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COMPLEX FOR INVESTIGATION OF ARC WELDING PROCESSES

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The work presents the results of development and manufacture of a unique research complex for investigation of fast processes of heat-mass transfer in consumable electrode arc welding. Advantages of the developed complex over the traditionally applied ones using film and video cameras with shadow principle of registration of heat-mass transfer characteristics are shown. Fast processes were studied with application of high-speed video recording with illumination of the arc gap by Cu–Br laser beam, improving visualization of the studied object — the process of melting and transfer of each drop of electrode metal under the conditions of intensive light of the electric arc. The paper contains explanatory diagrams, control algorithms, video frames of a separate welding microcycle, examples of oscillogram-recording and graphical representations of changes in their quantitative values. 13 Ref., 1 Table, 14 Figures.

Keywords: *welding, surfacing, video filming, melting, heat-mass transfer, laser, control, stability, electric arc, consumable electrode welding*

Processes of heating and melting of welding electrode or wire, formation and transfer of electrode metal drops in welding largely determine the stability of strength properties of permanent joints. The nature of melting and transfer of electrode metal in fusion welding is determined by a large number of physical phenomena, namely heat-mass transfer, gas- and thermodynamics, electromagnetic processes, running in the arc, on the surface and in the volume of the electrode, molten drops of both the base and electrode metal [1–3].

Analysis of the work devoted to kinetics of electrode metal melting, shows that metal transfer from the electrode into the weld pool, proceeds in the form of drops of different diameter [4, 5]. Transfer mechanism depends on many factors, namely, gravity force acting on the drop, force of surface tension of liquid metal, electromagnetic forces, pressure of evaporating metal vapours and other factors. Investigation of the kinetics of electrode metal melting and transfer into the weld pool is inextricably connected with recording the fast processes. The nature of melting and transfer can change, depending on the applied consumable electrode welding process. This is primarily related to the difference in the action on electrode metal drop located at electrode tip, of a complex of forces, determining not only the frequency of electrode metal transfer into the weld pool, but also the duration of molten metal staying under high-temperature impact of the electric arc. The latter fully determines the intensity of micrometallurgical reactions in the drop and the pool, which are responsible for the quality and strength properties of the formed permanent joint [6, 7].

For a long time high-speed filming has been one of the main methods for studying the fast processes of electrode metal melting and transfer. It is usually performed in synchronism with recording of the basic energy parameters of the technological process. For all the variety of the methods for visualization of the processes of electrode metal melting and transfer into the weld pool, fast processes running at the stage of molten metal melting and transition of each drop of electrode metal into the weld pool, are still insufficiently studied. This limits our understanding of the mechanism of heat-mass transfer, and requires development and realization of new experimental complexes. The noted circumstance is indicative of the urgency of the performed research, the results of which will provide a new highly efficient tool, when studying complex processes of heat-mass transfer, accompanying formation of permanent joints.

The objective of the work was studying the features of fast processes of heat-mass transfer at formation of permanent joints by the methods of consumable electrode arc welding with illumination of the

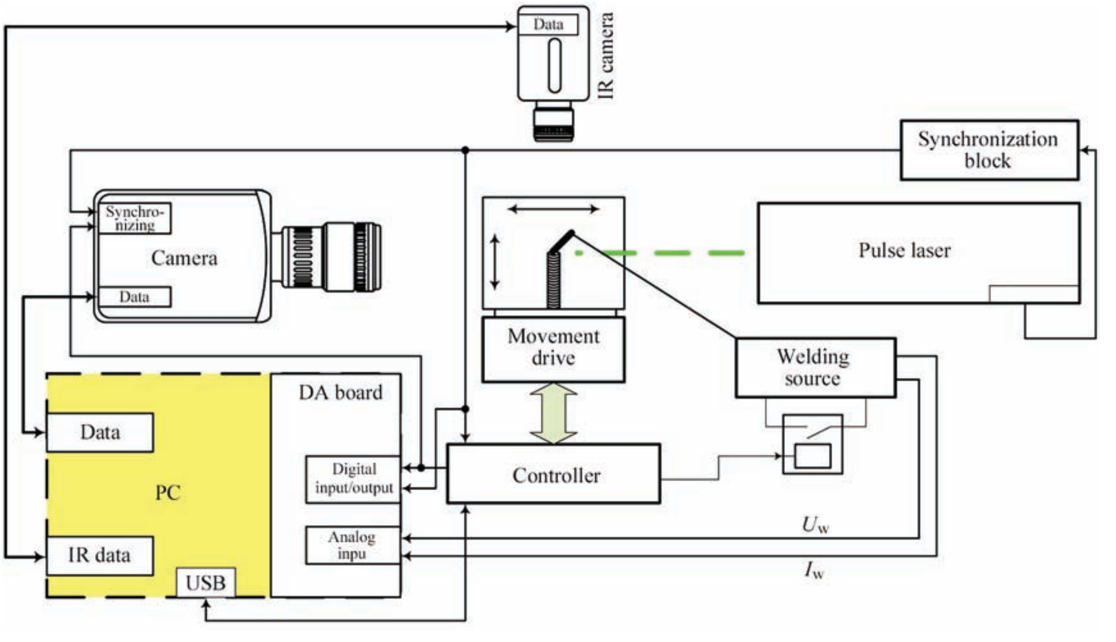


Figure 1. Complex for recording and investigation of fast processes of heat-mass transfer in consumable electrode arc welding

arc gap by a laser beam, in order to complement the modern concepts of the most effective methods of increasing the stability and effectiveness of the existing technologies.

