DOI: https://doi.org/10.37434/tpwj2024.10.01

DEVELOPMENT OF THE TECHNOLOGY OF PRESSURE WELDING WITH A MAGNETICALLY IMPELLED ARC OF SMALL-DIAMETER PIPES USING SUPERCAPACITORS

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ABSTRACT

Pipes of small diameters of up to 100 mm are used at various industrial and agricultural facilities. The methods of manual arc welding or automatic welding are traditionally used for joining the pipes. The issue of using supercapacitors in equipment for magnetically impelled arc butt welding (MIAB) process, to reduce peak loads on the electrical network, is considered. The need for such equipment is primarily determined by the tasks of “green” technologies. Application of supercapacitors in power sources allows ensuring further on the optimal parameters of pulse welding processes, in order to improve their quality and work productivity. A prototype of a new generation of power source for MIAB welding of pipes of a small diameter in the field and stationary conditions using an autonomous power supply source has been developed and manufactured.

KEYWORDS: welding current formers, magnetically impelled arc butt welding, autonomous sources of powerful current pulses and power supply, supercapacitors

INTRODUCTION

The world is becoming ever more dependent on electricity as the main source of energy. In view of this trend and increasing global competition, the manufacturers focused on increase of the efficiency and reduction of power consumption.

Energy efficiency of welding equipment is one of the main tasks of its further improvement. This also concerns the pulse processes of welding various parts. Application of supercapacitors as power sources for resistance spot welding ensures a significant weight reduction, compared to the usual approaches (transformer and power source) with further ergonomic advantages [1]. One of the developed at PWI processes of joining pipes is magnetically impelled arc butt (MIAB) welding [2]. In order to reduce peak loads from equipment power on the mains during welding of pipes under field and stationary production conditions [3], studies were performed on development of an equipment complex for MIAB process with power supply from an autonomous power plant (APP) based on supercapacitors. For optimal selection of its power, preliminary analysis of power consumption was performed, proceeding from the value of power consumed under load. The capacitors are charged at a low rate for a long period of time and discharge quickly, ensuring high currents with minimal influence on peak consumption from the mains. Capacitor charging at low current levels also allows the manufacturers to connect the welding systems without upgrading the distribution power of their plants. The supercapacitors accumulate energy similar to a flywheel, storing the energy for a long period of time, and then quickly releasing this energy, when required. This approach is more effective at power application and reduces the expenses for the infrastructure and capital equipment.

At application of classical supply circuits, achieving high efficiencies (EF) of the welding equipment involves considerable difficulties. It is anticipated that application of capacitive energy storages based on supercapacitors will allow solving the energy storage issue. Application of supercapacitors in pipe welding equipment will allow reducing energy consumption and the demand for power supply, will significantly reduce the weight and overall dimensions of welding equipment, and will allow development of autonomous welding complexes with power supply from mobile power plants for working under the field and stationary conditions.

The question of development of pulse current generators (PCG) for MIAB welding is urgent. The experimental mock-up of MIAB welding equipment was based on the method of forming a powerful pulse of welding current, which involves application of supercapacitors (SC) as energy storage [4–6]. It allows significantly lowering the level of peak loads on the mains and, consequently, the value of the source installed power. One of the important tasks at development of MIAB welding equipment is formation of a powerful current pulse at the final stage of welding before upsetting the heated pipe edges.

