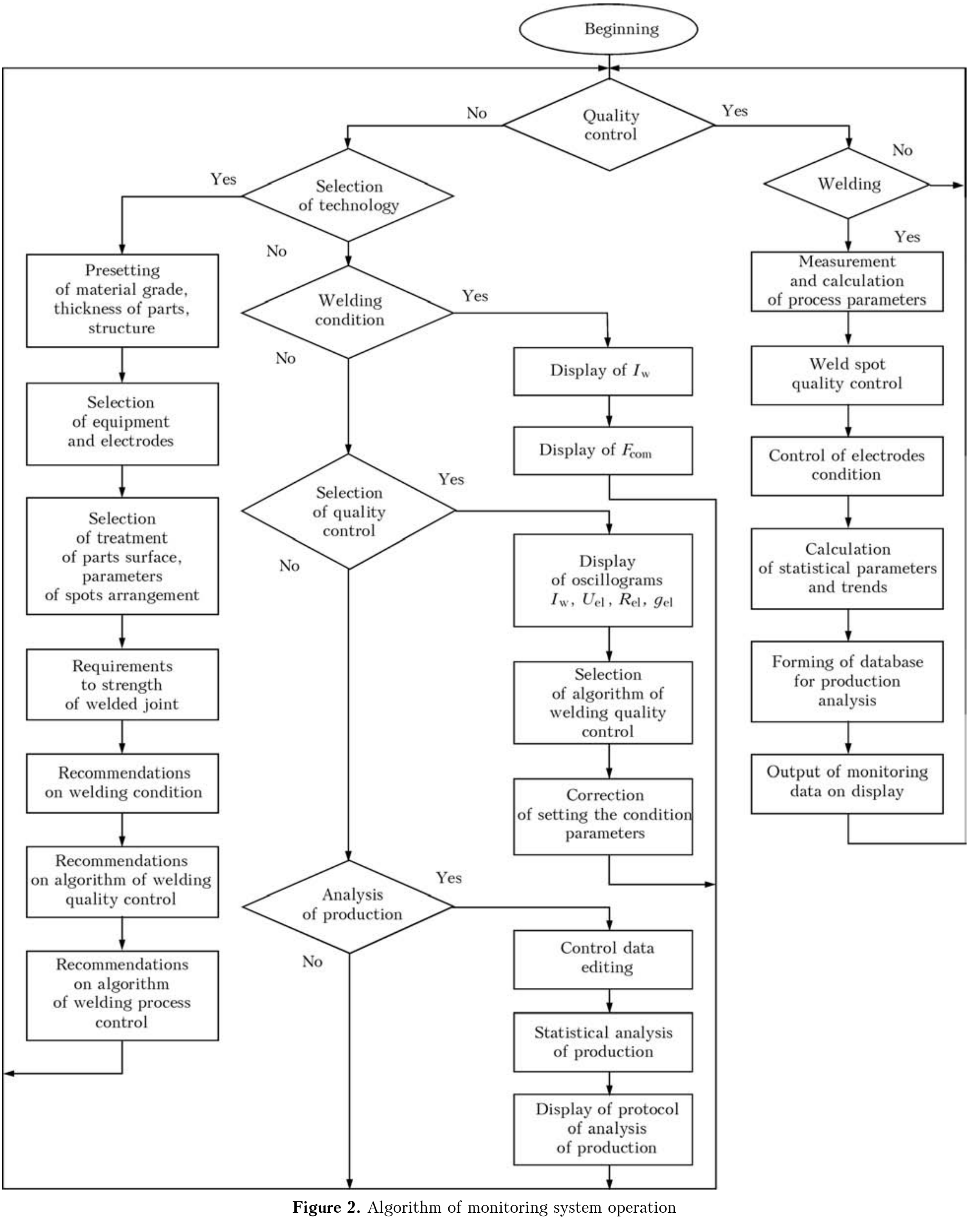

Figure 2. Algorithm of monitoring system operation

Besides there is a pair of measuring conductors with special terminals to measure voltage between electrodes.