Procedure and technique of experimental investigations. Research complex, presented in Figure 1, can be an example of realization of the research direction, which can allow achievement of the above-defined goal.

Recording of the technological process parameters is performed as follows. Special software (SW) is used to define the algorithm for performance of the welded joint (or surfacing), and the task is sent from personal computer (PC) to the controller. The controller controls movement of the table with the sample and starts the welding process. After 1–2 s delay since the moment of welding start, the controller sends a signal (Trigger) of the start of recording to a high-speed video camera and data acquisition board, which records the electric parameters (current, voltage). Each frame of high-speed videorecording is synchronized with illumination laser pulses through a synchronization unit [8–10]. Synchronization pulses also provide marking of current and voltage oscillograms for a more precise alignment of the oscillograms with videorecording frames [11]. Recording is stopped by a controller signal.

The complex envisages application of an infrared thermal imaging camera for recording the thermal fields during welding (surfacing). Thermogram interpretation provides information about the kinetics of heat propagation, rate of weld pool and HAZ cooling, dimensions of weld pool and HAZ, and change of their temperature in time [12, 13].

Robotized welding platform. Possibility of obtaining repeatable results, when studying gas-shielded arc welding is largely determined by the human factor. Therefore, stability and accuracy of maintaining the main parameters of the welding mode are directly related to welder's skills. Moreover, during performance of high-speed videofilming of the welding process, there is an additional problem of its synchronization with the moment of appearance of the studied object in the video camera focus.

Solution of the problem of repeatability of experimental results is complete automation of the welding process during investigations. At present the industry is widely applying various mechanisms for automation of arc welding processes, for instance, six-axis robotic manipulators. However, application of ready solutions is impossible, because of basic shortcomings, namely: welding torch is always moving that makes high-speed videofilming difficult. Moreover, such manipulators feature excess capabilities, making their maintenance more complicated.

An important link in the developed complex is the robotic welding platform, which during investigations ensures automatic movement of the sample being welded by one of the selected movement trajectories, in order to ensure the required weld geometry, in keeping with the requirements of GOST 6996–66 «Welded joints. Methods of mechanical properties determination». Realization of the method of movement of the sample using a robotic-type platform, is related to the need to obtain repeatable results during investigation performance, particularly in the field of gas-shielded mechanized arc welding. To eliminate the human factor and solve the problem of repeatability of experimental results, the presented complex ensures full automation of the welding process during investigation performance.

Taking into account the above-said, a working model of a robotic platform for performance of arc welding and surfacing of test samples during experimental studies, was developed and manufactured. The platform was designed proceeding from the considerations of correspondence of its technical characteristics to the parameters of typical test welded joints, namely, dimensions and weight of the real samples. As in most cases welding or surfacing are performed in the downhand position during experiments, and there is no need to change the length of the interelectrode gap, two axes are sufficient for sample movement. Accuracy of torch movement in gas-shielded semi-automatic welding is not more than 1 mm, so that the discreteness and accuracy of sample positioning are sufficient. Overall dimensions of the platform are selected so as to provide the possibility of its mounting into a standard 19-inch stand 800 mm deep.

Main technical parameters of the platform

Number of motion axes, pcs	2
Maximum size of samples being welded (W×D×H), mm	200×300×20
Carrying capacity, kg	20
Discreteness of sample movement, mm	0.1
Accuracy of sample positioning, mm	±0.1
Range of setting sample movement rate, mm/min	0–5000
Overall dimensions of the platform (W×D×H)	505×740×350
Platform weight, kg	40

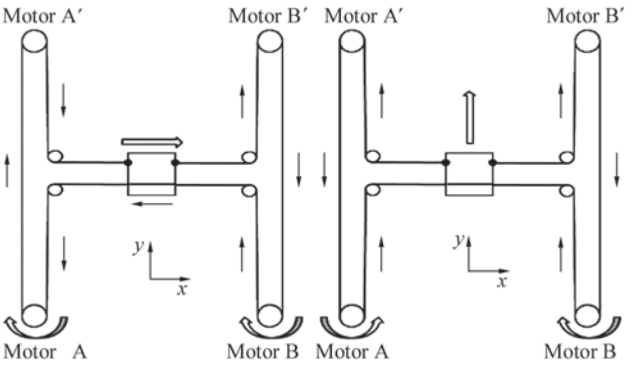


Figure 2. Kinematic diagram of robotic platform

H-BOT kinematic diagram of the platform was selected (Figure 2), as the most optimum and reliable for the specified technical characteristics. In order to increase the precision, rigidity and carrying capacity of the platform, the sample mounting stage moves on linear bearings along cylindrical guides of 20 mm diameter, using a reinforced toothed belt 25 mm wide. Applied as a drive are step electric motors of NEMA 34 type size, which operate in microstepping mode to increase the smoothness. Platform protection from moving beyond the limits of movement axes is realized by applying inductive limit switches, which are also used for moving it to «zero» initial position.