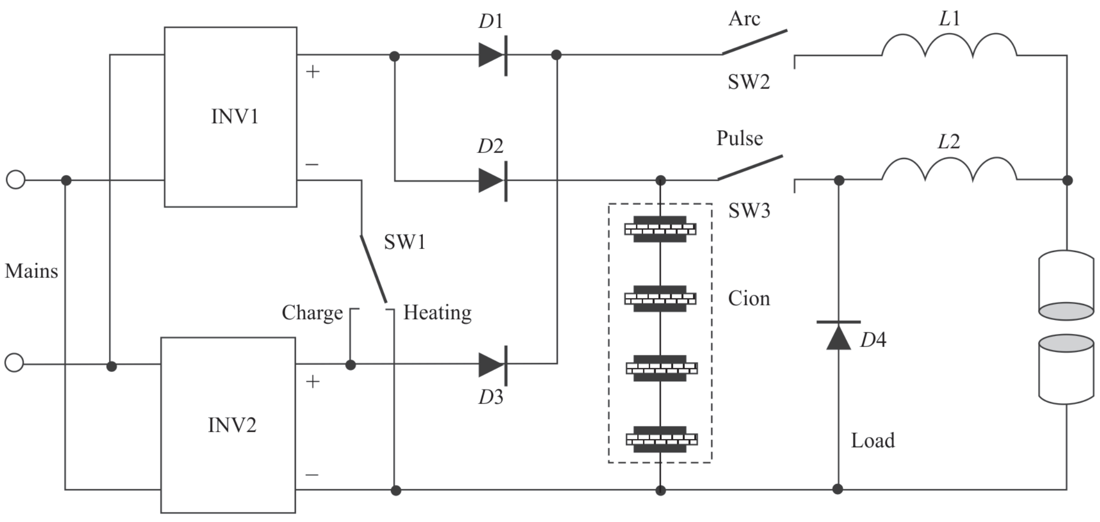


Figure 1. Scheme of pulse forcing of the welding arc: INV1, INV2 — the inverter voltage converters; SW1–SW3 — mechanical current switches; *D*1–*D*4 — diodes; Cion — supercapacitor battery; *L*1, *L*2 — forming inductors; the Load is the MIAB welding unit

Until lately, direct welding current sources of Lincoln Electric — DC1000 or Miller-DC1000 with up to 1000 A peak current pulse were used for this purpose. A circuit (Figure 1) of a pulse welding current source, in which SC battery was used to form pulse current, was developed and tested by the results of the conducted studies.

The circuit includes two inverter converters DC INV1 and INV2 with rated welding current of 150 A, separating diodes *D*1, *D*2, *D*3; reverse protection diode *D*4; forming inductances *L*1, *L*2; circuit mode switches SW1, SW2, SW3 and energy storage, based on a battery of Cion SC connected in series. The device work cycle consists of three phases: *1* — phase of charging the pulse energy storage; *2* — phase of heating the edges to be welded by a pilot arc; *3* — phase of pulsed increase of the arc current for pipe edge melting.

Cion pulse energy storage is charged through separating diode *D*2 from inverters INV1 and INV2 connected in series via SW1 switch. Capacitor charge voltage is controlled by the monitoring and control circuit (not shown in Figure 1). Preheating of the pipes being welded is performed from inverters INV1 and INV2, connected in parallel by switch SW1, and connected to the item via diodes *D*1, *D*3, choke *L*1 and switch SW2. Arc current forcing pulse is executed at closing of contactor SW3 by the following circuit: +Cion, SW3, *L2,* load*,* –Cion. Diode *D*3 protects contactor SW3 from failure when extinguishing the arc forcing current pulse. Switches SW1, SW2, SW3 are controlled by the monitoring and control circuit (not shown in Figure 1).

PCG laboratory mockup with a controlled current pulse shape was made for performance of further studies of the welding processes. In it power current switches based on fully controlled semi-conductor structures are used [7, 8].

In keeping with modern tendencies in power electronics [8], power transistors with MOSFET structure were used for welding processes at conditionally low voltage of the current pulse. Their selection is substantiated by the peculiarities of their properties that allows performing parallel connection of the transistors of a conditionally unlimited number, and enables building powerful current switches. Supercapacitor batteries (SCB) were applied as the power source to form powerful current pulses. SCB application as powerful current sources allows essentially reducing PCG weight and size characteristics, compared to the traditional solutions, in which the industrial mains are used as the pulse current source. Moreover, mains power can be much lower, as the SCB forms the current pulse. Here, just the power required for SCB charging, distributed over SCB charging time, is consumed from the mains.

The generalized structural-functional scheme of the pulse current generator with charging circuit optimization for application in MIAB welding equipment is given in Figure 2.

In PCG circuit stepdown type voltage converter (SVC) with pulse-width modulation (PWM) are used as current pulse formers, where M1 module forms the current of pipe edge heating, and M2 module generates the pulse of edge melting current. Application of PCG modular structure allows improvement of the conditions of power loss dissipation, as well as more flexible adaptation of the power part of the circuit for different welding applications.

Overall monitoring and control of the circuit operation is performed by the control unit (CU). SC battery charging is conducted by charging device (CD), which in its turn is powered from the initial voltage inverter with power corrector INV1. SVC is controlled from local PWM controllers.

