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Numerical and Physical Simulation of Pulsed Arc Welding with Forced Short-Circuiting of the Arc Gap

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1. Introduction

The essence and complicacy of approach to computer design of an optimal pulsed arc welding technology is that programmed periodic action should be developed on the one hand to exert its effect on melting and transfer of an electrode metal, and on the other hand, to control over the molten pool fluidity, the structural formation of weld and heat-affected zone (HAZ) that appears as result of the weld pool crystallization whilst ensuring stability of the pulsed regime in welding in different spatial positions. The results of physical simulation and mathematical modelling permit to design optimal algorithms of pulsed control of energy parameters of welding - arc current and voltage, arc heated efficiency, peak short-circuiting current. The results of computer experiments permit to establish pulsed welding controlled parameters - service properties of welded joints (such as the sizes of welds and HAZ, quality and strength properties of welded joints) relation.
The solution of the pulsed arc welding and surfacing processes optimizing problem is a matter of great significance because of continuously increasing requirements on quality and reliability of welded joints, saving in welding fabrication cost. The construction of welded structures has a number of special features. These are associated with the character of welding metallurgy and solidification processes in the weld metal, the welded joint heating and cooling conditions and others, influenced on the stability of parameters of the complex electrodynamics' system: "power source – electrode – arc – weld pool – welded joint". It is necessary to ensure the regulation of the penetration depth, welding in wider gaps and in different spatial positions, joining metals and alloys of dissimilar chemical composition, decreasing the degree of splashing of electrode metal, increasing the stability of arc ignition and arcing. Arc heating sources energy concentration is unable to solve these technological problems including increasing the productivity of welding operations and improving the welded joints quality parameters.
The rate of assembling operations in the construction of pipelines is increased mainly as a result of automation of welding non-rotating joints. The main part of the system of transmission pipelines in Russia for the transport of natural gas, oil and products of processing mainly of the high-pressure type and with a large diameter (1220-1420 mm) has been operating for a relatively long period of time: 30% of gas pipelines have been operating for more than 20 years and 15% for more than approximately 30 years. In order to maintain

the pipelines in good operating condition, it is necessary to carry out either running repairs of defective areas with the application of effective and universal technologies, or replace defective sections completely in individual long areas. In addition, the expansion of the existing network of transmission pipelines, used for the transport of oil and gas to neighbouring countries, requires the application of more productive methods of welding and technological means for the realization of these methods.

The advantages of new high-productivity methods of mechanized welding in CO_2 and gas mixtures and also with self-shielding flux-cored wires include the decrease in the welding time of the root and filling layers, decreases in the dimensions of the cross-section of the welding gap and, correspondingly, in the volume of deposited metal, and increases in the productivity of welding and assembly operations. However, the mechanized welding methods also have disadvantages, associated with the presence of defects in welded joints, lack of fusion at the edges and between the layers, determined by the instability of the welding process, continuous changes of the spatial position of the welding pool and more extensive splashing of electrode metal.

Further progress in welding fabrication ensuring higher rate of assembling and repair, lowering of the welding operations cost, while providing the required level of quality and service properties of the welded joints, is possible by development of new high-efficient adaptive pulsed welding technologies and specialized equipment for their implementation.

In contrast to the well-known methods of arc welding, including pulsed methods, using “rigid” control programmes, the adaptive pulsed processes are based on the correction of selected algorithm through feedback channels on the basis of instantaneous values of the main energy parameters of the welding process in relation to the condition of the “power source $\rightarrow$ arc $\rightarrow$ weld pool $\rightarrow$ welded joint zone” control object.

Such parameters as: the arc voltage; duration of typical stages of microcycle - arcing time in the pulse, the break with the duration t_p; instantaneous and mean values of current; arc power in a separate microcycle; melting energy of every electrode metal droplet can be the main controlled parameters of adaptive pulsed technological process.

The adaptive pulsed technological process of welding in comparison with the stationary one permits:

- to control the processes of melting and droplet transfer of electrode metal, the solidification in the weld metal in all spatial positions of the weld pool in the range of significantly smaller mean values of the main technological parameters;
- to form a good conditions for transfer of every droplet of electrode metal into the molten pool. This makes it possible to reduce sputtering of electrode metal from 20% to 3% as a result of controlling the energy parameters of the welding;
- to increase the rate of weld pool solidification in 2 – 3 times as a result of the nonstationary energy effect of heating source on the weld pool with decreasing the temperature of molten metal;
- to decrease the degree of residual strains in the welded structures;
- to improve the quality of the welded joints and deposited surfaces (to improve the formation of the weld in all spatial positions, the structure of the weld metal and HAZ. This is determined by the controlled solidification of the weld pool. This is accompanied by the intensification of the hydrodynamic processes in the molten pool resulting in a more uniform distribution of the alloying elements through the entire volume of molten metal and intensive weld pool degassing;

- to improve mechanical properties of the welded structures: the size of the HAZ is reduced and the structure of the weld metal refined. This is of considerable importance for repeated loading.

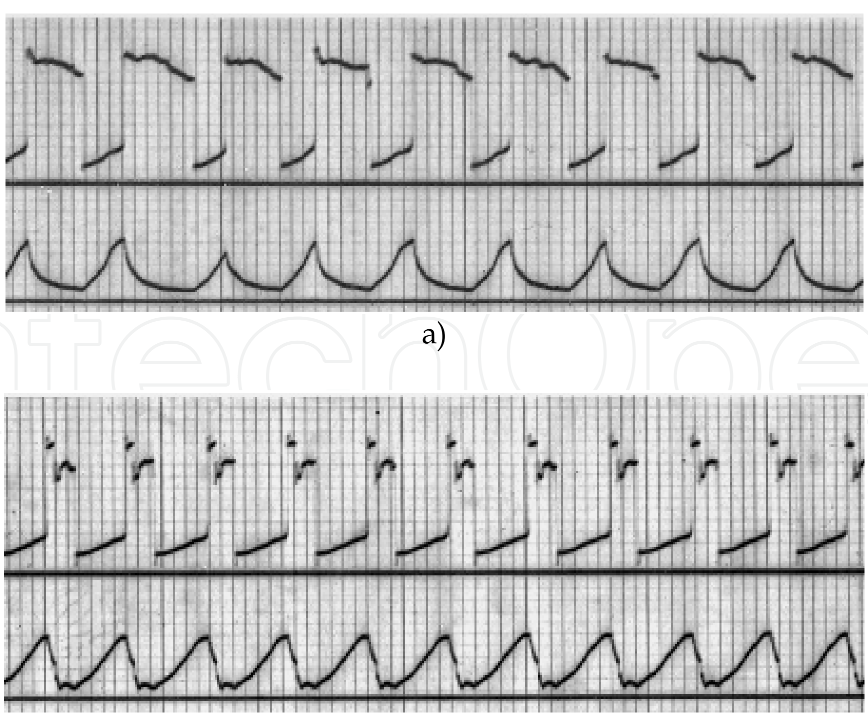
The important advantage of pulsed welding is the ability to stabilize the instantaneous values of main parameters in the stages of melting and transfer of an electrode metal droplet.

2. Quality of welded joint

The main problem in welding in different spatial positions of high-quality inspected welded structures (joints in transmission pipe-lines, containers for oil and gas, chemical industry, boiler and power equipment, components of road-building machinery, equipment in the industry of engineering materials), operating under different types of loading at a subzero temperature, is to ensure the required quality of root, filling and capping layers and high mechanical properties of the welded joint. Up to 90% of defects, detected in the inspection of the quality of welded joints, are associated with defects in the root layers of welded joints, for example: undercutting, lack of fusion, nonmetallic inclusions or pores. The main reason for the formation of these defects, in addition to those associated with low quality of preparation, is the disruption of the welding conditions (welding speed, arc voltage, current), and that the regimes are not adhered to an optimum values.

Conventional welding processes can ensure the required quality of welded joints only in the case of efficient preparation of the welded joint and with the use of high-quality materials.

The above disadvantages can be eliminated by providing the welding process energy parameters constant in time, or varying them by a certain program.



a)

b)

Fig. 1. Oscillograms of current (lower curve) and voltage (upper curve) of: a) unstabilized and b) stabilized processes of CO_2 welding

The pulsed technologies are more efficient from the viewpoint of controlling the formation of welded joints in the presence of a large number of perturbing factors (defects in assembly of the joints, low quality of electrode materials, changes in the spatial position of the weld pool, variation of mains voltage, etc.). These are characterized by a stable penetrating capacity of the arc on the level of the instantaneous values of current and voltage with only slight dependence on the quality of electrodes.