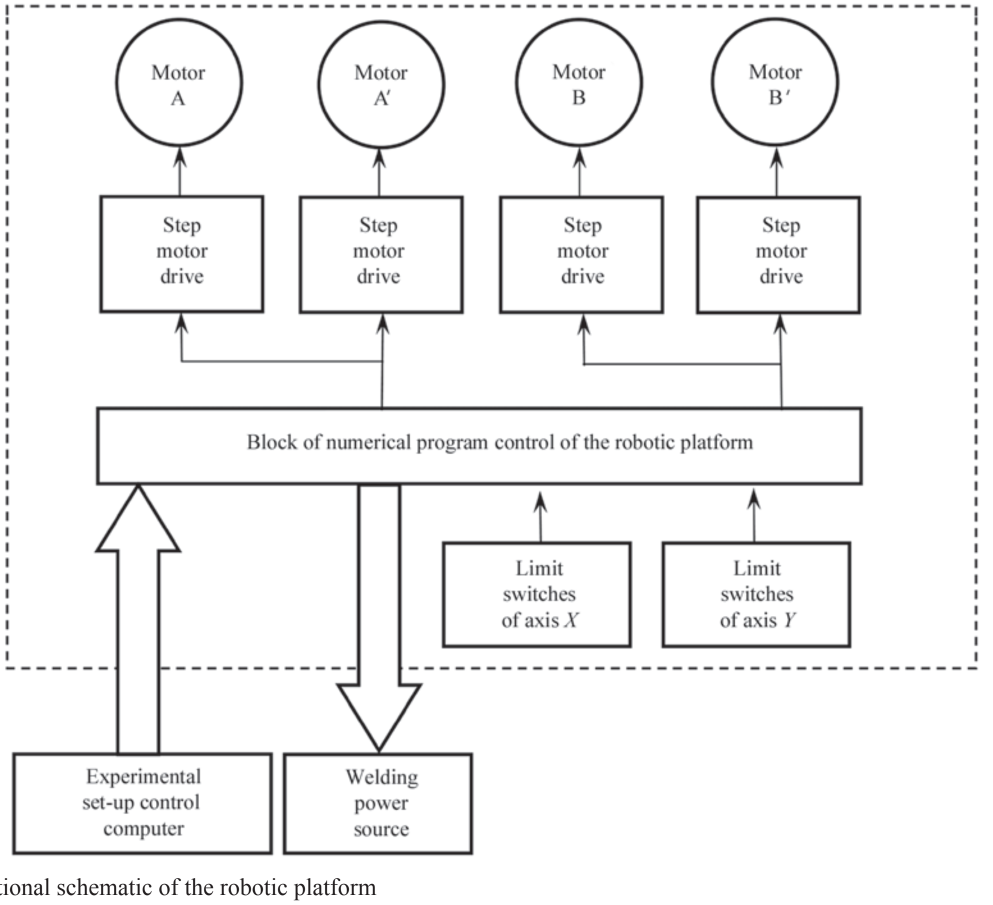


Figure 3. Functional schematic of the robotic platform

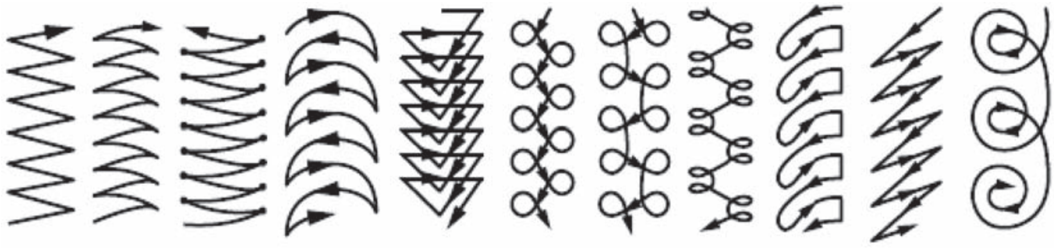


Figure 4. Variants of platform movement trajectories

Oscillograms of current in the welding circuit and voltage in interelectrode gap

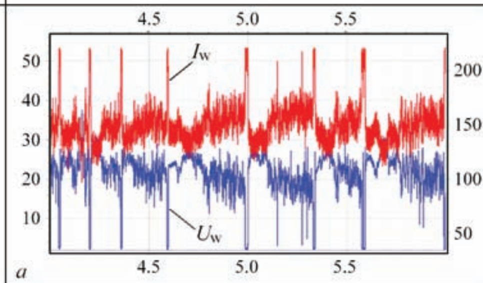
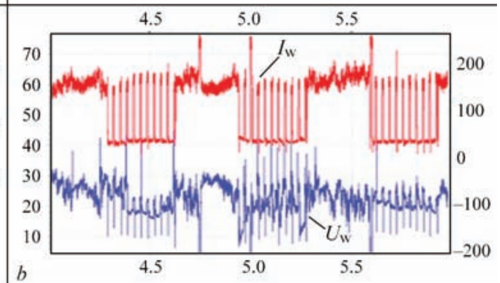
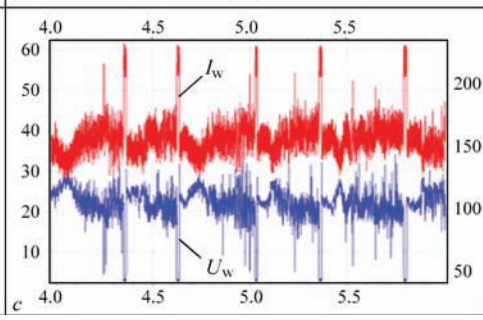
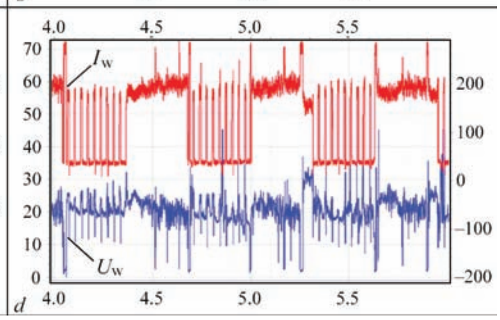
Sample number	Electrode	Direct current welding	Modulated current welding
DCW1 MCW2	UONI 13/frost. 4 mm		
DCW3 MCW4	LB–62D 4 mm		