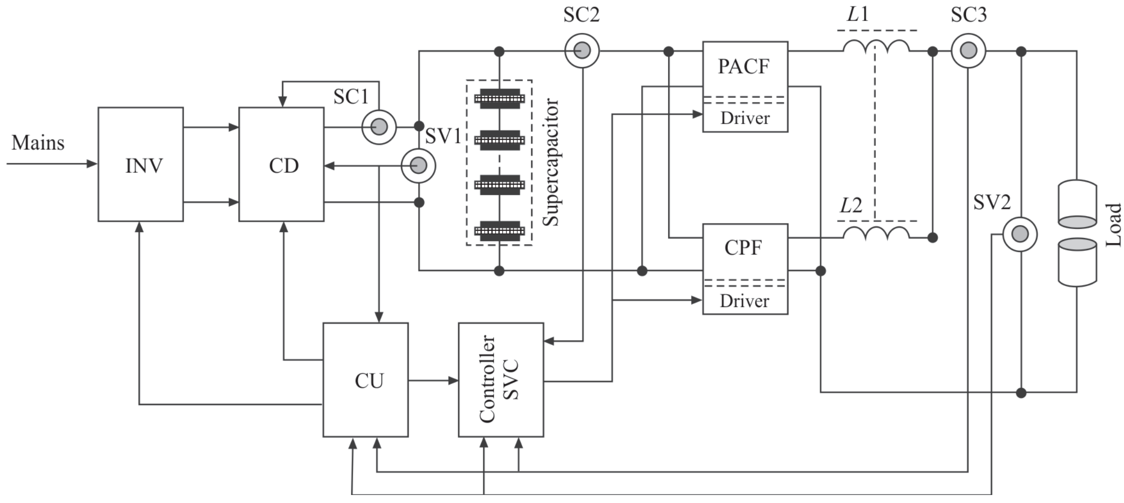


Figure 2. Generalized structural-functional scheme of pulse current generator for MIAB welding: INV — power inverter; CD — charging device; CU — control unit; SVC — controller of stepdown voltage converters; PACF — preheating arc current former; CPF — current pulse former; SC, SV — current and voltage sensors

Table 1. Chemical composition of pipe metal, wt.%

Steel grade	C	Si	Mn	Ni	S	Cu	P	Cr	V
09G2S	0.11	0.61	1.48	0.21	0.021	0.21	0.02	0.23	0.11

DEVELOPMENT OF EXPERIMENTAL TECHNOLOGY OF MIAB WELDING, USING AN AUTONOMOUS POWER SUPPLY SOURCE

Pipes from structural low-alloyed steel 09G2S which can withstand a wide working temperature range from –70 to +450 °C, were used for investigations. High mechanical strength allows using steels of this grade in the oil industry, pipeline construction and agriculture. Table 1 gives the chemical composition of the pipe metal.

In order to conduct studies on welding steel pipes of Ø38×3 mm, welding current and arc voltage and relative movement of pipes being welded were programmed, in keeping with the cyclogram (Figure 3). At the start of the process, during time t_1, the pipes are pressed together to provide reliable contact of their edges and the arc power source is switched on, and then the pipes are moved apart for the arc gap width, thus exciting the arc. The arc is first burning at higher current I_1 during time t_2. Then the welding current decreases to current I_2 and the pipes are heated during time t_3. After the necessary heating of the pipe edges has been achieved, the welding current from SC is increased up to value I_3, and then pipe upsetting and welded joint formation are performed. After time t_5 the arc power source is switched off, and after time t_6 the upsetting force is removed. The welding cycle is over.

The welded pipe sample is shown in Figure 4. Welding was performed with application of the developed autonomous PCG power source for MIAB welding equipment.

A study with current increase after heating, but without upsetting, was performed additionally (Figure 5). Results showed that the pipe edges before upsetting are uniformly melted over the entire heated metal surface that promotes optimal formation of the welded joint.

MECHANICAL TEST RESULTS

Mechanical testing was conducted in keeping with API 1104 standard [9]. Test results are given in Table 2.

