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The influence of pulse current on drop transfer during double-electrode gas surfacing

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Abstract: The application of a circuit with a common pulse current source for surfacing with two electrode wires increases the energy efficiency of the arc process and the welding arc technological properties, but requires a more detailed study of the influence of the mode parameters on its stability. In this regard, this paper focuses on studying the dynamics of formation and transfer of metal drops under various modes of pulsed power supply of the welding arc. Using high-speed video filming of the welding arc and synchronized recording of current and voltage signals, a mode was set (average current value was 250 A, maximum current value in pulse was 600 A, arc voltage was ~30 V), which ensured a stable process of transfer of electrode metal by a drop common to two wires without short circuits. It was found that the common drop under the action of electrodynamic forces acquires centripetal acceleration, which contributes to its directed transfer to the weld pool and allows minimizing the amount of spatter on the surface of the base metal. Using mathematical modeling, the nature of the interaction of welding arcs on two wires was confirmed and it was found that even at the stage of the current pulse "hot" phase (600 A, t=0.8 s), the arc pressure on the plate surface is less than when welding with one wire at direct current. The identified effect is associated with a change in the direction of the plasma flow to perpendicular to the wire axis due to an increase in the electrodynamic attractive force of the magnetic fields around the two wire conductors. Together with a decrease in the arc temperature and pressure on the plate surface during the "heat input control" phase of the current pulse (180 A, t=1.4 s), this should help to reduce the heat input and the depth of penetration of the base metal, and, consequently, reduce the degree of dilution of the deposited alloy by the substrate metal. The latter is especially relevant when solving problems of creating a technology for surfacing of relatively thin layers of corrosion-resistant alloys, in particular, on the surface of petrochemical equipment products.

Keywords: double-electrode surfacing; pulse-arc process; welding arc; drop transfer; numerical simulation.

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INTRODUCTION

The quality and service reliability of products in the metallurgical and mechanical engineering industries are largely determined by the level of development of technological processes of welding and surfacing. As a result, the priority task is the continuous improvement of welding technologies aimed at developing methods to increase the productivity of these processes and improve the properties of welded joints and deposited metal. One of these methods is double-electrode welding and surfacing, when the wire electrodes are connected to a common power source [1; 2]. It is widely used both for welding thick-walled structures and for forming a layer of high-tin bronze on steel [3] and corrosion-resistant deposited coatings [4], which expands the technological capabilities of welding production.

Using mathematical modeling methods, it was found that the plasma temperature of a double-electrode arc is generally lower compared to a single-electrode process, its maximum temperature and arc pressure on the surface of the weld pool are also lower [5]. At the same time, the average temperature of the electrode metal is lower [6]. In the case of double-electrode surfacing, the heat flow into the product is reduced [7], which helps to reduce the deformation of the surfacing product. A similar result can be achieved by applying current pulses to the arc using special control algorithms [8–10], which is currently widely implemented in serially produced semiautomatic machines and has actually become the basic solution for single-electrode mechanized welding and surfacing in shielding gases. Existing equipment for using pulse current with two electrode wires has been industrially mastered for the process of two-arc welding "tandem", when each wire is connected to a separate power source [11–13].

The use of a circuit with a common power supply for two electrode wires [14] increases both the energy efficiency of the arc process and its manufacturability, since its implementation does not require equipping each electrode wire with a feed mechanism and additional equipment. The existing positive experience of using double-electrode surfacing to form corrosion-resistant cladding coatings is based on the use of relatively low arc voltage values, which ensures the transfer of electrode metal in the mode of forming a so-called "common" drop for two melting electrode wires and minimizes the share of the base metal in the deposit one to 30 % [15].

The use of a common pulse current source for surfacing with two electrode wires is of interest, which will make it possible to develop the advantages of the double-electrode scheme in improving the technological properties of the arc (the quality of the transfer of electrode metal in the arc, heat input into the base metal, etc.). For this reason, it is necessary to study the influence of both the main parameters of the mode and the pulse current on the arc.

The relevance of this topic is also caused by the necessity of improving the quality of welding and surfacing processes when assimilating new products at petrochemical engineering enterprises and solving the problems they face in technological advancement. This will improve the quality of deposited coatings, reduce costs and increase the efficiency of production processes.

The aim of this work is to determine the optimal mode of pulsed power supply of the welding arc during double-electrode surfacing, ensuring the formation of a common drop and its directed transfer into the weld pool without short-circuiting the arc gap.

METHODS

Modernization of welding equipment

For the experimental studies, the Lorch S8 Pulse XT semiautomatic pulse welding machine (Germany) was retrofitted with a pair of rollers (manufactured using FDM printing) with two identical V-shaped grooves for use in the feed mechanism of two wires with a diameter of 1.6 mm at the same time, which were fed through a fluoroplastic flexible tube into an external current-supplying unit equipped with a water-cooled nozzle. The "Pulse" program was selected in the semiautomatic machine settings.