Figure 3 shows the functional schematic of the robotic platform. The purpose of most of the blocks is described above, except for numerical control block, which is designed for conversion of the commands of experimental set-up control computer into the respective signals for step motor control. Standard G-codes are used as the commands. They are described in detail in GOST 20999–83 «Numerical control units for metal-working machines. Part program data coding», that greatly simplifies programming the path of platform movement (Figure 4). Welding power source switching-on and-off is performed using «dry» contact that allows connecting it to the experimental set-up in most of the cases without any additional matching devices.

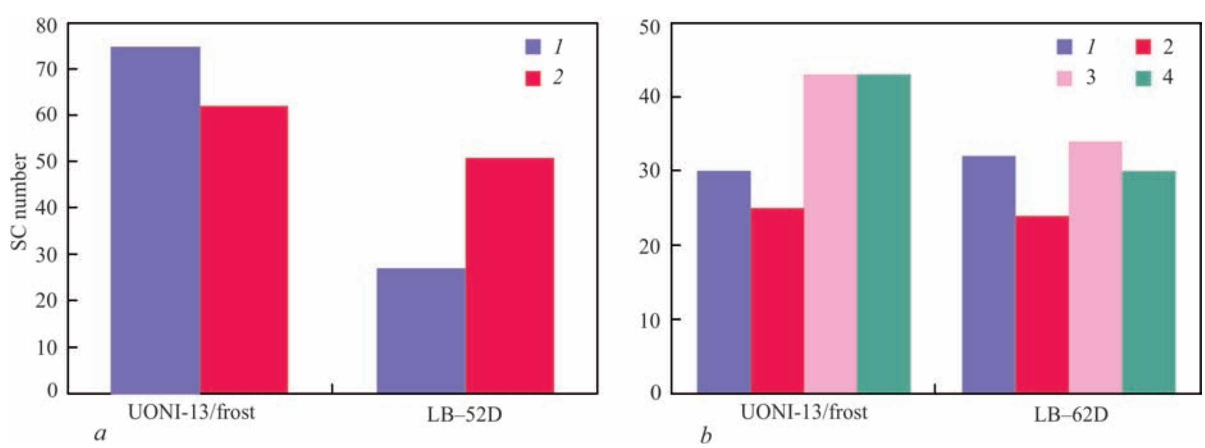


Figure 5. Number of short-circuits per 10 s: *a* — welding the root weld (RW) with 3 mm electrodes (*1* — root, direct current; *2* — root, modulated current); *b* — making the filling weld (Fil.W) and facing weld (Fac.W) with 4 mm electrodes (*1* — filling, direct current; *2* — filling, modulated current; *3* — facing, direct current; *4* — facing, modulated current)

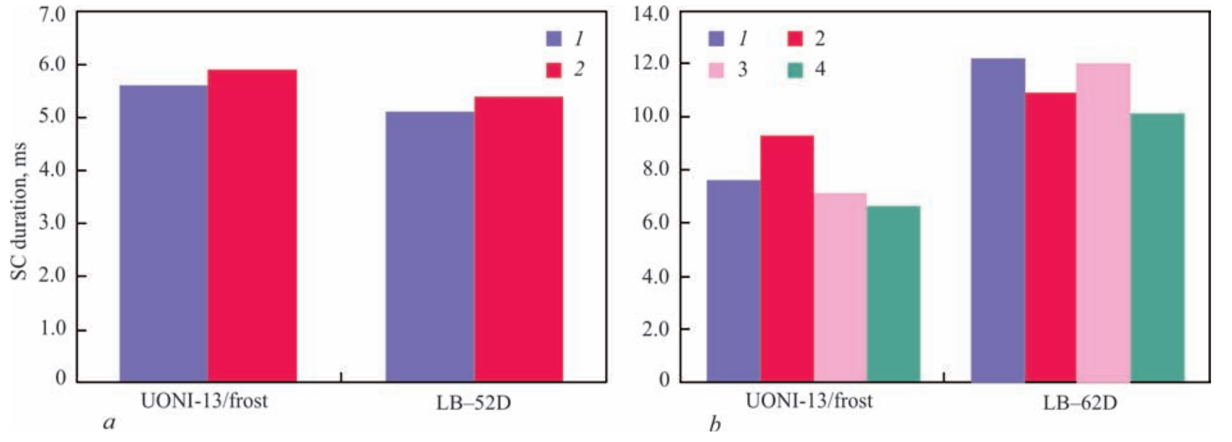


Figure 6. SC duration: *a* — making RW with 3 mm electrodes; *b* — making Fil.W and Fac.W with 4 mm diameter electrodes (same designations as in Figure 5)