DEVELOPMENT OF SPECIFICATION PROCEDURE FOR MIAB WELDING WITH AN AUTONOMOUS POWER SOURCE

Proceeding from the developed parameters of MIAB welding process, recording of the procedure of welding with application of supercapacitors from an autonomous power source was conducted. Based on the results of the conducted mechanical tests, the weld-

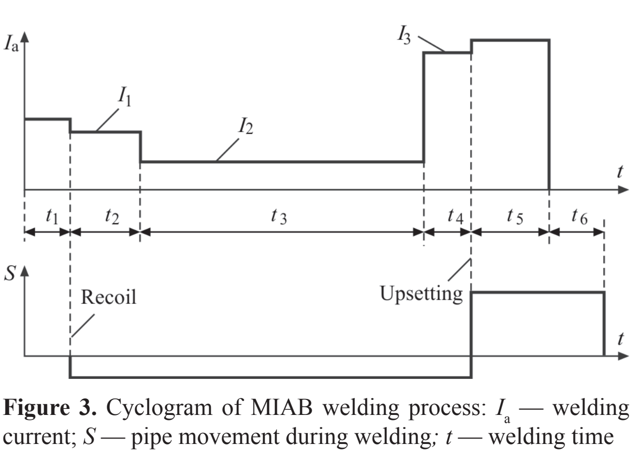


Figure 3. Cyclogram of MIAB welding process: I_a — welding current; S — pipe movement during welding; t — welding time

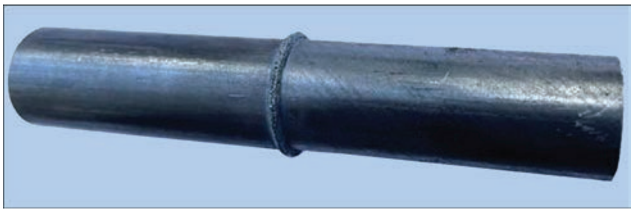


Figure 4. Welded joint of a pipe of Ø38×3 mm

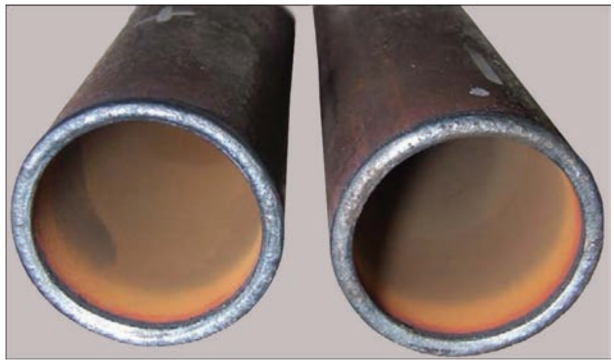


Figure 5. Appearance of pipe edges before upsetting

ing procedure recording was further developed into the welding procedure specification (WPS). Figure 6 gives the specification of the welding procedure, developed for Ø38×3 mm pipes from 09G2S steel.

RESULTS OF METALLOGRAPHIC INVESTIGATIONS

Investigations were conducted on microsections of welded joints of Ø38×3 mm pipes, which were polished on high-speed wheels, using diamond pastes of different dispersity. Metal structure was revealed by chemical etching in 4 % alcohol solution of HNO_3. Investigations were performed in Neophot-32 and Versomet microscopes at different magnifications. Microhardness was determined at 1 N load in M-400 microhardness meter of Leco Company. Grain size was determined by GOST 5639–82 scales. Digital image of the microstructures was obtained using Olympus camera.

The joint line is quite pronounced along the entire weld height. The width of the joint line band is 30–50 μm, near the flash it is up to 180 μm (Figure 7).

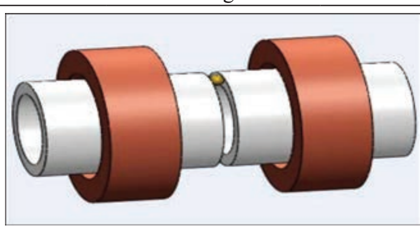
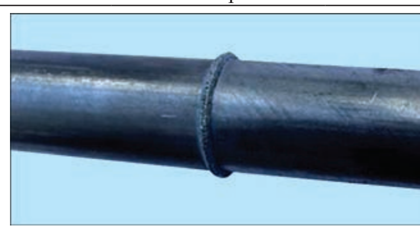
<table>
<tr><td colspan="6">E.O. Paton Electric Welding Institute of the NAS of Ukraine</td></tr>
<tr><td colspan="6">Procedure specification of MIAB welding with an autonomous welding source</td></tr>
<tr><td colspan="3">API 1104 Specification
Welding process: MIAB welding
Steel grade: 09G2S
MIAB welding machine model: MD-101</td><td colspan="3">PWI WPS/MIAB – 001
Process mode: automatic
WPS: Procedure for carbon steels
Pipe diameter: 38 mm
Wall thickness: 3 mm</td></tr>
<tr><td colspan="3">Joint configuration</td><td colspan="3">Joined parts</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Joint characterization</td><td colspan="3">Shielding gases and materials</td></tr>
<tr><td colspan="3">Joint type – butt joint</td><td colspan="3">Shielding gases: not used
Internal blowing: not used
Welding wire: not used
Water cooling: not used</td></tr>
<tr><td colspan="6">Welding parameters for pipes of 38 mm dia</td></tr>
<tr><td>Stage number</td><td>Welding current, A</td><td>Welding time, t</td><td>Arc voltage, V</td><td>Arc gap, mm</td><td>Upsetting force, kN</td></tr>
<tr><td>1</td><td>220–240</td><td>2.5–2.7</td><td rowspan="3">24–27</td><td rowspan="3">1.7</td><td rowspan="3">41–44</td></tr>
<tr><td>2</td><td>180–190</td><td>10–12</td></tr>
<tr><td>3</td><td>570–610</td><td>0.2–0.4</td></tr>
<tr><td colspan="3">Prepared:</td><td colspan="3">Certified:</td></tr>
<tr><td colspan="3">Date:</td><td colspan="3">Date:</td></tr>
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Figure 6. WPS for MIAB welding using an autonomous power source