Experimental facility and measurements

The scheme of arc surfacing process study (Fig. 1) included an iSpeedy 50MT13M-SE high-speed photography system (China) and a LA-20USB multichannel analog-to-digital converter (Russia) for monitoring voltage and current changes over time with a sampling frequency of 5 kHz. The obtained oscillograms were processed in specialized PowerGraph 3.3 Pro software.

The high-speed photography system included a camera connected to a laptop via a 10 Gbps Ethernet interface and specialized iSpeedyPro software, which was used to configure the camera operating mode parameters and perform primary processing of the obtained video signal. The camera has an extended high-speed memory of 64 GB. A special housing was used to protect the camera and the front lens from welding spatter. Video recording of the welding arc zone was performed at a speed of 5000 frames per second. The shooting direction was perpendicular to the connecting line between the two welding wires. High-speed arc frames were synchronized with the recording of electrical signals, which made it possible to compare the dynamics of drop formation and transfer in the arc with changes in current and voltage in it.

Surfacing parameters

Surfacing was performed on St3sp plates of 200×100×10 mm in size moved at a surfacing speed of 13 m/h by a special mechanism relative to a stationary welding head. Surfacing in pulse mode was performed at a current of I=280 A and a voltage of U_{arc}=24 V with a center-to-center distance of b=6 mm. An AG ER-347Si (Sv-08H19N10G2B) welding wire with a diameter of 1.6 mm and a mixture of argon and carbon dioxide (97.5 % + 2.5 %) were used. The gas mixture flow rate was 25–30 l/min.

Arc mathematical modeling

For a more visual and comprehensive assessment of the electro- and thermal-physical processes occurring in the welding arc under the influence of pulse current, mathematical modeling was performed in the Comsol Multiphysics software package. The approach to creating a welding arc model used in the work is based on a system of interrelated equations describing the complex interaction of hydrodynamic, electromagnetic and thermal processes in a plasma discharge, as well as on the fundamental laws of conservation of mass, momentum and energy, supplemented by the equations of electrodynamics for a conducting medium[1]. The hydrodynamic part of the model considers plasma as a viscous electrically conductive liquid, the movement of which is determined by the balance of the forces of pressure, viscosity and electromagnetic action. Electromagnetic processes are described taking into account the generation of a magnetic field by the arc current and its reverse effect on the distribution of charged particles. Thermal effects include Joule heating, convective and conductive heat transfer, and radiation energy losses. The arc length was set in the model according to high-speed video footage (l_{arc}=6 mm).

[1] *Elsukov S.K. Povyshenie effektivnosti dvukhelektrodnoy naplavki v zashchitnykh gazakh khromonikelevykh austenitnykh staley na detali neftekhimicheskogo oborudovaniya [Improving the efficiency of two-electrode surfacing in protective gases of chromium-nickel austenitic steels on petrochemical equipment parts], diss. kand. tekhn. nauk. Volgograd, 2023. 143 p. EDN: MEZKRU.*