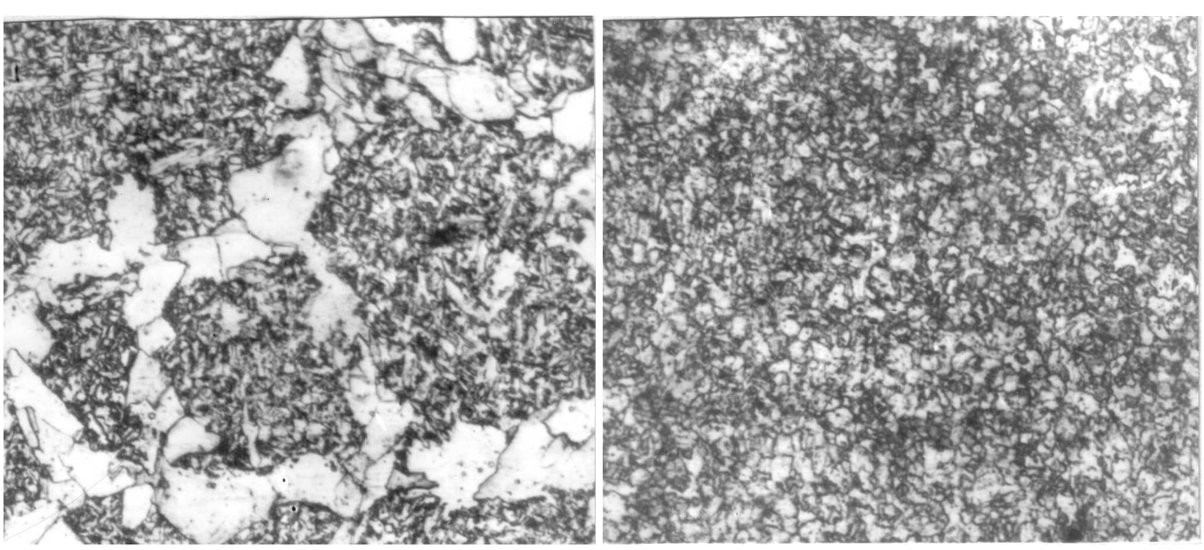
Fig. 1 shows oscillograms of the stabilised pulsed arc CO_2 welding process using Sv-08G2S wire and the conventional process without stabilisation of the energy parameters.

Primarily, this relates to one-sided pulsed-arc welding of root joints with the formation of the reversed bead without any backing strip and welding on reverse side in all spatial positions. The welding speed reaches 20 - 30 m/hr, whereas in uphill welding it is no more than 5 – 7 m/hr (Saraev & Shpigunova, 2002).

The technology of pulsed welding in different spatial positions is greatly simplified, the required properties and service reliability of welded joints are easily achieved, and the quality parameters of the welded joints improve: the size of the HAZ and zone of overheating near the surface of weld is reduced and the size of the normalized ferrite grain decreases (Fig. 2).

Transition to the pulsed regime of variation of the energy characteristics in surfacing makes it possible to control the processes of solidification in the weld pool and HAZ and decrease the degree of burnout of alloying elements from the weld pool. This is determined by the restriction of the time during which they are held at the high-temperature of the melt of the weld pool and by the increase of the rate of solidification of the weld pool. This is accompanied by the intensification of the hydrodynamic processes in the weld pool resulting in a more uniform distribution of the alloying elements through the entire volume of molten metal.

The application of adaptive pulsed welding of low-alloy steels results in formation of more dispersed and homogeneous structure of welded joint, than in welding by a permanently burning arc. The effect takes place in all layers of welded joints: root, facing, filling (Shpigunova & Glazunov, 2008 a).



a) b)

Fig. 2. Structure of the welded joint in: a) stationary and b) pulsed regimes of welding of 12X1MΦ steel, ×500

3. Optimal algorithms of pulsed control of the energy parameters of the welding process

The main purpose of computer aided design of pulsed technology is the development of an optimum algorithm of control over all links of technological chain from effective using of dynamic properties of power sources and programmed variation of the arc heat output to the HAZ microstructure changes, which provide required strength properties of welded joints and hard-facing coatings. The complexity of the problem is the necessity of welding phenomena studying from the viewpoint of kinetics of melting, thermodynamics, physical metallurgy of welding, the theory of heat conduction, hydrodynamics, the plasma theory, strength theory. Computer aided design of pulsed arc welding technology permits to solve such technical problems as the creation of new materials with preset thermo-mechanical and strength properties.

Extensive use abroad is made of welding with algorithms of pulsed control of the energy parameters of the process, as a rule, on the basis of a strictly defined programme. In this case, the main energy characteristics of the welding arc are calculated in advance and are set in strict accordance with the varied technological parameters (feed rate of electrode wire, open circuit voltage of the power source, etc.) These processes, such as: inert gas welding, non-consumable-electrode arc welding, plasma-arc welding can be used efficiently in the absence of perturbing influences on the object of automatic control.

The important advantage of pulsed welding is the ability to stabilize the instantaneous values of main parameters in the stages of melting and transfer of an electrode metal droplet. Such parameters as: the arc voltage; duration of typical stages of micro cycle - arcing time in the pulse t_{pulse}, the break with the duration t_p; instantaneous and mean values of current; arc power in a separate microcycle; melting energy of every electrode metal droplet can be the main controlled parameters of adaptive pulsed technological process.

Adaptive algorithms of pulsed control are corrected, during a technological process, through channels of feed backs in relation to the variation of the instantaneous values of the main energy characteristics of the welding process (arc current and voltage, peak short-circuiting current, arc power in a separate microcycle, melting energy of every electrode metal droplet). This makes it possible to supply more efficiently the energy required for melting and transfer of every droplet of electrode metal, control weld formation, taking into account its spatial position, reduce deformation of the welded joint by regulating the heat input in the welding and surfacing zone.

These processes take place with minimum deviations of the instantaneous values of the energy characteristics of the process, so that it is possible to calculate with sufficient accuracy the moment of separation and transfer of every electrode metal droplet to the molten pool and ensure detailed examination of the processes in the "power source - electrode - arc - molten pool" electrodynamic system as in a single object of automatic control.

The realization of the algorithms of pulsed control in current welding and surfacing equipment is associated with the introduction of additional sections and units into the structure of equipment. The units are introduced both into the circuits for controlling the output parameters of the power system and directly into the welding circuit (Fig. 3).

Selection of a specific technical solution depends on solving the technological problems and is determined by the frequency range of the algorithms of pulsed control of the energy parameters of the welding and surfacing processes.

- The following frequency ranges of the algorithms of pulsed control are selected:
- 5000 ÷ 100 Hz – for increasing the stability of arcing and decreasing the size of transferred droplets;
- 100 ÷ 25 Hz – for controlling the transfer of electrode metal in all spatial positions;
- 25 ÷ 0,25 Hz – for improving the formation of the welded joint in all spatial positions as a result of decreasing the size of the weld pool and increasing the rate of solidification;
- from 0,25 Hz and lower – for controlling the solidification processes in the weld metal and the HAZ (Fig. 2).