Table 2. Mechanical properties of pipe welded joints

Steel grade	Pipe wall diameter/ wall thickness, mm	σ_t, MPa		$KCV_{+20\,°C}$, J/cm^2	
		Base metal	Welded joint	Base metal	Welded joint
09G2S	38×3	488±11	492±12	56±12	52±13

The microstructure is a ferrite-pearlite mixture, where pearlite is found in the form of thin plates within the ferrite precipitates.

Hardness measurement was performed in the weld, HAZ and base metal. The measured hardness values on test samples are as follows:

- welded joint: *HV*1-2070–2200 MPa
- HAZ: overheated subzone *HV*1-1910–2210 MPa, overheated zone width 1200–1300 μm;
- complete recrystallization subzone *HV*1-1610–1790 MPa, subzone width 1400 μm;
- base metal: *HV*1-1510–1710 MPa.

Proceeding from the results of mechanical tests and metallographic investigations it was established that the pipe welded joints are within the admissible limits, in keeping with standards, applied in industry of Ukraine and other countries.

TECHNICAL MEANS FOR AUTONOMOUS MIAB WELDING COMPLEX

In case it is necessary to conduct MIAB welding of pipes under field and stationary production conditions [2, 10–12], at low input power levels, there is the need use supercapacitors and power supply from APP. Analysis and optimization of charge-discharge processes in capacitive energy storages (CES) is one of the main tasks in design of pulse technological installations, to which MIAB equipment belongs. At selection of the method of CES charging, we usually proceed from technical-economic indices, where the price-quality criterion is used. As is known [13, 14], at technical realization of charging devices, three charging methods are mainly used:

- Charging from constant voltage source (U_{ch} = = const);

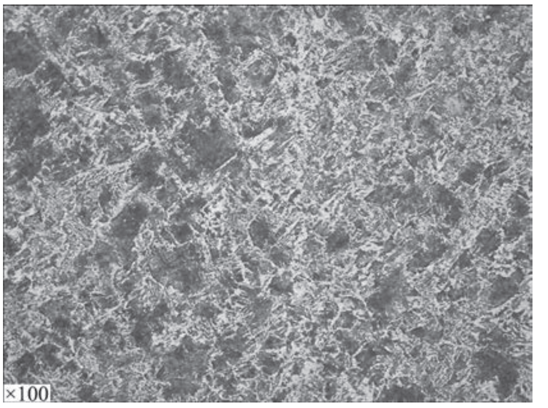

Figure 7. Joint line and HAZ of the welded joint (×200)

- Charging from direct current source (I_{ch} = const);
- Charging in the constant power mode (P_{ch} = = const).

In work [15] it is shown that application of inductive-capacitive converters (ICC) as current sources in charging devices can provide the efficiency close to 100 %.

As regards technical realization of MIAB welding units, Figure 8 shows a variant of structural-functional scheme of the unit with application of SCB for energy accumulation. Such a schematic is the most advanced technologically in terms of optimal use of APP resources, in view of absence of peak loads during operation of the welding complex. SC charging is performed directly from a special charging device (CD) with application of ICC technology that allows maximum use of SC, and PFC application at the device input increases the efficiency of electric plant power utilization. This is due to the fact that at the device operation during the welding cycle, the plant load power is practically constant, that is related to application of energy storage based on SC.