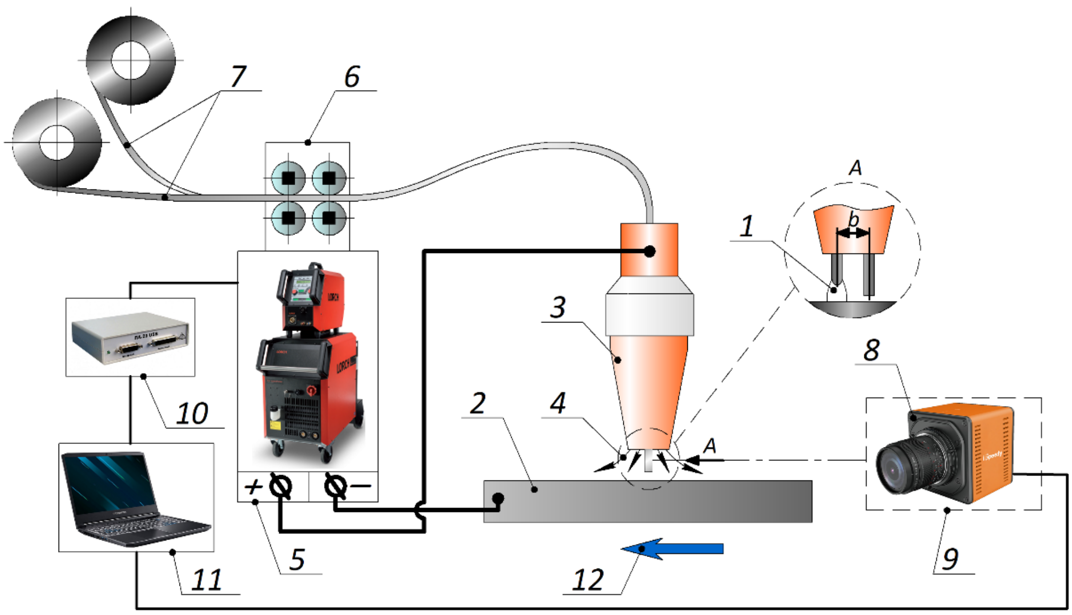

Fig. 1. *Scheme of the study of the welding arc reaction zone in the process of double-electrode pulsed surfacing:*
1 – welding arc; 2 – deposited plate; 3 – shielding gas supply nozzle;
4 – shielding gas flow; 5 – semiautomatic welding machine; 6 – feed mechanism; 7 – welding wires;
8 – high-speed camera; 9 – protective camera housing; 10 – analog-to-digital converter;
11 – computer; 12 – plate movement direction
Рис. 1. *Схема исследования реакционной зоны сварочной дуги в процессе двухэлектродной импульсной наплавки:*
1 – сварочная дуга; 2 – наплавляемая пластина; 3 – сопло подачи защитного газа;
4 – поток защитного газа; 5 – сварочный полуавтомат; 6 – подающий механизм; 7 – сварочные проволоки;
8 – высокоскоростная камера; 9 – защитный корпус камеры; 10 – аналого-цифровой преобразователь;
11 – компьютер; 12 – направление перемещения пластины

The model is based on a number of reasonable assumptions, including the assumption of local thermodynamic equilibrium of the plasma, the laminar nature of the flow, and neglect of phase transition processes in electrode materials. The relationship between the equations was ensured through the constitutive relations for the thermophysical and electrodynamic properties of the plasma, which made it possible to create a closed system for the numerical solution. This approach allowed studying the influence of various welding arc parameters on the temperature distribution, pressure, and flow rates in its plasma column.

RESULTS

Analysis of the modulated current oscillogram obtained at a welding wire feed rate of 2 m/min shows that the average welding current was 280 A at a modulation frequency of ~333 Hz (Fig. 2).

Large droplets are simultaneously formed at the ends of the welding wires (Fig. 3, frame *a*), which are held by surface tension forces and attracted by the action of electrodynamic force (Fig. 3, frames *b*, *c*). At the moment of frame *d*, the droplets at the ends of the wires merge, one of the droplets flows to the other. The resulting common drop of electrode metal closes on the surface of the weld pool and passes into it (Fig. 3, frame *e*).

A further increase in current to 280 A disrupts the stability of the drop transfer process and the formation of a common drop, which is pushed toward the current-carrying tip (Fig. 4).

When using the pulse welding mode at a wire feed speed of 2 m/min and an arc voltage of 24 V, the average current value reached 280 A. In this mode, the Lorch S8 Pulse XT current source generates a complex-shaped pulse signal (Fig. 5). At the beginning of each pulse, the current strength sharply increases to 620 A and is maintained at this level for 3 ms. Then, smoothly decreasing over 5 ms, it reaches 200 A, after which it decreases at the same speed to the base value of 60 A. The pulse repetition frequency is 105 Hz, ensuring the stability of the welding process.

During the analysis of the obtained frames of the arc zone with its pulsed power supply, it was found that at the moment of the current pulse, the detachment of welding droplets from the electrode does not occur (Fig. 6, frame *b*), unlike the single-electrode process. Instead, the pulse energy is spent on the formation of large droplets, which, as they grow, merge into a common drop. The transition of the common drop occurs through a short circuit (Fig. 6, frame *d*), which is similar to the nature of drop transfer when using direct current.

The obtained results do not allow revealing fully the capabilities of the pulsed power supply of the welding arc due to the preservation of the mode of drop transfer through their short circuits on the surface of the weld pool. To prevent this, it is possible to increase the arc length by setting

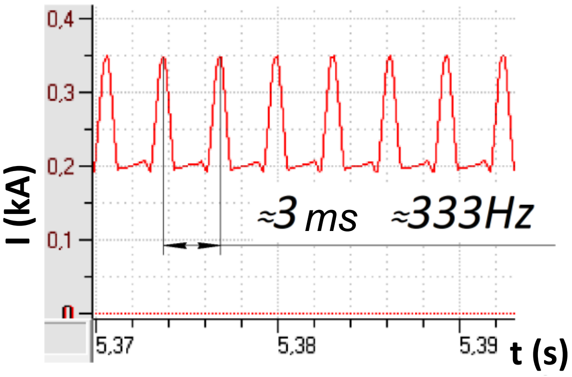

Fig. 2. *External appearance of the oscillogram of the modulated current of the Lorch S8 Pulse XT power supply*
Рис. 2. *Внешний вид осциллограммы модулированного тока источника питания Lorch S8 Pulse XT*