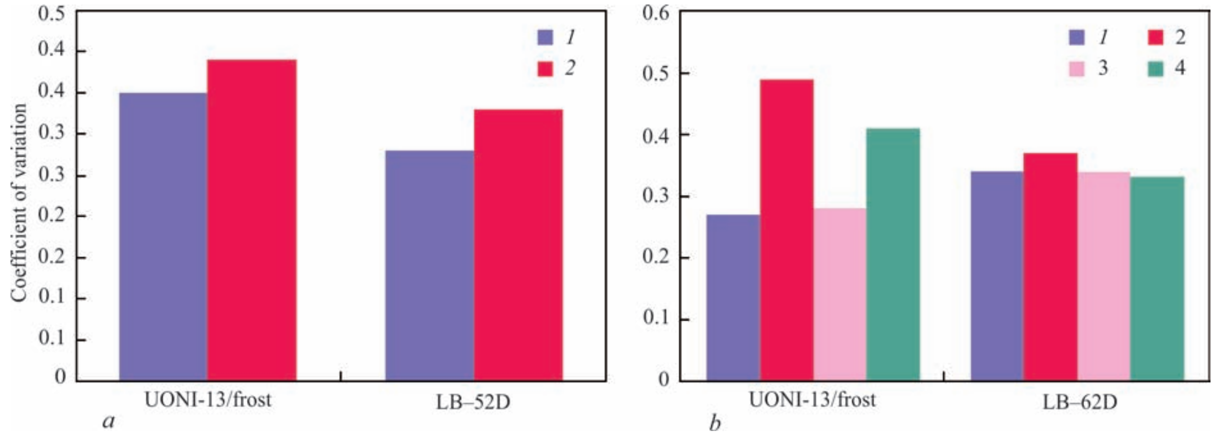


Figure 7. Coefficient of variation of SC duration: *a* — making RW with 3 mm electrodes; *b* — welding Fil.W and Fac.W with 4 mm electrodes (same designations as in Figure 5)

Processing investigation results. Processing procedure consists of three stages: determination of average values of current, voltage, power and heat input in the specified time range; statistical processing of the parameters of short-circuits (SC) during welding (surfacing), i.e. obtaining information about the number of SC per a unit of time, average SC duration, average value of SC current, coefficient of variation of SC duration; plotting comparative diagrams of obtained parameters from welding modes, electrode types, etc.

The Table gives the characteristic oscillograms of arc current and voltage, recorded during welding, where DCW is direct current welding, MCW is welding in the mode of low-frequency modulation of welding current, *1*, *3* is welding of root welds; *2*, *4* is welding of filling layers.

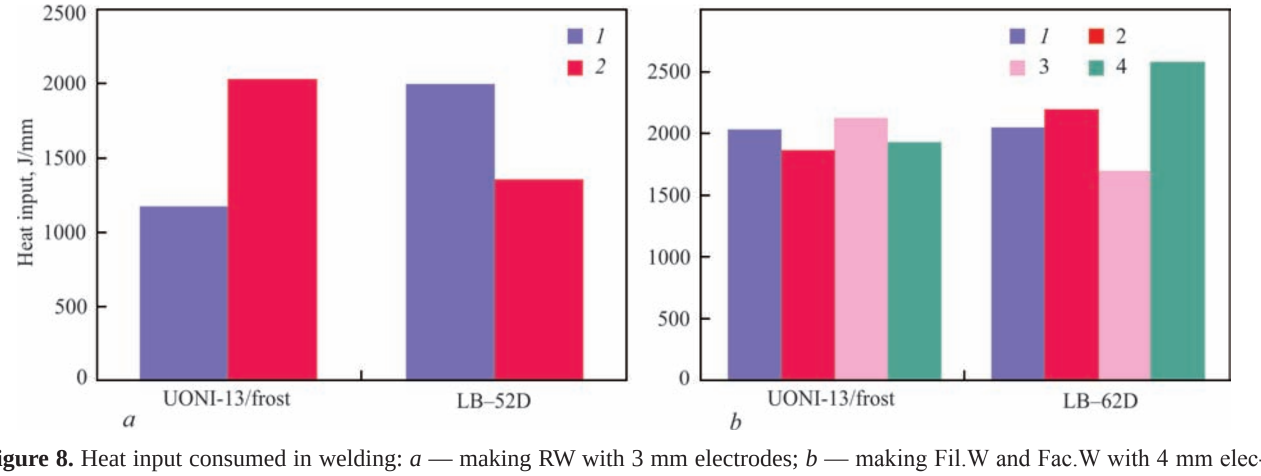


Figure 8. Heat input consumed in welding: *a* — making RW with 3 mm electrodes; *b* — making Fil.W and Fac.W with 4 mm electrodes (designations are the same as in Figure 5)

Figure 9. Thermal imaging of temperature fields on the plate surface in downhand welding

Figures 5–8 show bar charts, plotted as a result of processing experimentally obtained oscillograms of the main energy parameters of welding modes. Analysis of the given diagrams allows making a quantitative assessment of the characteristics of heat-mass transfer in coated electrode manual arc welding, which, together with analysis of experimentally obtained thermal imaging fields allow full assessment of heat-mass transfer characteristics.