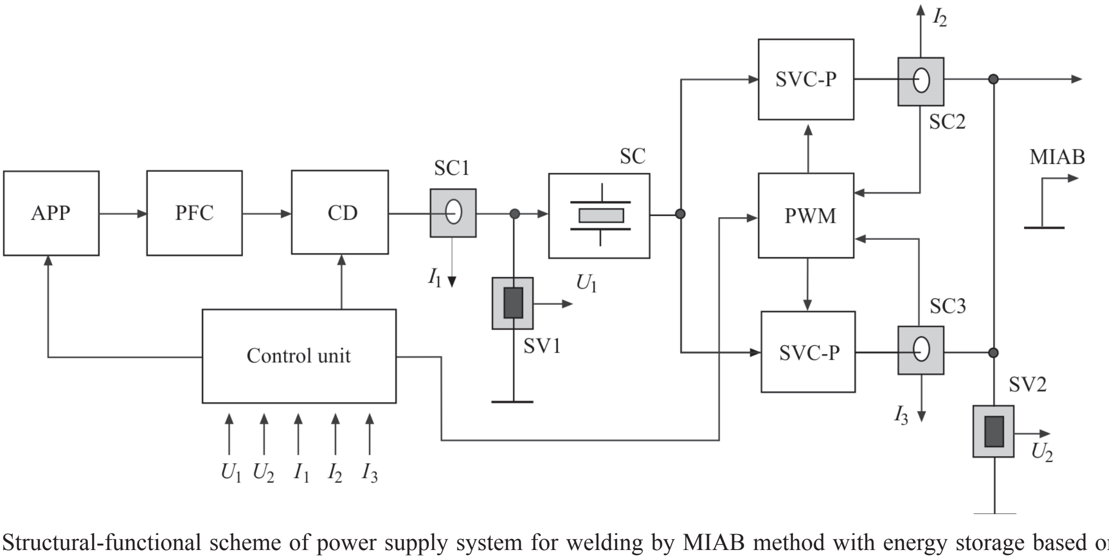

Figure 8. Structural-functional scheme of power supply system for welding by MIAB method with energy storage based on supercapacitors: APP; PFC — power factor corrector; CD — charging device for supercapacitor battery; SC — supercapacitor battery; SVC-P — stepdown converter of preheating arc supply voltage; PWM — pulse-width modulation controller; SVC-P — stepdown coverter of pulse arc supply voltage; SV1, SV2 and SC1–SC3 — voltage and current sensors