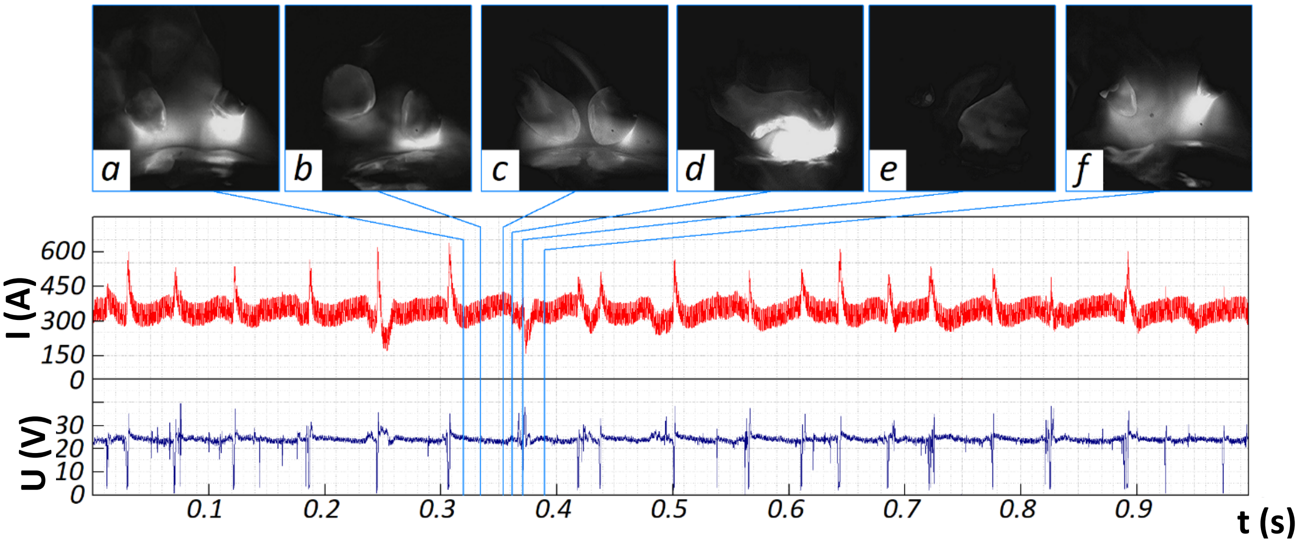

Fig. 3. *External appearance of the oscillogram of the direct current and voltage and high-speed video footage (I=280 A; U_{arc}=23 V)*
Рис. 3. *Внешний вид осциллограммы постоянного тока и напряжения, а также кадры высокоскоростной видеосъемки (I=280 А; $U_д$=23 В)*

Fig. 4. *Displacement of the common drop to the upper part of the arc reaction zone*
Рис. 4. *Оттеснение общей капли в верхнюю часть реакционной зоны дуги*

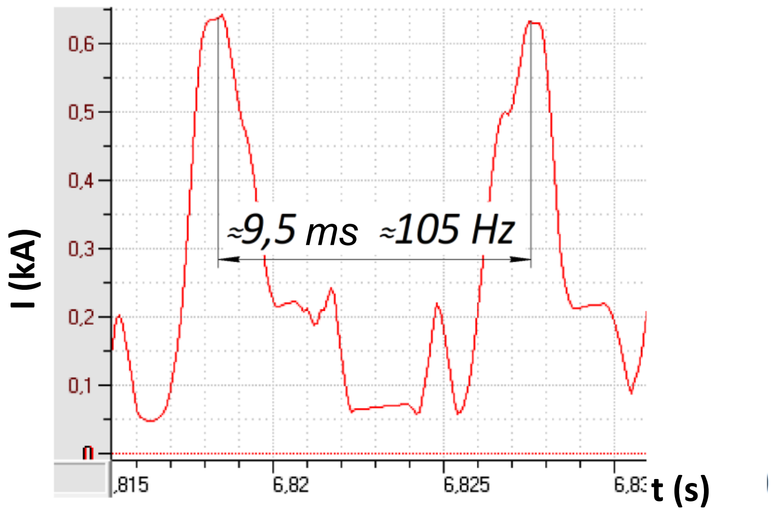

Fig. 5. *External appearance of the oscillogram of the pulse current of the Lorch S8 Pulse XT power supply*
Рис. 5. *Внешний вид осциллограммы импульсного тока источника питания Lorch S8 Pulse XT*