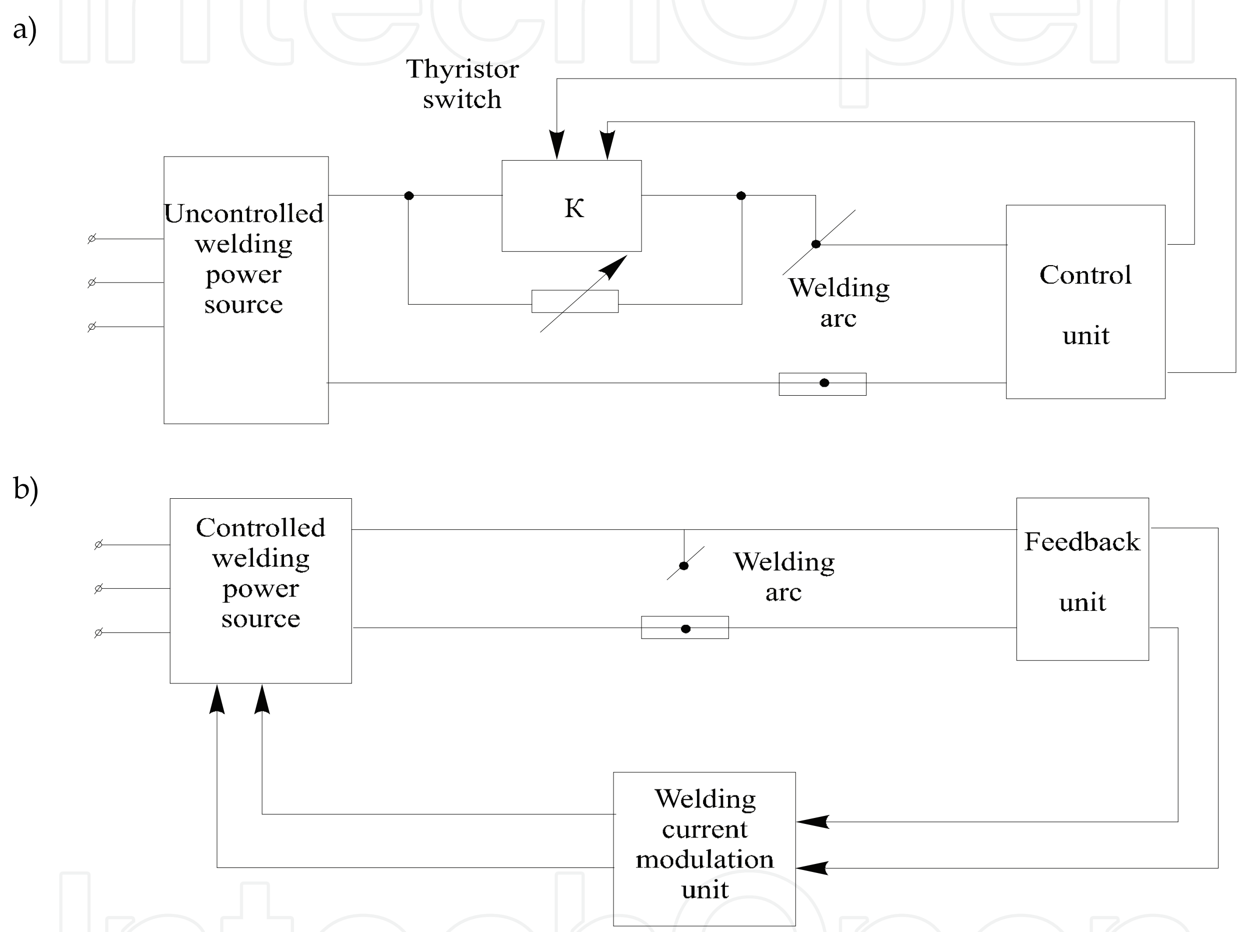


Fig. 3. Systems realizing adaptive pulsed technological processes of welding with:
a) uncontrolled and b) controlled power sources

The most complicated electrical engineering problem is the development of regulators for the frequency range 25 ÷ 5000 Hz. This is associated with the fact that sections of the regulator must ensure a very short restoration time of the controlled properties. In practice, this approach can be realized by introducing into the structure of the power supply system special high-current semiconductor regulators capable of switching large pulsed currents of 1000 A or even higher (Fig. 3 a).
Development of regulators in the frequency range 25 ÷ 0,25 Hz and lower is possible on the basis of semiconductor elements with low and medium power. As a result of the relatively long duration of current pulses, they can be shaped through the channels of phase control of

welding rectifiers and through the power circuit of the excitation windings of welding generators (Fig. 3 b) (Loos et al., 1998).

The developed technology of single-sided arc welding of root welds with formation of the reversed bead by the modulated current using coated electrodes is based on the special algorithm of control over the energy parameters, which permits to form during the technological process a condition of the welded zone as the result of pulsed arc action, when the components of melted electrode coating are intensively displaced beyond the forming permanent joint. Such an approach allows supply the formation of root welds without additional backing strips by electrodes of any coating, including the main type, to use coated electrodes manufactured in Russia instead of expensive imported electrodes. Well-known in a world practice the welding technological processes of root welds in condition of free formation (without additional backing strips) are based on application of special electrodes with a thin coating, that limits the fields of application of the given technologies. The proposed technology gives the possibility of downward welding of vertical welds that significantly increases the welding speed and simplifies welding technique in various spatial positions for a welder of lower qualification.

A large amount of experience has been accumulated in the last decade with the application of mechanized CO_2 welding in the production of metal structures in different spatial positions. The experience of production trials, however, has revealed a number of disadvantages related to defects in welded joints, lacks-of-fusion along the edges and between the layers due to instability of the welding process, and continuous change of the weld pool position in space. The above disadvantages can be eliminated by providing the welding process energy parameters constant in time, or varying them by a certain program. The optimal algorithms of control of the energy characteristics of the process, developed by computer-aided design methods, and specialized equipment (UDGI-201UKhLZ thyristor regulator) permit conducting the technological process of single-sided pulsed arc welding of the root welds with reverse bead formation without additional backing or backing run welding from the inside in CO_2. The using of UDGI-201UKhLZ regulator makes it possible to stabilize the welding process as result of fine-droplet transfer of electrode metal into the weld pool with the minimum 2 - 3% splashing of electrode metal in the range 70 - 200 A in mechanized and automatic welding with electrode wires with a diameter of 0,8 - 1,2 mm; simplifies welding technology in all spatial positions in the presence of large variations of the gap between the welded edges; increases 3 - 4 times the productivity of welding operations as a result of ensuring the possibility of downward welding. The speed of downward welding runs into 20 – 30 m/hr and upward welding speed is no more than 5 – 7 m/hr. The characteristic lack of penetration of downward welding, as a result of the weld pool inleakage in traditional CO_2 welding methods, is absolutely absent.

Fig. 4 shows typical oscillograms of such process. The proposed technological process has additional regulation parameters: t_i – arcing time in the pulse and t_{p11} – time of the break introduced at the moment of rupture of the liquid bridge. These parameters in accordance with the adaptation scheme are able to automatically correct the energy parameters of welding regime in relation to the perturbing influences so that it is possible to stabilize the heating and energy indicators of the process. The stability of such a welding process predetermines a stable quality of weld formation which also depends on the short-circuiting frequency $f_{s.c.}$, the holding time of the liquid droplet on the electrode tip, the droplets size and uniformity of their transfer.

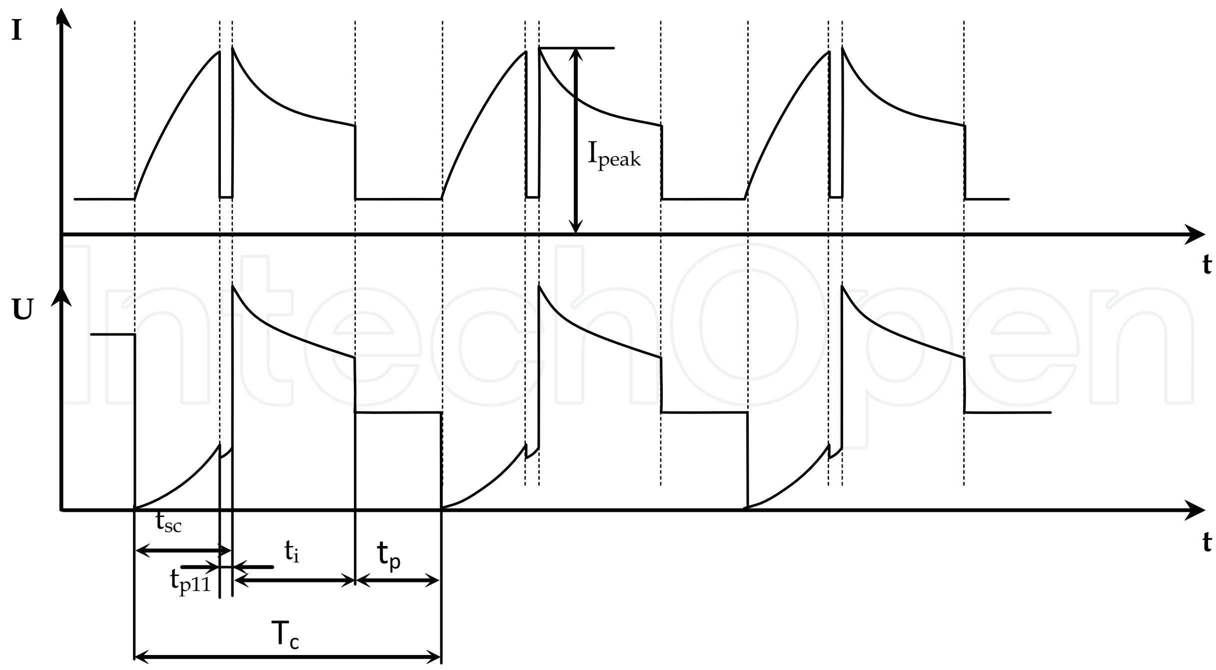


Fig. 4. Oscillograms of current I and voltage U of adaptive pulsed arc CO_2 welding

This set of process parameters can be optimized at the stage of technological preparation of production, in order to produce a sound welded joint operable under different types of loading in cold climate region. The results of research of the developed models of melting and metal transfer with systematic short-circuiting of the arc gap during the pulsed welding process, using a computer experiment, permits: to evaluate the influence of technological and energetic parameters complex of the process on the penetration of the weld metal, the shape and sizes of the weld and heat-affected zone; to predict strength properties and quality of welded joints (Shpigunova & Saraev 2003).