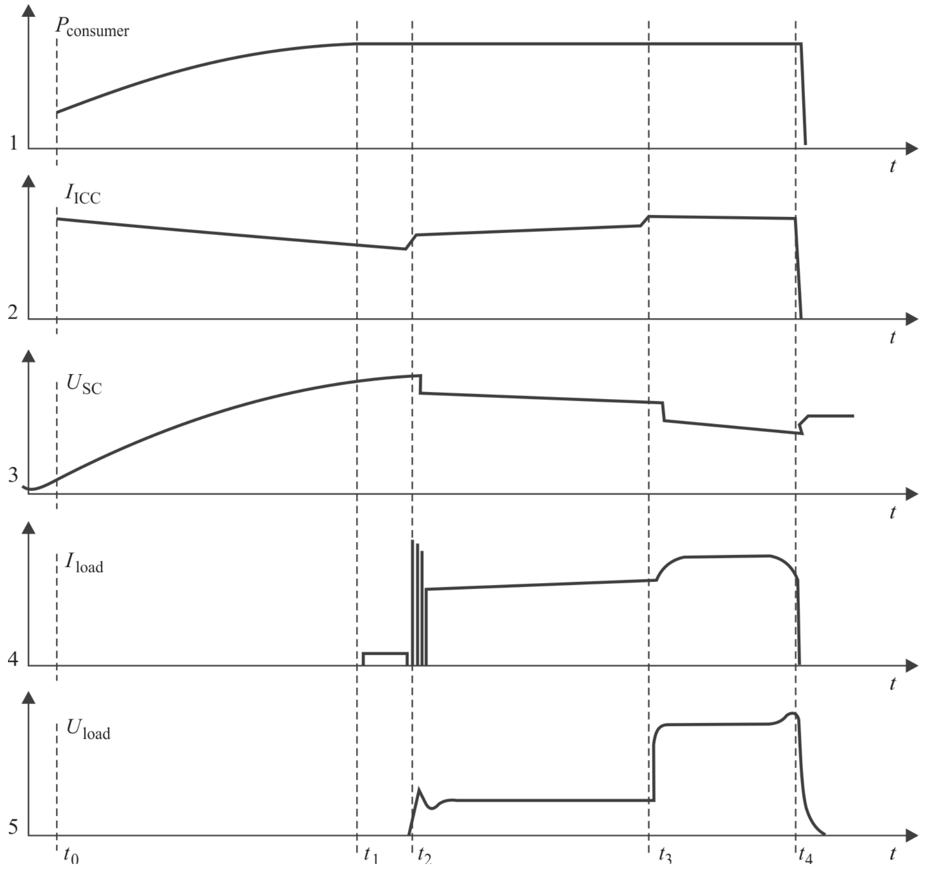

Figure 9. Current and voltage diagrams in the time interval of the complex work cycle: *1* — power consumed from APP; *2* – SCB charging current; *3* — SCB voltage; *4* — load current; *5* — load voltage

The operation of MIAB welding power source can be broken into the following main phases, Figure 9: SC energy storage charging (t_0 – t_1); heating of the edges to be welded by a low-ampere arc (t_2 – t_3); edge melting by a forced arc (t_3 – t_4); upsetting (t_4). Current pulse extinguishing takes place in the upsetting mode.

Each mode of power source operation is characterized by its own circuit operation algorithm, and consequently, different losses in the power unit proper, which should also be taken into account at selection of APP power level.

For stable operation of stepdown converters of welding arc voltage, the voltage at SVC input should not drop below $1.5U_a$. For maximum use of the properties of SC-based energy storage, the SC battery discharge by more than $0.5U_{SCmax}$ is not rational.

Figure 10, *a* shows one of the variants of experimental sample of the power supply system for MIAB welding machine (Figure 10, *b*), based on 6 kW mini-power plant, and Figure 11 is its structural-functional block-diagram.

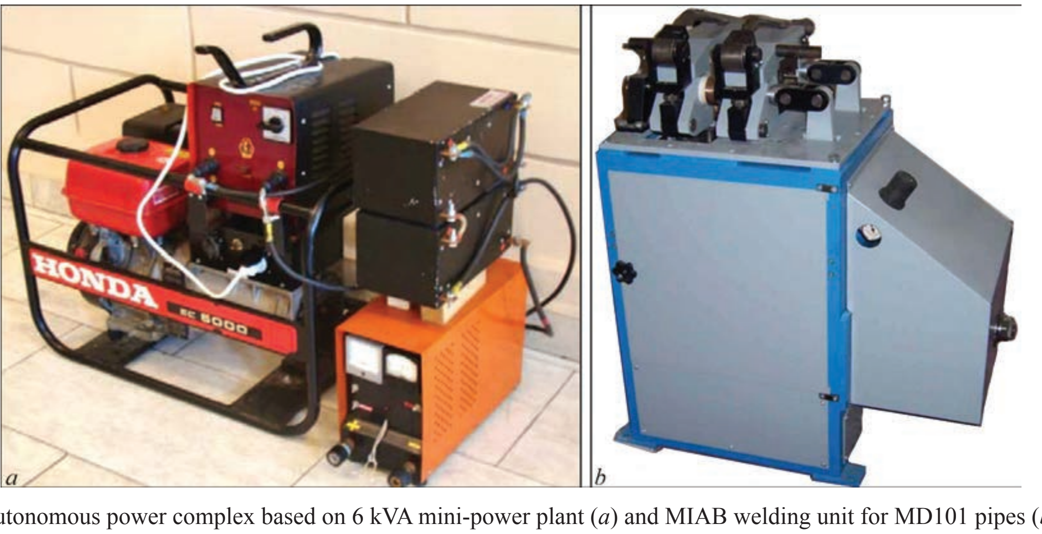

Figure 10. Autonomous power complex based on 6 kVA mini-power plant (*a*) and MIAB welding unit for MD101 pipes (*b*)