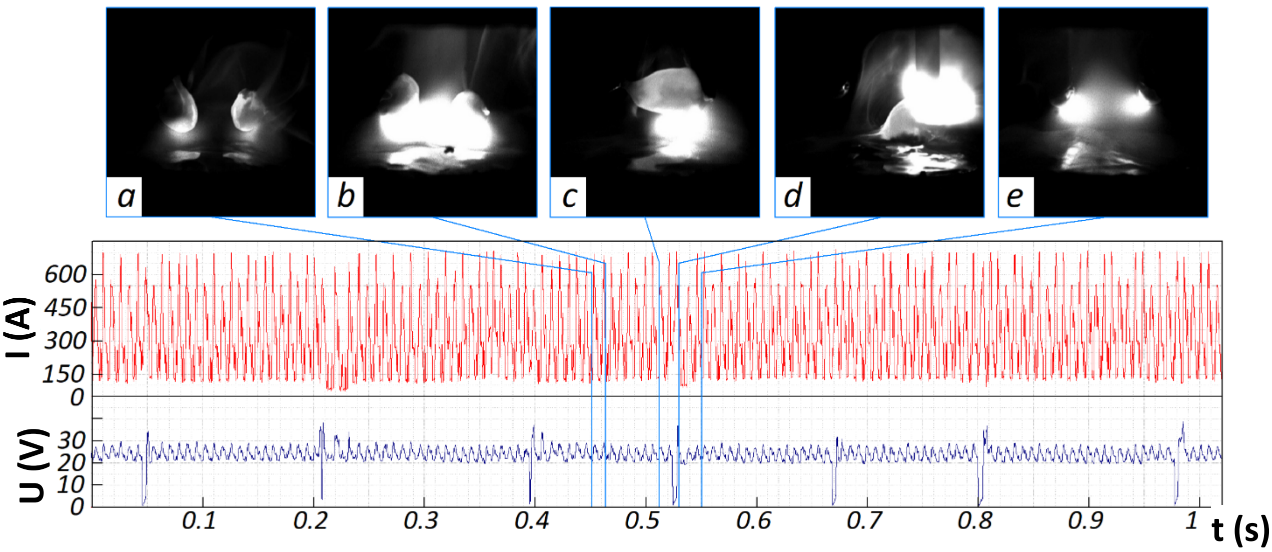

Fig. 6. *External appearance of the oscillogram of the pulse current and voltage and high-speed video footage (I=280 A; U_{arc}=24 V)*
Рис. 6. *Внешний вид осциллограммы импульсного тока и напряжения, а также кадры высокоскоростной видеосъемки (I=280 A; $U_д$=24 B)*

an increased voltage value (for example, up to 30 V) on the welding semiautomatic device. In this case, the drop transfer process begins with the alternating existence of the arc on the ends of the welding wires (Fig. 7, frames *a*, *b*). The arc movement frequency is on average 150 Hz, which corresponds to the current pulses generated by the power source. As the droplets grow (Fig. 7, frames *c*, *d*), after about 100 ms, the arc switches to the mode of simultaneous melting of the wires, and as the volume of the droplets increases, they merge into a common drop after 50 ms. After that, a large common drop flows to the end of one of the wires and goes into the weld pool. The duration of the overall cycle of drop formation and transfer is approximately 300 ms. The transition of the drop into the weld pool differs from the transition during direct current welding: at the moment of detachment, a powerful current pulse imparts additional centripetal acceleration to the drop (Fig. 7, frame *e*). This mode is characterized by the absence of short circuits of the common drop, which allows minimizing the amount of spatter on the base metal surface. Therefore, this surfacing mode is the most promising. A further increase in the current strength to 350 A in the welding current source, according to the obtained oscillogram, occurs due to an increase in the pulse frequency to 166 Hz and an increase in the base current strength to 120 A.