4. Mathematical modelling of heat and mass transfer in pulsed arc welding by melting electrode

4.1 Physical simulation of pulsed arc welding with forced short-circuiting of the arc gap

It is necessary to provide complex investigation of the welding arc physics and the electromagnetic processes in welding power source. The principle of metal transfer "one drop per pulse" is realized in adaptive pulsed arc welding in CO_2 medium.

The block-scheme of the power supply of adaptive pulsed arc welding is shown in Fig. 5.

The examination will be based on one of the control algorithms examined in (Saraev & Shpigunova, 1993).

The period of arcing in the pulse (Fig. 6) is characterized by rapid melting of the electrode tip under the welded component. As a result of the force effect of the arc, the weld pool metal is displaced into the tail part and is maintained there throughout the entire melting stage. After this period of arcing, the welding current in the pulse is increased in steps to the value of the background current. This results in a corresponding decrease in the melting rate of the electrode and a weakening of the force effect of the arc on the weld pool which tries at this moment to fill the crater formed below the electrode tip in the stage of the current pulse. Together with this effect, the electrode metal droplet tries to occupy a position, coaxial with the electrode, mainly as a result of a decrease in force of reactive pressure of release of the gas, and also due to the forces of the weight of the droplet and surface tension.

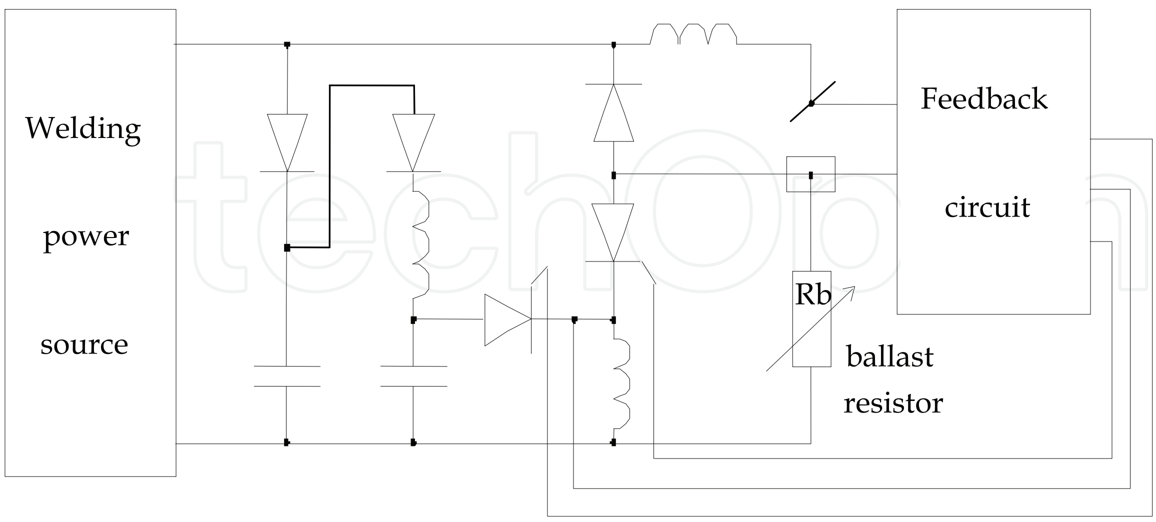


Fig. 5. Block-scheme of the power supply of adaptive pulsed-arc welding process

Forced short circuiting takes place as a result of these counter movements, and the initial moment of the short circuit is characterized by an increase in current in the welding circuit which increases along an exponent determined mainly by the interactive resistance of the smoothing choke coil. With this mechanism of electrode metal transfer, the formation of a stable bridge between the electrode and the weld pool is achieved in the first stage of short circuiting. This greatly increases the rate of increase of the short circuit current and, at the same time, accelerates the formation and fracture of the liquid bridge. In the short circuit stage, the transfer of electrode metal into the weld pool is accompanied by an increase in voltage (also in the case of the avalanche-like increase of current). This indicates the irreversibility of fracture of the bridge, as a result of a stepped decrease in current.

The entire period of short circuiting is characterized by the fact that the controlling effect in acceleration of failure of the bridge is played by the electrodynamic force which tries to "squash" the electrode metal along the melting line, separate the electrode metal droplet and apply to it the accelerating "pulsed force" for movement in the direction of the weld pool.

The final stage of fracture of the bridge (approximately 10^{-4} sec prior to the moment of arc reignition) is accompanied by the dominant effect of the surface tension force. However, as a result of the short duration of the given period, its contribution to the fracture of the liquid bridge is negligible. The duration of the break is set either parametrically, or in relation to the condition of the arc gap in the given stage.

After completion of the break, increasing current, the electrode starts melting in the pulse current period. Subsequently, the course of the process is identical with that described previously.

Such mechanism of controlled transfer of electrode metal into the weld pool is operating in the realization of other adaptive algorithms of the pulsed control of the energy parameters of the process. The only difference is that the perturbation effects, determined by the droplet transfer of electrode metal and the special features of formation of the weld metal in different spatial positions, operate in different stages of the welding microcycle, depending on the variation of the arc gap length at the start of the effect of the pulse current or the integrated value of high-voltage in the stage of parametrically specified background period up to the moment of fracture of the bridge, or when the force effect of the arc on the weld pool in the period of the current pulse is determined in relation to the duration of the break prior to a short circuit, indicating the ability of the weld pool during changes of its special positions (Saraev, 1994).

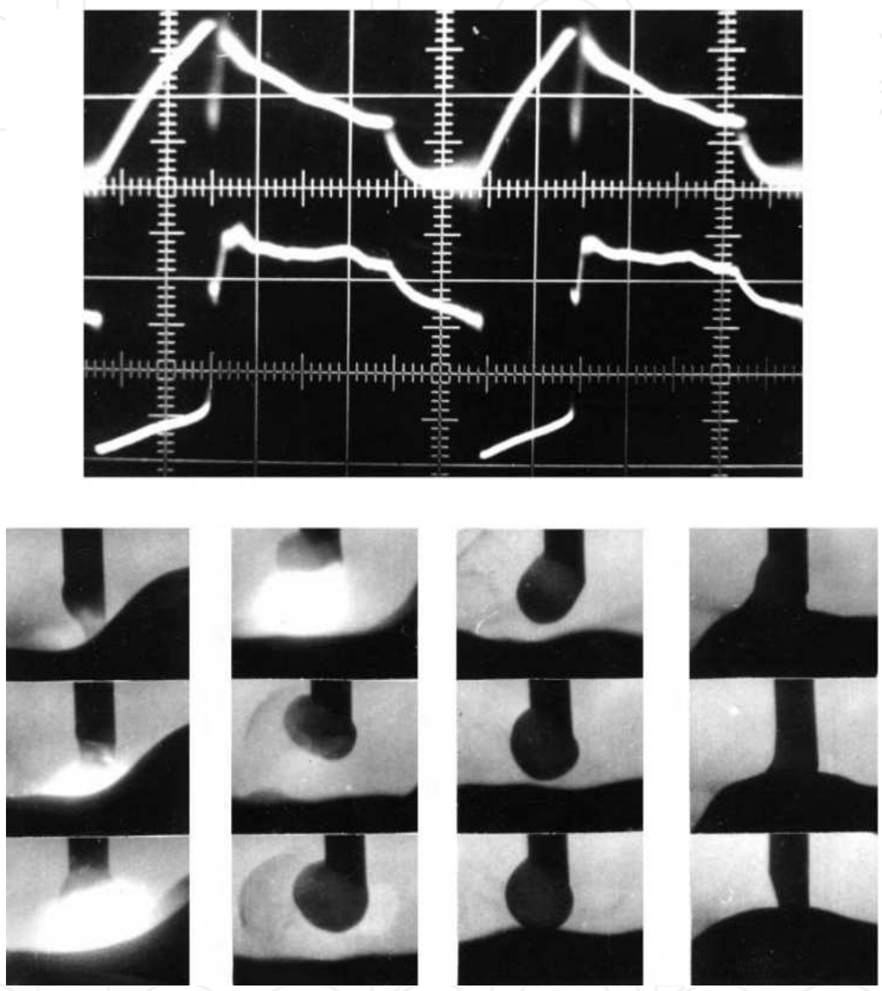


Fig. 6. Oscillograms of current (upper curve) and voltage (lower curve) and film frames of microcycle of CO_2 welding with forced short-circuiting of the arc gap