Figure 9 shows the fragments of thermal image filming.

Results of thermal imaging obtained with application of a special processing program of the research complex, can be represented in the form of thermal imaging pictures, which are shown in Figure 10. Experimentally obtained thermal fields allow establishing the weld pool length, and, therefore, also solidification process rate in the formed welded joint.

In mechanized welding processes, the frequency of transition of molten electrode metal into the weld pool is equal to 25–300 drops per second that makes it very difficult to study the fast processes, either at the melting stage or at the stage of their transition to the weld pool.

In order to process the results of experiments on studying the heat-mass transfer characteristics in mechanized welding processes, special software was applied as part of the complex. It allows presenting them, similar to manual arc welding, in the form of graphic images and numerical values of heat-mass transfer characteristics: heat input, frequency of electrode metal drop transfer, coefficients of variation of frequency, SC current duration and amplitude, thermal field isotherms and graphs of the change of thermal cycles of welding.

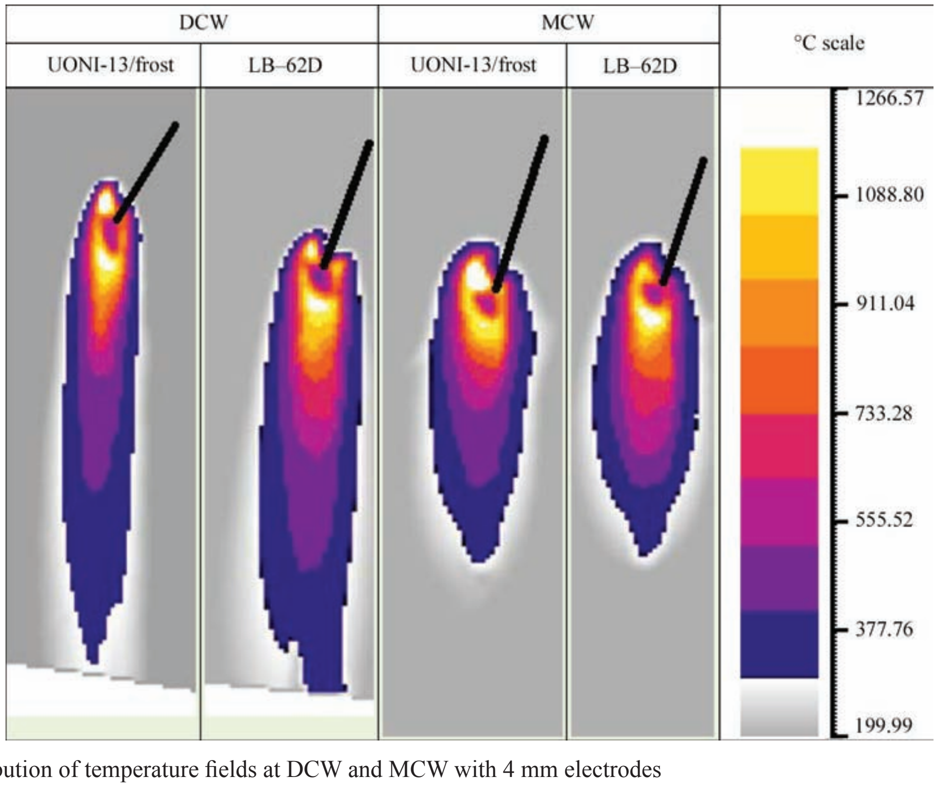


Figure 10. Distribution of temperature fields at DCW and MCW with 4 mm electrodes

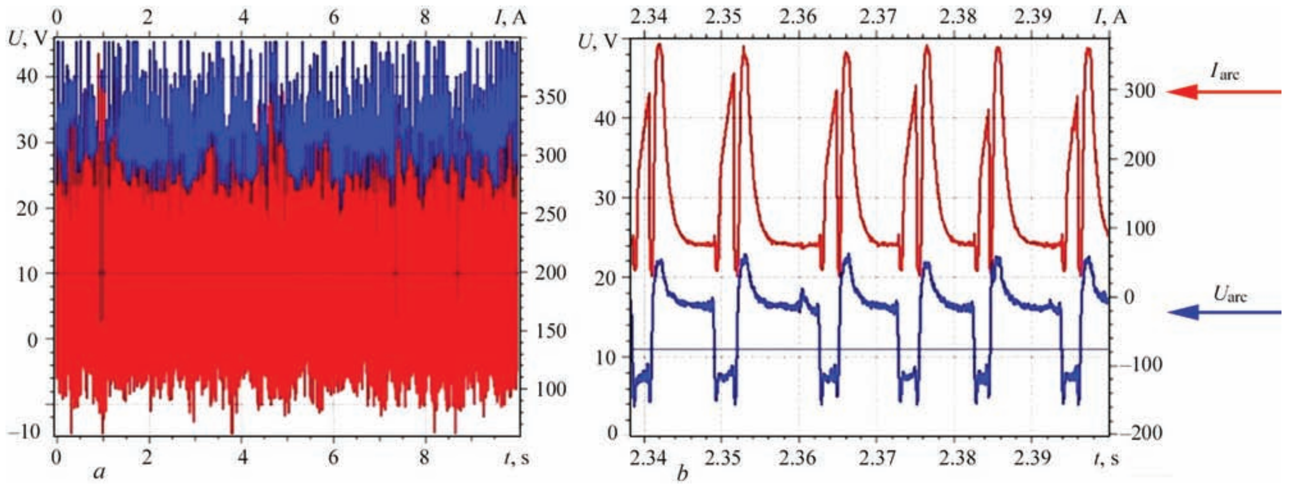


Figure 11. Example of processing the results of measurement of current and voltage of the arc during experimental studies: *a* — without filtering background noise; *b* — after filtering at result output for analysis