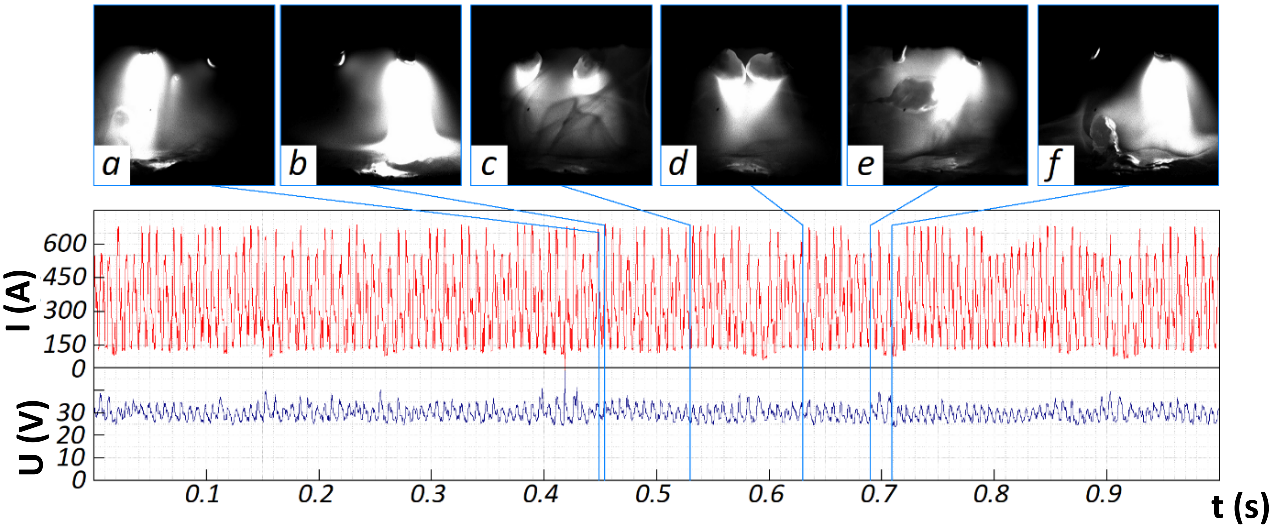

Fig. 7. *External appearance of the oscillogram of the pulse current and voltage and high-speed video footage (I=280 A; U_{arc}=30 V)*
Рис. 7. *Внешний вид осциллограммы импульсного тока и напряжения, а также кадры высокоскоростной видеосъемки (I=280 А; $U_д$=30 В)*

An increase in the current strength leads to an increase in the electrodynamic force, which tends to attract the droplets to each other. The resulting force at the moment of the pulse swings them, due to which the drops vibrate on the end of the electrode and detach asynchronously. This leads to the fact that at the moment when the droplet shifts to the axis of symmetry of the electrode, under the action of the pinch effect, the current pulse detaches it, imparting a rotational motion. When colliding into a common drop, they break up due to their high speed, which disrupts the drop transfer process (Fig. 8).

It follows from the simulation results that a typical current pulse begins with a smooth linear increase from 85 to 600 A in 1.5 ms. At this point, the maximum temperature region moves up the electrode axis, as the intersection point of the opposing flows does, while their intensity increases (Fig. 9, frame *a*). The pressure distribution in the pulse current arc differs from that in the direct current arc. As the pulse increases, two zones of maximum pressure are formed: in the anode spot region – 620 Pa and in the zone of intersection of flows at an angle of ≈130° – 517 Pa (Fig. 9, frame *e*).

After the current stabilizes for 0.8 ms at 600 A (the "hot" pulse phase), the plasma flow acquires a perpendicular direction relative to the wire axis due to an increase in the electrodynamic attractive force. The temperature near the anode spot reaches its maximum – 24,987 K (Fig. 9, frame *b*). The increased density of current vector lines is also observed in this area. The pressure on the surface of the model plate is 826 Pa (Fig. 9, frame *f*), which is lower[2] than the arc pressure value during single-wire welding with direct current (about 1000 Pa).

Then the current value decreases linearly to 180 A in 0.7 ms (the "heat input control" phase) and is maintained at this level for 1.4 ms. At this stage, the arc temperature decreases, and the zone of maximum heating shifts closer to the surface of the plate (15,209 K) (Fig. 9, frame *c*). The plasma flow stops deviating to the upper part of the arc. The pressure on the surface of the plate decreases to 329 Pa (Fig. 9, frame *g*).

The final phase is a pause of 3.3 ms at a current value of 85 A (the "cold" phase). At this point, the minimum pressure is recorded – 76 Pa, and the temperature field retains a structure (Fig. 9, frames *d*, *h*) similar to the previous phase. Then the cycle repeats.

DISCUSSION

Analyzing the obtained results, it can be concluded that the nature of drop transfer in the modulated current mode is generally similar to the transfer during surfacing with direct current of reverse polarity. The average time of electrode drop transfer was 320 ms, which is comparable with previously obtained data [15]; therefore, there is no advantage of arc supply with modulated current over direct current.

Assessing the results obtained when supplying the arc with pulse current, one should note an interesting feature of the transition of the total drop into the weld pool with centripetal acceleration under the influence of the pinch effect that occurs at the moment of reaching the highest power of the current pulse (at 600 A). As a result, the drop, rotating, enters the weld pool exactly along the axis of the welding wire. This allows avoiding a common defect – crystallized splashes and drops of electrode metal on the surface of the product both in double-electrode welding in a shielding gas and in single-electrode welding [16]. A further increase in current (up to 350 A) disrupts the stability of

[2] *Elsukov S.K. Povyshenie effektivnosti dvukhelektrodnoy naplavki v zashchitnykh gazakh khromonikelevykh austenitnykh staley na detali neftekhimicheskogo oborudovaniya [Improving the efficiency of two-electrode surfacing in protective gases of chromium-nickel austenitic steels on petrochemical equipment parts], diss. kand. tekhn. nauk. Volgograd, 2023. 143 p. EDN: MEZKRU.*