The results of analyzing the oscillograms and experimental data obtained by high-speed filming of pulsed-arc welding process in CO_2 with SV08G2S wire ∅ 1,2 mm (Fig. 6) make it possible to specify the following main features of the pulsed process and formulate a number of assumptions for mathematical modeling of such a process:

- the molten pool moves with specific periodicity in such a manner that prior to every short-circuit, the molten pool occupies the same position in relation to the continuously fed electrode. Therefore, in calculations, these movements can be ignored;
- the break current prior to a short-circuit is low and has no marked effect on melting of the electrode in the break period;
- the break introduced at the moment of arc reignition does not affect the thermal processes in the system and, consequently, its effect can be ignored in the calculations;

- electrode metal formed at the electrode tip as a result of melting of the continuously fed electrode has the form of a spherical segment;
- thermophysical constants ($\alpha, c\,\gamma m$), used in calculations, do not depend on temperature, where α is the temperature coefficient of resistance; $c\gamma$ is the volume heat capacity of electrode wire; m is the latent heat of electrode melting which takes into account transition from one aggregate state to another;
- the resistance of electrode extension R_e depends on both the temperature to which it is preheated T_p and the steel grade.

Every microcycle T_c consists of the three typical stages (Fig. 6, Fig. 7):

1. short-circuiting with the duration $t_{s.c.}$;
2. arcing in a pulse with the duration t_{pulse};
3. the break prior to a short-circuit, duration t_{pause} (I_{peak} is the peak value of the short circuit current).

The simplified mechanism of droplet formation and electrode metal transfer to the molten pool can be described as follows.

After rupture of a bridge, the energy build-up in the choke coil during a short-circuit generates in the arc gap and rapidly melts the electrode. At the initial moment, the melting rate of the electrode V_e is higher than the feed rate V. Consequently, the width of the arc gap increases. Part of the molten electrode metal, which remains at the end from a previous microcycle, rapidly increases in the volume at the start to a hemisphere with the diameter $2R_e$ and then to a spherical segment with the height h. When welding current is reduced and the volume of the spherical segment increase the burn-off rate decreases and the width of the arc gap slightly decreases. After completion of the arcing process in the pulse and a reduction of welding current to the break current I_o, the burn-off rate rapidly decreases and the arc gap closes up as a result of continuous electrode feed. A short-circuit takes place, during which metal is transferred to the molten pool.

In accordance with the described mechanism of growth of the electrode metal droplet, the volume of the spherical segment in the second period increases at the rate dh/dt in the direction of the continuously fed electrode with the speed $\boldsymbol{V}$. This is accompanied by countermovement of the melting line of the electrode with the melting speed $\boldsymbol{V_m}$.

4.2 Mathematical modelling of heat and mass transfer in welding with systematic short-circuiting of the arc gap

Taking into account these special features of the pulsed process and the assumptions, a cyclogram of welding current I and voltage U, as well as a simplified diagram of growth of the droplet of molten electrode metal and the shape of the finite weld are shown in Fig. 7 and Fig. 8, respectively.

The object of our research is a mathematical model of melting and transfer of electrode metal with systematic short-circuiting of the arc gap in carbon dioxide medium on the base of algorithm of control, shown in Fig. 7 (Saraev & Shpigunova, 1993).

There are a large number of investigations (Dyurgerov, 1974), (Popkov, 1980), (Lebedev, 1978) which have been carried out to describe mathematically the power source – welding arc system in welding with systematic short-circuiting of the arc gap using the mean parameters of the conditions. However, they did not reflect the technological stability of the process, because a deviation of one of these parameters within the limits of a separate microcycle leads to its disruption. In particular, when welding in different spatial positions, the deviation resulting in an increase of a specific parameter, such as the peak short-circuit current within the limits of the microcycle, leads to splashing of the metal from the molten pool during arc reignition. The variation of electrode stick-out results in a change of the heat generated in the stick-out, which in turn affects the energy balance of the arc, etc. In this case, the amount of heat generated in the extension may reach 15,6% of the entire arc heat (for low-carbon electrodes), which is equal to 55% of the heat required for melting the electrode. In rapid heating of the electrode with passing current, the burn-off rate of the electrode increases.

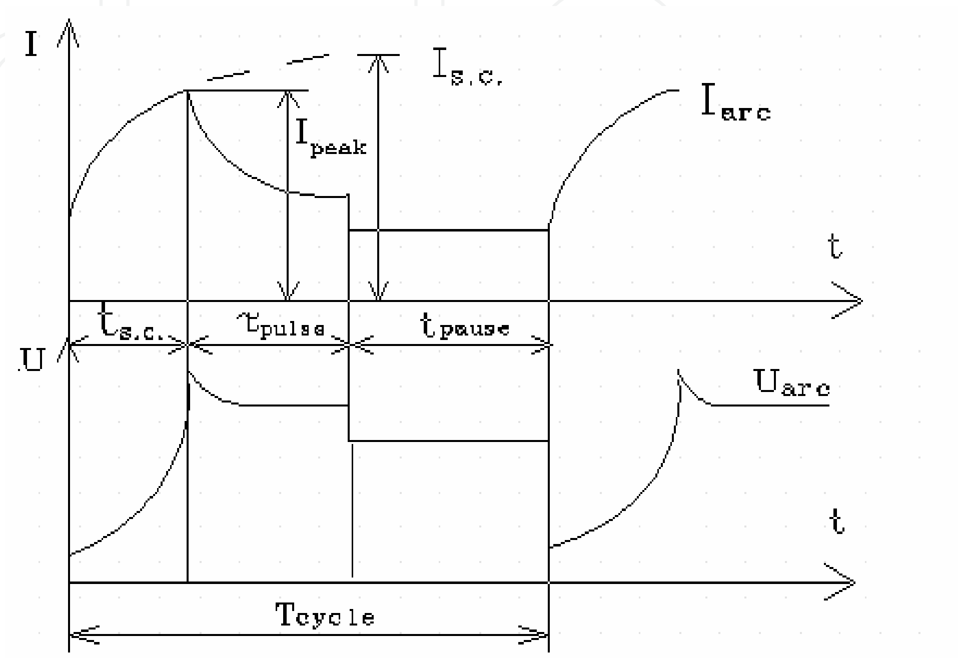


Fig. 7. The cyclogram of current I and voltage U for the power source – welding arc system

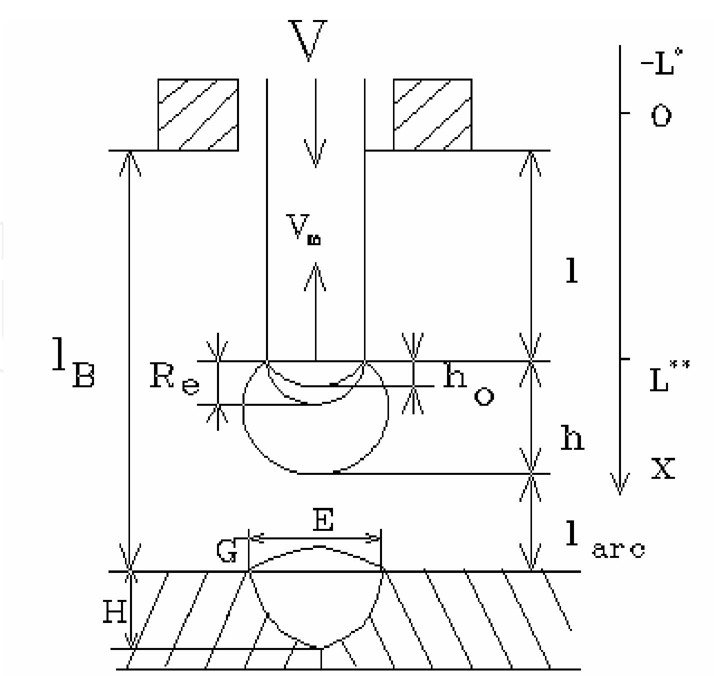


Fig. 8. The scheme of growth of a droplet of molten electrode metal and shape of the finite weld