Current sensor is flexible and split and has 150 mm diameter, sensitivity of 1 V·s/kA, current measuring error does not depend on position of the sensor. The sensor of compression force is manufactured of high-quality steel, the working temperature range is −10 − +40 °C, variant IP66. The acceleration sensor is uniaxial, sensitivity of 1 V/g, zero shift at 0 g is 2.5 V.

Measuring sensor transducers are also included into the unit. In the package with a sensor of compression force the measuring transducer MEGATRON IMA 3-DMS-2405 is used. The measuring transducer of voltage sensor eliminates interference brought by welding current and allows measuring of signal di-

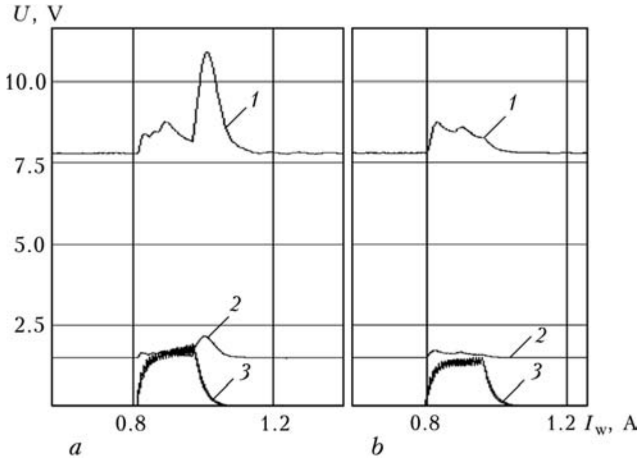

Figure 3. Oscilogram of signals from outputs of measuring transducers of accelerometer *1* and current *3* during splash (*a*) and without it (*b*) (*2* — signal at the output of accelerometer)

rectly on the electrodes with laying of measuring circuits along the welding circuit.

The algorithm of monitoring system operation is given in Figure 2.

During the monitoring of technological process the control unit at a period of 10 ms issues integral values of a current, voltage, forces of compression and acceleration of electrodes for the computer of upper level to calculate input values of algorithm of quality control and stability of production:

• input parameters of tolerance control: current, voltage, displacement and resistance in the last period of welding, relative variation of resistance, integral error evaluations in correction of curves of current, voltage, displacement (the sum of absolute values of deviation of current values relative to reference curves);

• input parameters of regression model: energy Q, generated in welding contact;

• input parameters of neuron network: average values of current and voltage at four sequential and possibly equal intervals which in sum are equal to time of welding.

During the tolerance control of quality the algorithms are used based on the fuzzy logics [8].

The monitoring of diameter of weld spot nugget according to regression equations was performed using following expression:

$$d = a_0 + a_1Q + a_2Q^2,$$

where a_0, a_1, a_2 are the coefficients of equation.

During the monitoring of welding quality according to the neuron networks the dependencies, given in the work [9], were used.

To monitor the splash, the indications of the accelerometer are used (Figure 3), which is mounted on electrode holder. Here, the time of its occurrence is taken into account: splash at the beginning of welding is not admissible and can indicate an insufficient force of compression of electrodes, non-quality preparation of surface of parts being welded or wear of the working surface of electrodes. In any of these cases it is necessary to interrupt the welding of workpiece and to detect the cause of instable process. At the same time the splash at the end of welding is not a rejection feature in many cases.

According to obtained value of weld spot nugget diameter the following values are further calculated: average value, mean square deviation, and also sliding average value and sliding mean square deviation which can help in determination of undesirable tendencies in welding quality. For clearness, except of data about welding quality the data, plots and histograms on the whole file and sliding average values are shown on display.