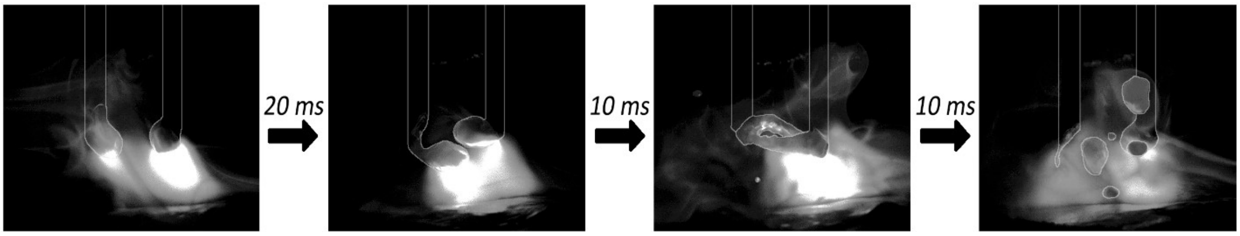

Fig. 8. *Cross-movement of electrode drops with drop transfer disruption (I=350 A; U_{arc}=30 V)*
Рис. 8. *Перекрестное перемещение электродных капель с нарушением каплепереноса (I=350 A; $U_д$=30 B)*

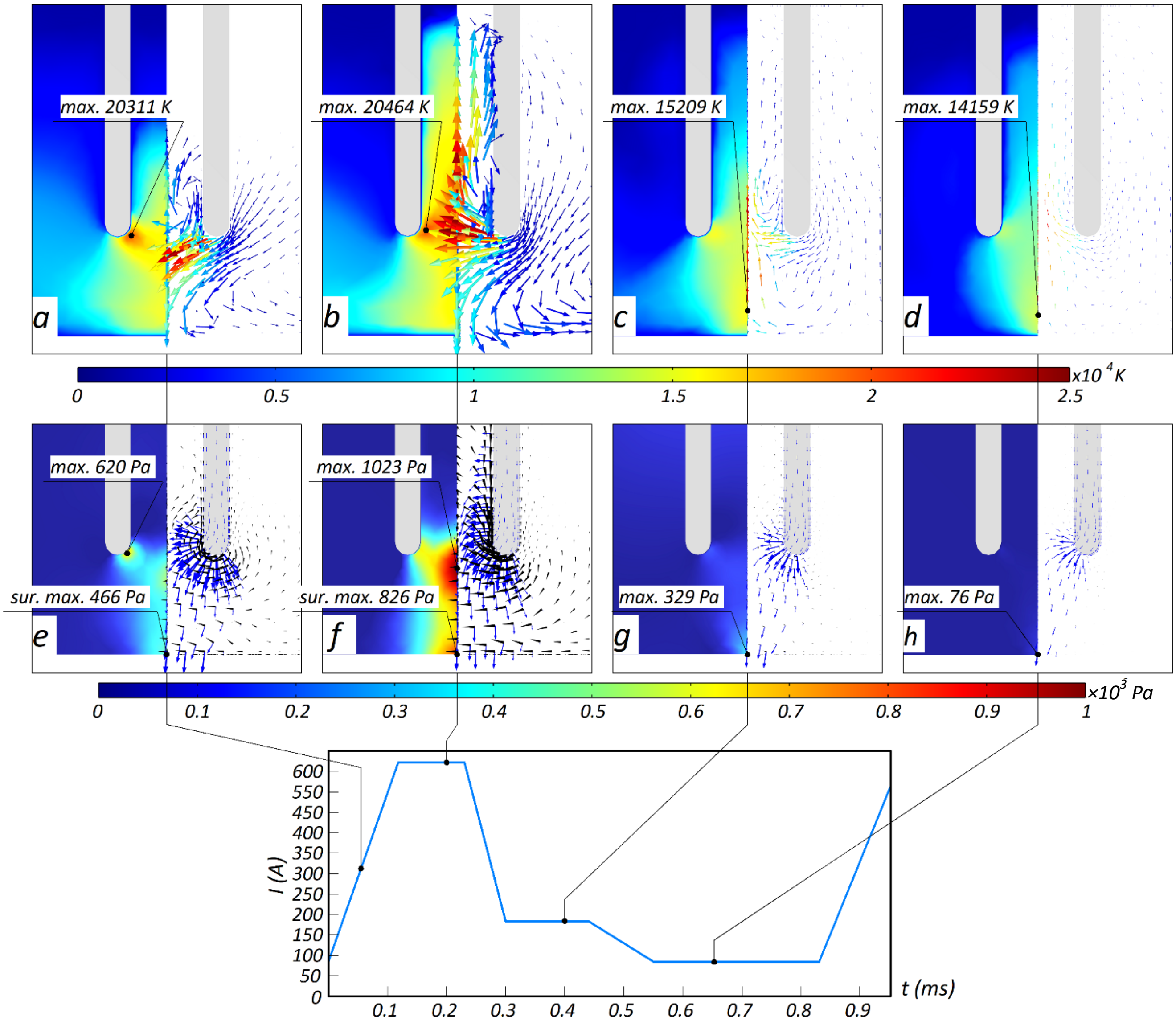

Fig. 9. *Distribution of temperature in the model arc, direction and plasma flow rate (**a–d**);*
distribution of arc pressure, current density vector (blue arrows)
*and Lorentz force vector (black triangles) (**e–h**) depending on the phase of the current pulse cycle*
Рис. 9. *Распределение температуры в модельной дуге, направления и скорости плазменного потока (**a–d**);*
распределение давления дуги, вектора плотности тока (синие стрелки)
*и вектора силы Лоренца (черные треугольники) (**e–h**) в зависимости от фазы цикла импульса тока*

the formation of a common drop, which was also observed when using carbon dioxide as a shielding gas [17]. Therefore, the use of this mode for surfacing is impractical.

Mathematical modeling confirmed the nature of the interaction of welding arcs on two wires and found that even at the stage of the "hot" phase of the current pulse (600 A, t=0.8 s), the arc pressure on the plate surface is less than when welding with one wire at direct current. The identified effect is associated with a change in the flow direction to perpendicular to the wire axis due to an increase in the electrodynamic force of attraction of magnetic fields around two wire conductors. Together with a decrease in the arc temperature and pressure on the plate surface in the "cold" phase of the current pulse (180 A, t=1.4 s), this should help to reduce heat input and the depth of penetration of the base metal, and, consequently, reduce the degree of dilution of the deposited alloy by the substrate metal. The latter is especially relevant when solving problems related to the creation of a technology for surfacing relatively thin layers of corrosion-resistant alloys, in particular, on the surface of petrochemical equipment products.

One of the prospects for developing the method under consideration is more precise control of heat input into the product by changing the pulse frequency or using the "double pulse" program [18]. Both in the case of using direct current and when using the pulse mode, the anode-to-cathode distance has a significant influence on the process of double-electrode surfacing, which also requires further study.

CONCLUSIONS

It has been found that the use of pulse current in double-electrode surfacing makes it possible to expand the area of existence of electrode metal transfer by common drops from 24 to 30 V in the absence of arc gap short circuits. At the moment of drop detachment, a powerful current pulse (~600 A) imparts additional centripetal acceleration to the drop directed toward the surface of the weld pool, which virtually eliminates metal spatter.