The temperature distribution along the electrode is defined on the base of solution of heat conduction equation in consideration of convective heat exchange to space. Therefore, an examination is made of one-dimensional heat propagation in cylindrical electrode bar, fixed in current lead tip, within the limits of statement of a problem from (Saraev & Shpigunova, 1993). The interval on which a function is defined changes from $-L^*$ (L^* = const) to $L^{**}(t)$ in axis OX (Fig. 8).
$L^{**}(t)$ - is the length of the unmelted part of the heated electrode extension in moment of time t,
L^* - is the part of electrode with temperature gradient from T (in the point x = 0) to T^* (in the point x = $-L^*$) and convective heat transfer coefficient $\tilde{\alpha}$. In interval from x = 0 to x = L^{**} the arc and passing through the electrode current are a heat sources. There are no internal heat sources in interval from x = 0 to x = $-L^*$.
It is necessary to note the following: the electrode is moving with the speed $\boldsymbol{V}$ (Fig. 8) that means position change concerning to the current lead tip and upper boundary. This is equal to the regular feed of the "cold" mass. The lower boundary is moving with speed $\boldsymbol{V_g} = \boldsymbol{V} - \boldsymbol{V_m}$, where $\boldsymbol{V_m}$ - the melting speed of lower end of electrode as a result of the heat release from the arc.
Heat conduction equation is solving within the limits of statement of a problem (Saraev & Shpigunova, 1993). It means that the amount of heat flow on the lower boundary of the electrode and value of passing through the electrode current are determined by the problem solving from paper (Saraev & Shpigunova, 1993) in every time moment. The electrode resistance in interval from x = 0 to x = L^{**} and melting speed are determined subject to the temperature distribution calculated from the heat problem solution.

4.3 Heat conduction equation with boundary conditions:

Thus:

$$\frac{\partial}{\partial t}(\gamma \cdot T) = \frac{\partial}{\partial x}\left(\frac{\lambda}{c} \cdot \frac{\partial T}{\partial x}\right) + \frac{\rho \cdot I^2}{c \cdot F^2} - \frac{\alpha \cdot P}{c \cdot F} \cdot \left(T - T^*\right) - \frac{\partial}{\partial x}(V \cdot \gamma \cdot T) \tag{1}$$

Note, that:
ρ - specific resistance,

$$\rho(T) = \rho * (1 + \alpha * \Delta T) \tag{2}$$

$$\Delta T = T - T * \tag{3}$$

ρ^* - specific resistance at T^*,
α^*- temperature coefficient of resistance.
Here:
t - time,
γ - the density of electrode material,
T - temperature,
T_m - melting temperature,
T_d - drop temperature,
λ - thermal conductivity,
I - current,
c - specific heat of electrode material,
α- convective heat exchange coefficient,

F - cross-section area of electrode,
P - electrode perimeter.
The boundary conditions for the short circuit interval and arcing in a pause interval are:

$$T(-L^*,t)=T^* \tag{4}$$

$$T\left(L^{**}(t),t\right) = T_m \tag{5}$$

For the arcing in a pulse interval:

$$T(-L^*,t)=T^* \tag{6}$$

$$\frac{\partial}{\partial x}T\left(L^{**}(t),t\right)=-\vec{q} \tag{7}$$

The amount of heat flow - ***q*** on the lower (moving) boundary of solution field get from the law of conservation of heat energy (*Mathematical Modelling*, 1979):

$$Q^+ = Q_1^- + Q_2^- + Q_3^- \tag{8}$$

Where: Q^+ - heat quantity from arc;
Q_1^- - heat quantity consumable to electrode melting;
Q_2^- - heat quantity consumable to the increase in molten metal temperature from $T = T_m$ to $T = T_d$;
Q_3^- - heat quantity transferred for a depth into metal.
The complete version of the Eq. 8 is:

$$U_a^e \cdot I \cdot F^{-1} = \left[M + C\cdot(T_d - T_m)\right]\cdot\gamma\cdot V_m - \lambda\frac{\partial T}{\partial x} \tag{9}$$

Where:

$$V_m = dL_m / dt\,;$$

U_a^e - effective anode voltage,
M - specific heat of melting.
Another condition on moving boundary is that its temperature approximately equal to the temperature of melting:

$$T\left(L^{**}(t),t\right) = T_m \tag{10}$$

Let's develop moving differential grid. Melting speed is determined by iterations.
Discrete analogue of Eq. 1 is developed according to digitization method (Patankar, 1984) and “check volumes” method and solved by the run method.
Therefore, there is the system of differential equations for each interval of microcycle:
"short circuit" (Fig. 7, Fig. 8):

$$\frac{\partial I}{\partial t}=\frac{U_{xx}-R_s I(t)}{L_G} \tag{11}$$

$$R_s = R_\Sigma + R_L, \qquad R_L = F^{-1} \cdot \sum_{i=1}^{N-1} \rho \cdot \Delta x_i$$
$$dL = V \cdot dt \tag{12}$$

$$t_{s.c.} = \frac{L_G}{R} \ln\left(\frac{U_{xx} - R_s \cdot I_0}{U_{xx} - R_s \cdot I_p}\right) \tag{13}$$

$$I_p = 1{,}5 \cdot 10^5 \cdot h + 154 \tag{14}$$

$T(x,t)$ is determined from Eq. 1 for all intervals.
For "arcing in a pulse":

$$dL = (V - V_m)\, dt, \quad l_g = l_b - (L + h)$$
$$\frac{dh(t)}{dt} = 2r^2 \frac{V_m}{h^2 + r^2} \tag{15}$$

$$\frac{dI}{dt} = \frac{U_{xx} - (U_{ak} + \beta \cdot l_g) - R_s \cdot I}{L_G} \tag{16}$$

For "pause":
$I = I_0$,
h = const,
$t_p = l_g/V$,

$$dL = V \times t \tag{17}$$

Here:
U_{ak} - anode-cathode voltage,
β - gradient of voltage of arc column,
L_G - inductance of welding circuit,
U_{xx} – open circuit voltage of the power source,
R_s - resistance of welding circuit,
r - radius of electrode.

4.4 Results of computer simulation

The system of non-linear differential equations for each interval of microcycle is realized by means of numerical methods in a computer. To solve a system of non-linear differential equations, the authors used an explicit two-step method of the predictor – corrector type of the second order of accuracy on smooth functions. Since the model process must be cyclic (output parameters of a single microcycle represent input parameters for the next microcycle), the problem was solved by an iteration approach. The criterion for convergence of the process is the difference ΔI of the values of the current curve on adjacent iterations: $\Delta I \le 0.01\%$. Original software for realization of such problems have been developed (Shpigunova et al., 2000; Shpigunova & Glazunov, 2008 b).

The results of numerical solution of the problem give the full information about object of control at each time moment: the value of current $I(t)$, arc voltage $U(t)$; the size of the drops transferred from the electrode $h(t)$; the preheat temperature of the electrode extension $T(L,t)$;

the length of the arc gap l_g; the resistance of the unmelted part of the heated electrode extension R_L, and so on; permit to determine the interrelation between energetic characteristics of the pulsed arc welding process (*I(t), U(t)*), sizes of weld and HAZ (Fig.) with the most important regulated technological parameters of the process (V - electrode feed rate, L - electrode extension, U_{xx} - open circuit voltage of the power source, t_{pulse} - arcing time in the pulse, t_p – time of pause, frequency of transferred droplets of electrode metal) and to give the quantitative assessment.

Fig. 9 shows temperature distribution in electrode with length *L* (mm) at different time moment of microcycle for following values of the thermophysical quantities and parameters of the process of CO_2 pulsed welding with Sv-08G2S wire: L = 12 mm, t_{pulse} = 10 ms, $t_{s.c}$ = 2.16 ms, U_{xx} = 45 V, V = 0.222 m/sec, β = 3.6 V, L_G = 0.00018 H, I_0 = 20 A, r = 0.5 mm, T_d = 2673 K, U_{ak} = 22 V, $c\times\gamma = 5.23\times10^6$ J/m$^3\times$K, λ = 39.65 W/m×K, α* = 0.003 1/K, α= 100 W/m$^2\times$K, R_s = 0.05 Ω.

Every temperature curve consists of two ranges: range of smooth change of temperature as a result of heat release by passing current and range of quick increasing of temperature as a result of heat input by arcing. The depth of heat penetration by arc depends on the speed of melting front motion very much (Fig. 9).

Fig. 10 shows melting speed of electrode depending on time moment of microcycle for different values of U_{xx} – open circuit voltage of the power source and V = 0.138 m/sec.