Visualization of measurement results and their processing depend entirely on methods of parameter recording, which determine the ability of measurement system to ensure suppression of high-frequency noise by removing from the spectra of voltage and current oscillograms the high-frequency components, having a high amplitude, determination of threshold value of voltage at SC (this task is the responsibility of the researcher and is performed by manual assignment of the threshold by a marker line on voltage oscillogram), Figure 11. This is followed by: automatic sampling of SC in the required time range, determination of current and duration of each SC, calculation of average value of SC current in the obtained sample, average duration of SC and coefficient of variation SC duration. Obtained data can be presented in the form of tables, as well as bar charts (Figure 12).

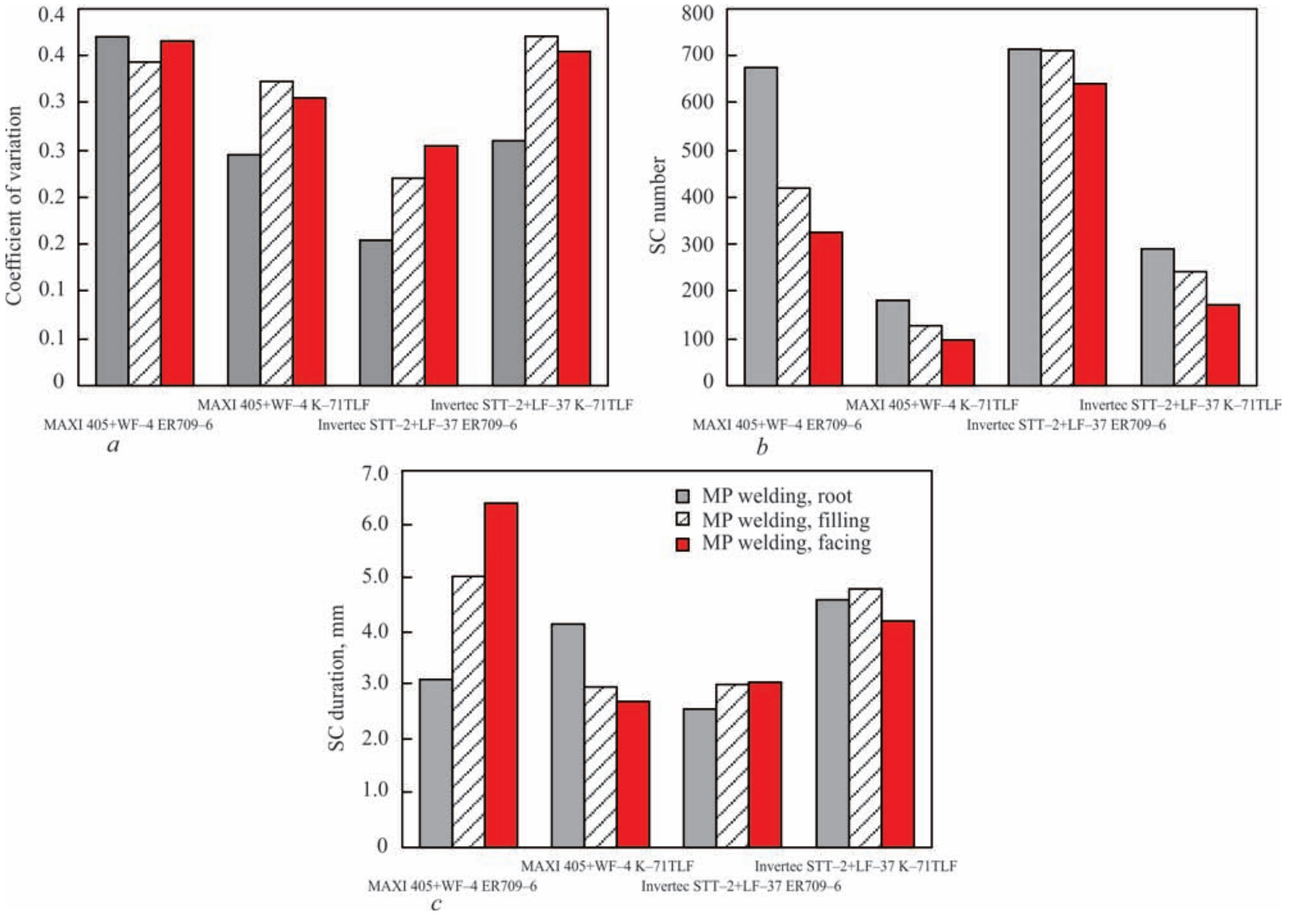


Figure 12. Examples of bar charts for mechanized welding in CO_2 with short-circuiting of the arc gap: *a* — coefficient of duration variation (MP welding); *b* — SC number (MP welding); average SC duration (MP welding)