The conducted mathematical modeling of pulse arc surfacing with a consumable electrode allowed identifying the dynamics of temperature and pressure changes in various pulse phases, which is important for further optimization of the process.

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Влияние импульсного тока на каплеперенос при двухэлектродной наплавке в газах

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Аннотация: Применение для наплавки двумя электродными проволоками схемы с общим источником импульсного тока повышает энергоэффективность дугового процесса и технологические свойства сварочной дуги, но требует более детального изучения влияния параметров режима на ее стабильность. В связи с этим в данной работе основное внимание уделено изучению динамики формирования и переноса металлических капель при различных режимах импульсного питания сварочной дуги. С использованием скоростной видеосъемки сварочной дуги и синхронизированной записи сигналов тока и напряжения установлен режим (среднее значение тока 250 А, максимальное в импульсе 600 А, напряжение на дуге ~30 В), который обеспечивает стабильный процесс переноса электродного металла общей для двух проволок каплей без образования коротких замыканий. Обнаружено, что общая капля под действием электродинамических сил приобретает центростремительное ускорение, что способствует ее направленному переносу в сварочную ванну и позволяет максимально снизить количество брызг на поверхности основного металла. С использованием математического моделирования был подтвержден характер взаимодействия сварочных дуг на двух проволоках и установлено, что даже на стадии «горячей» фазы импульса тока (600 А, t=0,8 с) давление дуги на поверхность пластины меньше, чем при сварке одной проволокой на постоянном токе. Выявленный эффект связан с изменением направления плазменного потока на перпендикулярное к оси проволоки вследствие увеличения электродинамической силы притяжения магнитных полей вокруг двух проволочных проводников. В совокупности со снижением температуры дуги и давления на поверхность пластины в фазе «контроля тепловложения» импульса тока (180 А, t=1,4 с) это должно способствовать уменьшению тепловложения и глубины проплавления основного металла, а следовательно, уменьшить степень разбавления наплавляемого сплава металлом подложки. Последнее особенно востребовано при решении задач по созданию технологии наплавки относительно тонких слоев из коррозионностойких сплавов, в частности, на поверхности изделий нефтехимического оборудования.

Ключевые слова: двухэлектродная наплавка; импульсно-дуговой процесс; сварочная дуга; каплеперенос; численное моделирование.

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