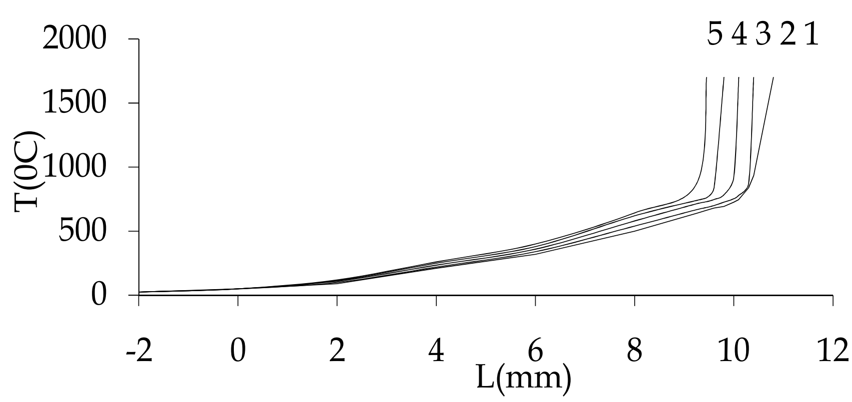


Fig. 9. The temperature distribution in electrode extension at different time moment: 1 – t_1 = 2.16 msec; 2 – t_2 = 4.66 msec; 3 – t_3 = 7.16 msec; 4 – t_4 = 9.66 msec; 5 – t_5 = 12.16 msec

The examined pulsed technological process is characterised by the fact that its parameters can be regulated over a wider range than the stationary process. This is possible because, in addition to the generally accepted regulation parameters of the welding process (open circuit voltage of the power source $U_{o.c.}$, electrode feed rate V, electrode extension l_b), there is an another parameter: arcing time in the pulse which, combined with the general parameters, makes it possible to control the dimensions of the transfer droplets and their frequency. In addition, the regulating capacity of the power source – welding arc system is controlling the welding process and compensating different perturbing influences on the regulation object, i.e. the arc.

For example, when the electrode extension is varied in the range 8 ÷ 20 mm, the temperature to which the electrode extension is heated rapidly increases. This may be compensated by a corresponding increase of the arcing time in the pulse. It is thus possible to stabilize the mean value of welding current and, consequently, the electrode burnoff rate.

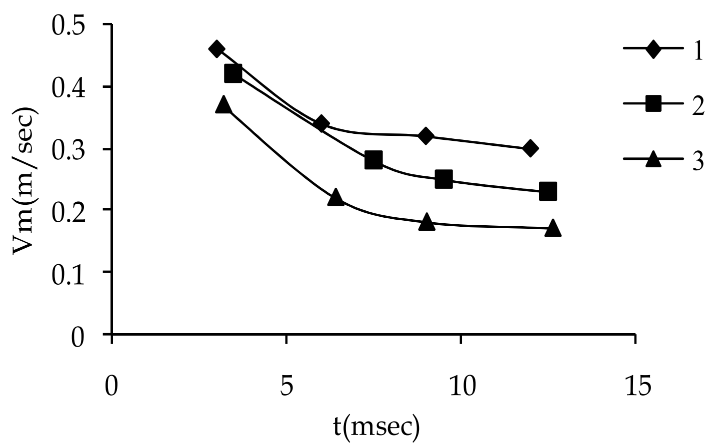


Fig. 10. Dependence of melting speed on time of microcycle at different values of open circuit voltage of the power source: 1 – U_{xx} = 45 V; 2 – U_{xx} = 40 V; 3 – U_{xx} = 35 V

Important technological parameters of the welding process are the frequency of transferred droplets of electrode metal and their volume, which determine to a large extent the required geometrical dimensions of the weld. These parameters can also be mutually compensated in accordance with the required ranges.

For example, an increase of the electrode extension reduces the frequency of short-circuits and increases the volume of molten electrode metal within the limits of a separate microcycle. These parameters can be maintained in the required ranges by reducing the arcing time in the pulse. This increases the frequency of short-circuiting and reduces the volume of molten metal (Fig. 11, Fig. 12).

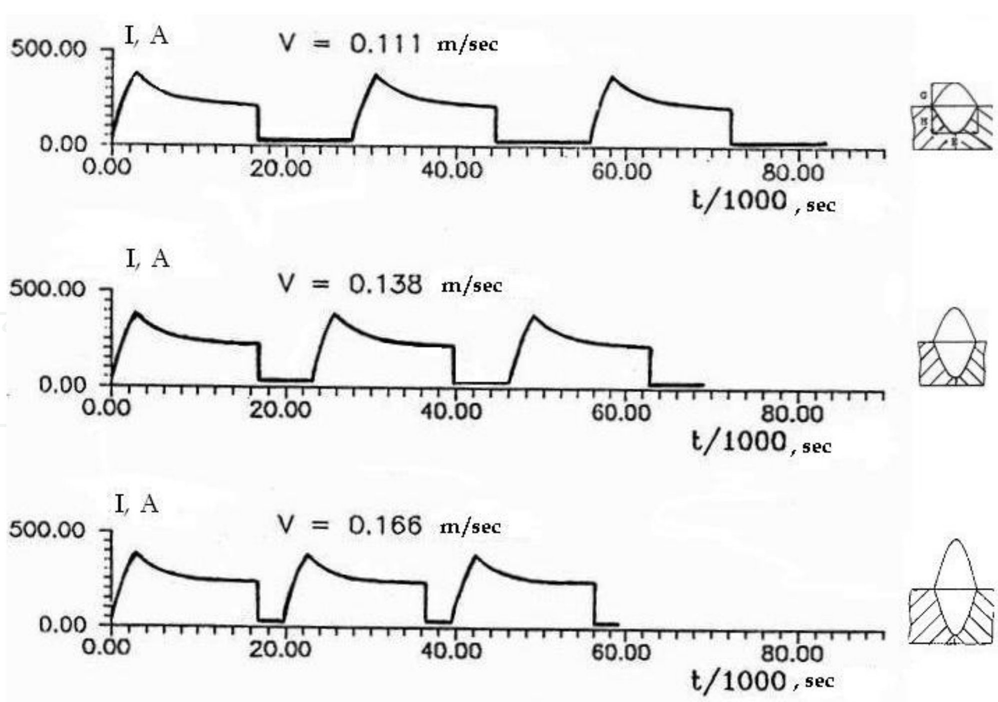


Fig. 11. Calculated cyclograms of welding current for different values of electrode feed rate V and correlative weld shape (H, E, G) for every complex of technological parameters of pulsed arc welding. $U_{o.c.}$ = 41 V, t_{pulse} = 7.5 ms, L = 12 mm, V = 0.110 ÷ 0.220 m/sec, I_0 = 30 A

This approach makes it possible to calculate the cyclograms of welding current as a result of computer experiments for wide range of values of regulated technological parameters for the CO_2 pulsed welding with Sv-08G2S wire: d = 0.8 ÷ 1.2 mm, L = 8 ÷ 12 mm, t_{pulse} = 5 ÷ 18 ms, $t_{s.c}$ = 2.16 ms, U_{xx} = 35 ÷ 45 V, V = 0.111 ÷ 0.222 m/sec (Fig. 11).
An increase of the electrode feed rate increases the frequency of short-circuits at almost constant instantaneous values of current in both in the short-circuit range and the arcing time range in the pulse. This results in a higher stability of the welding process, as well as constant dimensions of the transferred droplets of electrode metal irrespective of the spatial position of the molten pool. This is of considerable importance for maintaining stable parameters of the welding process.