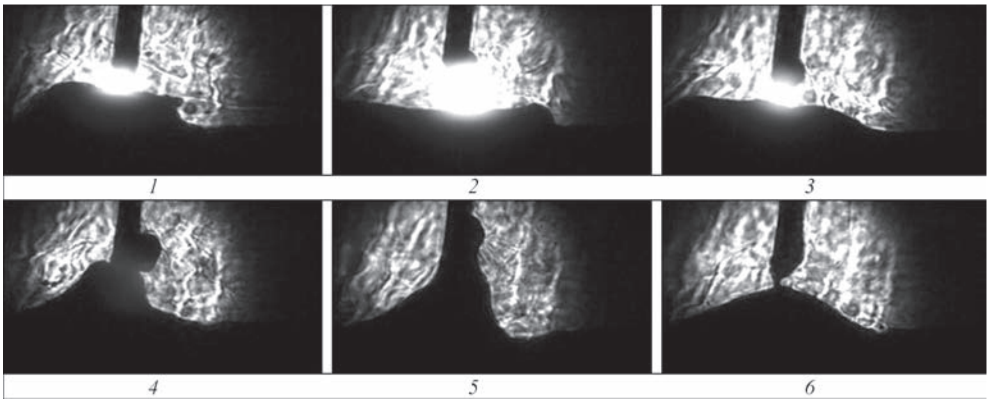


Figure 13. Videoframes of the process of electrode metal melting and transfer in mechanized CO_2 welding with solid wire, videofilming frequency of 5000 frames per second (illumination of the arc gap by a spotlight with xenon lamp)

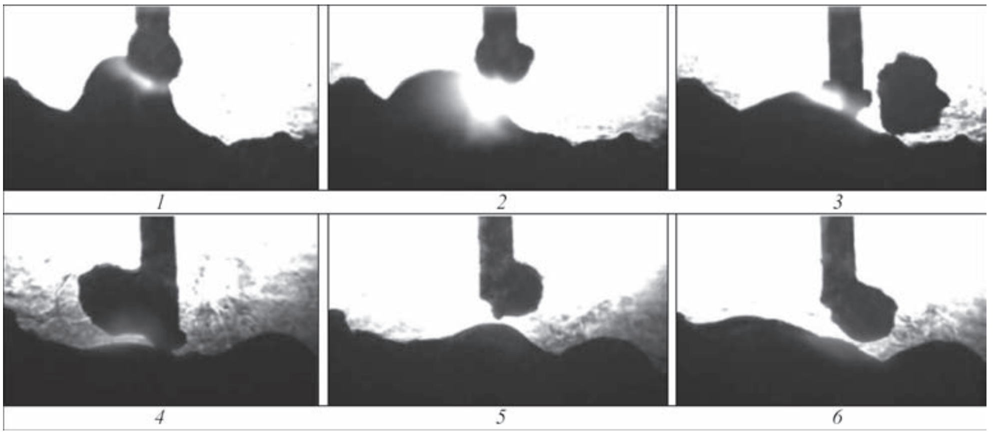


Figure 14. Videoframes of the process of electrode metal melting and transfer in mechanized welding in CO_2 with solid wire, videofilming frequency is 5000 frames per second (illumination of the arc gap by Cu–Br laser beam)

Average values are calculated by numerical integration of current, voltage and their product (power). Welding speed, which allows detemination of the heat input, is calculated as the ratio of the length of weld (deposited coating) to the time, consumed when making this weld (coating). In addition, the complex includes a module of high-speed videorecording of the process of electrode metal melting and transfer, as weld as module for oscillography of the main energy parameters of the welding process, which is performed in synchronism with recording of melting and transfer of each electrode metal drop. Pulsed laser illumination is used in order to improve the quality of videofilming of the process of electrode metal melting and transfer.

However, the processes of heat-mass transfer running in a complex electrodynamic system of power source–arc–weld pool–item at different welding processes, including those with pulsed variation of energy parameters of the mode, are still poorly understood. Studying these phenomena involves a number of difficulties, associated with the speed of running of heat-mass transfer processes at simultaneous action of powerful light of the welding arc (Figure 13).

Figures 13 and 14 show videoframes of welding microcycle (period of melting and transfer of one electrode metal drop). Comparison of videoframes confirms the earlier assumption that application of coherent laser radiation during filming should promote better visualization of the studied object of heat-mass transfer. Performed experiments fully confirmed the correctness of the selected direction of research complex development.

In conclusion it can be noted that the robotic type research complex, designed for studying the features of fast processes of heat-mass transfer, when making permanent joints by consumable electrode arc welding under the conditions of illumination of the arc gap by Cu–Br-laser beam, has the required technical characteristics and can be effectively applied for producing test samples during performance of experimental studies, related to finding the ways to improve the reliability of critical structures, operating under extreme conditions.

Conducted trials of the research complex fully confirmed its high effectiveness, when studying the fast processes of heat-mass transfer in consumable electrode electric arc welding, that certainly expands the modern understanding of the most efficient methods to improve the stability and performance of the current technologies.

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