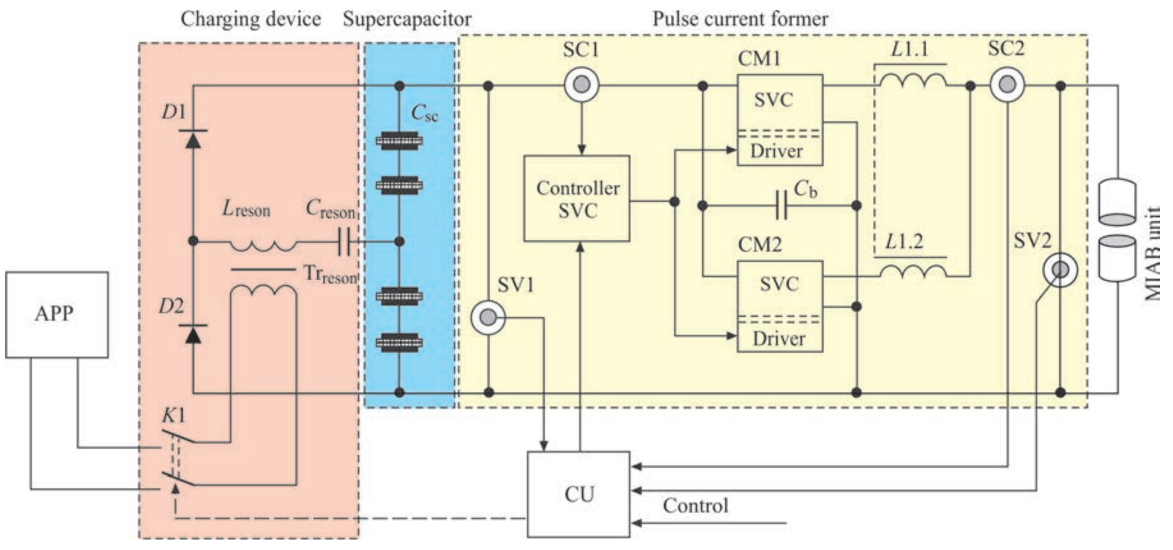

Figure 11. Structural-functional block-diagram of an autonomous power complex for MIAB welding: C_{SC} — supercapacitor battery; CM1 — stepdown converter of preheating arc supply voltage; SVC controller — pulse-width modulation controller; CM2 — stepdown converter of pulse arc supply voltage; CU — complex control unit; SV and SC — voltage and current sensors; *L*1.1, *L*1.2 — inductive storage chokes

Technical characteristics of the experimental autonomous power complex for welding small-diameter pipes by MIAB welding method are as follows:

- power of autonomous gasoline unit: $P = 6$ kVA, cos $\varphi > 0.8$;
- supercapacitor battery: $C = 60$ F, $U = 68$ V;
- range of current pulse amplitude values: $I_p =$ = 0.4–2.0 kA;
- range of preheating arc current values: $I_{pr} = 75$–200 A;
- range of current pulse time values: $T_1 = 0.05$–1.0 s.

CONCLUSIONS

1. With application of MIAB welding process with an autonomous power source based on supercapacitors the energy consumption costs can be lowered by 50–70 %, compared to the conventional welding process.

2. A pilot-production technology was developed for MIAB welding with supercapacitors.

3. Supercapacitors have the engineering potential for generation of the required welding current with the specified arc voltage and pulse duration at MIAB welding of small-diameter pipes.

4. Modern tendencies of development in the field of electric energy storages indicate that capacitive type devices are the most promising for pulse technological installations. This is particularly true for capacitors with a double electric layer — supercapacitors, where the specific capacitance already now is higher than 20 F/h. As their inner resistance is equal to units of mOhms, they can be effectively used in pulse technological units.

5. At development of units for pulse welding processes, it is necessary to take into account such an important capacitor parameter as energy efficiency. This is related to the fact that the discharge degree is determined by the minimal level of voltage, at which a specific technological process can occur, and with optimization in the processes of the charging-discharging of capacitive energy storages.

6. Application of supercapacitors in MIAB welding units significantly improves the energy efficiency of welding, and technological quality of welded joints, lowers the welding equipment cost, and reduces the peak loads on the mains.

7. Further work on determination of the effectiveness of supercapacitor application in the welding processes will be aimed at investigation of the process of MIAB welding and formation of welded joints of larger diameter pipes from steel of different classes.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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SUGGESTED CITATION
V.S. Kachynskyi, D. Allford, M.P. Drachenko, I.V. Ziakhor, V.I. Klymenko, S.M. Samotryasov (2024) Development of the technology of pressure welding with a magnetically impelled arc of small-diameter pipes using supercapacitors. *The Paton Welding J.*, **10**, 3–10.
DOI: https://doi.org/10.37434/tpwj2024.10.01

JOURNAL HOME PAGE
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Received: 24.04.2024
Received in revised form: 09.09.2024
Accepted: 29.10.2024