There is a possibility to reset data on the last point to exclude them from general evaluation, to reset the

Figure 4. Data on welding technology on pocket PC display

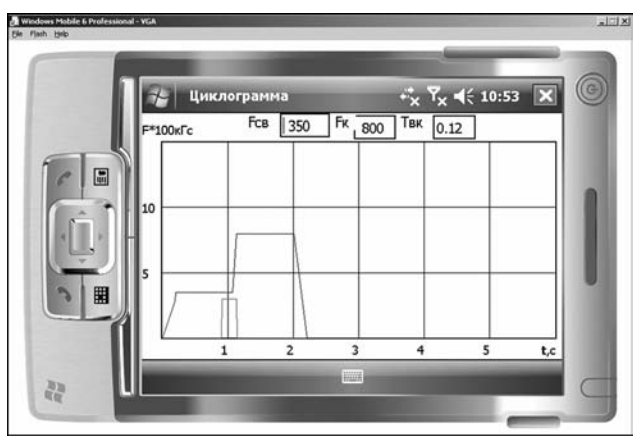

Figure 5. Cyclogram of compression force of electrodes on pocket PC display

whole database or to store it in the computer memory in the form a separate file for the further analysis.

The selection of welding technology, adjusting of parameters of algorithm of quality control and statistic analysis of production are performed in a dialogue mode.

The recommendations on selection of welding condition and equipment are issued on pocket PC display on the basis of the preset grade of material, thickness of parts, structure, method of surface treatment and also requirements specified to the quality of welding (Figure 4).

To measure the cyclogram parameters of compression force, it is necessary to optimize the preset condition with a switched welding current at the compression force sensor fixed between the electrodes. In this case the duration of current and its time in general cyclogram are determined by the sensor of voltage between electrodes (Figure 5).

In the process of welding of a workpiece or specimens during selection of the condition the values of current in the last period I_l, average current in the time of welding I_{av} and durability of current T_w are measured. For mentioned values the average values, mean-square and maximal relative deviations for mentioned values are calculated and shown on the display. Here, the database for calculation of these values in any time of tests can be reset to zero values or completely or only on the last point.

During statistical analysis of production any file of control of welding process can be selected from the memory of device. Usually one file corresponds to the operation of welding machine within a day and its name is chosen by the date of its creation (day, month, year). A protocol as a document of a programme Microsoft WORD is formed of it, where quantity of welded spots, data on welding quality, data on errors of reproduction of controllable parameters, recommendations on cleaning and change of electrodes are indicated. The histograms of controllable parameters can be produced on the display and compared with their similar histograms at selection of the condition.

Thus, the developed system of monitoring and control of resistance spot welding process on the basis of the modern devices of computer engineering widens greatly the possibilities of control, increases its validity and provides the required quality of welded joints.

1. (2007) *Miyachi Uniteck 991-041 03/07*: Resistance welding. Weld checkers. Spirit of innovation.
2. (2007) *TECNA*. Test and measurement instruments. 1000-10/2007.
3. Ioffe, Yu.E. (2006) System for control and monitoring of resistance welding. In: *Proc. of 3rd Int. Sci.-Pract. Seminar on Resistance Welding and Other Types of Pressure Welding, Technologies and Equipment* (13–15 June 2006, St.-Petersburg). St.-Petersburg.
4. Podola, N.V., Gavrish, V.S., Rudenko, P.M. (1994) Computer diagnostics of resistance welding. *Avtomatich. Svarka*, **7/8**, 32–35.
5. Podola, N.V., Rudenko, P.M., Gejts, V.I. et al. (1991) Computer system of RVK-100 type for control of resistance spot welding machine. *Ibid*., **7**, 61–68.
6. Rudenko, P.M., Gavrish, V.S. (2007) KSU KS 02 system for automatic control and monitoring of resistance spot welding process. *The Paton Welding J*., **11**, 34–36.
7. Gavrish, V.S., Rudenko, P.M., Podola, N.V. (2007) System of automatic control and monitoring of resistance spot welding. *Ibid*., **9**, 45–48.
8. Podola, N.V., Rudenko, P.M., Gorun, N.P. et al. (1999) Quality control of resistance welding of accumulator element-to-element joints on the base of fuzzy logic. *Avtomatich. Svarka*, **5**, 42–45.
9. Podola, N.V., Rudenko, P.M., Gavrish, V.S. (1991) Application of adaptive algorithm for welding quality control in control systems of resistance spot machines. *Ibid*., **7**, 61–68.