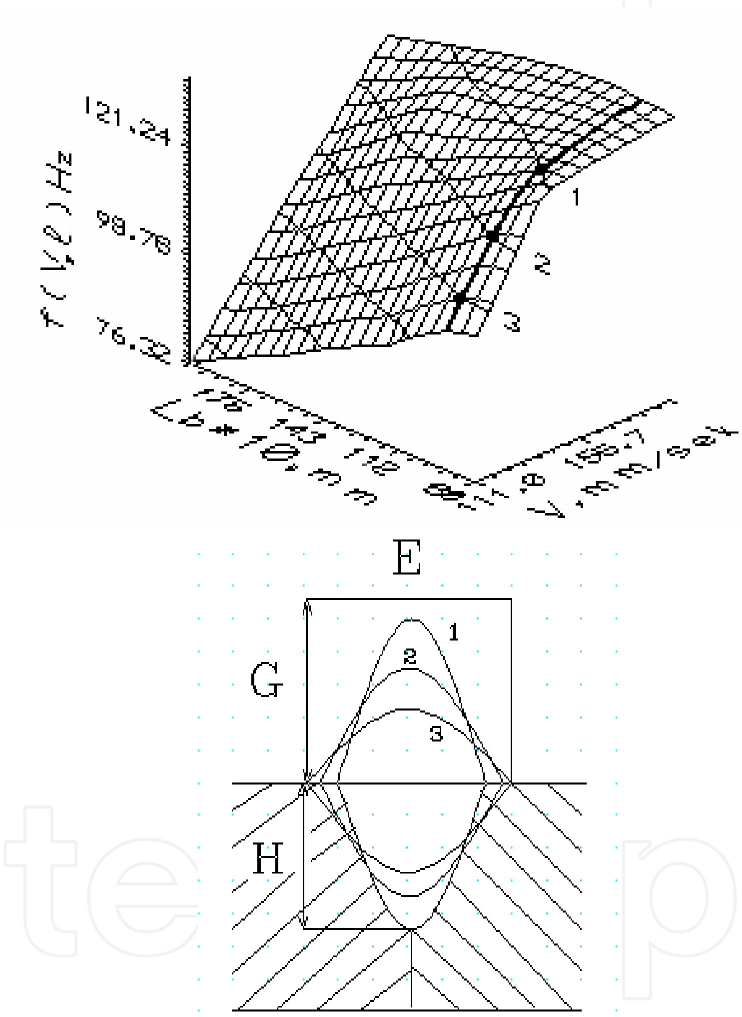


Fig. 12. Dependence of frequency of short-circuits $f_{s.c.}$ on electrode extension L_b at different values of electrode feed rate V ($U_{o.c.}$ = 35 V, t_{pulse} = 5 ms) and correlative weld sizes (H, E, G) for different complex of regulated technological parameters of pulsed arc welding ($f_{s.c.}$, L_b, V)

Fig. 12 shows the dependence of frequency of short-circuits $f_{s.c.}$ on electrode extension L_b at different values of the electrode feed rate V for open circuit voltage of the power source $U_{o.c.}$ = 35 V, pulse time t_{pulse} = 5 ms and the dependence of weld shape (H – penetration depth, E – weld width, G – throat) on complex of technological parameters of CO_2-shielded pulsed-arc welding (weld shape 1, 2, 3 correlate to complex of technological parameters 1, 2, 3).

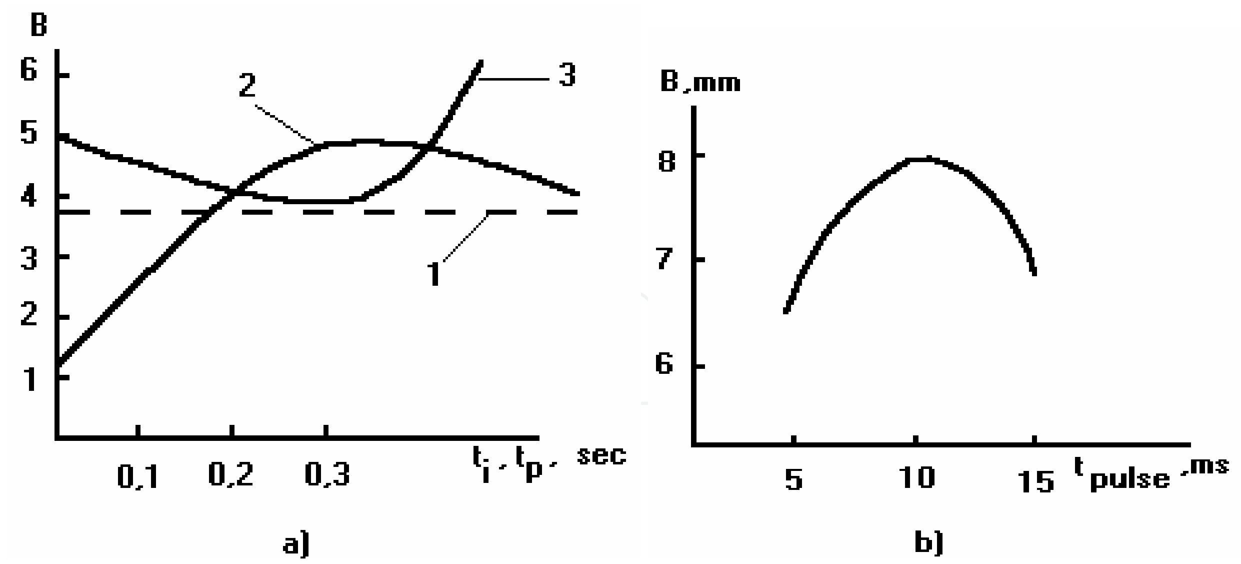


Fig. 13. Dependence of HAZ width on time of pulse (t_i) and time of pause (t_p) in pulsed arc welding:

a) by modulated current - experimental results for I_{mean} = 120 A:

1 - stationary arc;

2 – t_i – var, t_p = 0.3 sec;

3 – t_p – var, t_i = 0.3 sec.

b) pulsed arc welding in CO_2 of low carbonaceous steel – computer experiment (721° C isotherm)

4.5 Control of weld formation

During designing of optimum algorithm of control over pulsed regime of welding there is need to choose such combination of welding parameters (automatic welding, semiautomatic, submerged arc welding, and welding in an atmosphere of shielding gases): U_a, I(t), j - current density in electrode, v - welding speed, chemical compositions (the marks), granulation of flux, type of the current, its polarities which provide formation of the joints with proper sizes, shape and quality with high operating strength. The sizes - depth of penetration H (Fig. 12), breadth of weld E, height of deposited bead G, and shape of weld are determined by quantity of the heat transferred to the article and by the character of its introduction. Under the effect of high-speed heat source the penetration area (the area restricted by the isotherm of melting T_m):

$$F_p = \frac{1}{E \cdot c \cdot \gamma \cdot T_m} Q_p$$

$$Q_p = \frac{0.24 \cdot I(t) \cdot U_a \cdot \eta}{v}$$

Here:

$Q_p = Q/v$,

Q - arc power,

η - effective efficiency of arc.

Using of typical coefficients: ψ_p = E/H coefficient of penetration form, ψ_f = E/G coefficient of strengthening form and constants: A, K , μ - obtaining from experiments for low-alloyed steel and low-carbon steel during the welding in CO_2 medium by electrode wire Sv-08G2S and Sv-08GS gives the possibility to apply the equations connecting typical sizes of weld and energetic characteristics:

$$H = A \cdot \sqrt{Q_p / \psi_p}$$

$$\psi_p = k(19 - 0,01I)\frac{d \cdot U_a}{I}, \qquad E = \psi_p \cdot H$$

Where d – is the diameter of electrode.
During hard-facing or welding of butt joints without edge level with zero clearance the deposited metal is in the form of the bead above the sheet's surface, therefore $G = F_n / \mu^* E$, where μ - is the coefficient of bead completeness, F_n - the area of cross-section of deposited bead.
Using of this dependencies for research of the effect of the main technological and additional regulated parameters: $U_{o.c.}$, I_p, l_b, V, t_i, $f_{s.c.}$, t_p, *h* on the sizes of the given welded joint during welding and hard-facing on the base of computer experiment for wide range of values of technological and energy parameters of welding regime (Fig. 12) it is possible to design optimum regime, which provide required relationships of geometric sizes of the weld ψ_p, ψ_f for the given type of the welded joint, which characterize its technological and operating strength.
So, in automatic and semiautomatic welding with $\psi_p < 0.8$ the joints inclined to the hot crack formation are produced, with $\psi_p > 4$ - too wide welds with small penetration depth, what is inefficient from the viewpoint of arc power using and the result is deformation increasing. For the well formed welds the optimum range of values is $\psi_f = 7 - 10$. The narrow and high welds with small ψ_f do not have smooth connection with basic metal and have dissatisfied ability to work under variable loads. The large values ψ_f correspond to wide and low strengthening, what is undesirable because of decreasing of weld section in comparison with basic metal section because of the vibrations of molten pool level.

5. Conclusion

The results of analyzing the cyclograms of welding current and oscillograms show that they qualitatively coincide. The deviation of the calculated instantaneous values of welding current from the experimental data does not exceed 10%. This convergence level makes it possible to recommend the proposed mathematical model and original software for it numerical realization for examining actual pulsed technological processes.
The proposed mathematical model of melting and transfer of electrode metal in welding with systematic short-circuits of the arc gap and original software for it realization takes into account the heat generation in the electrode extension (heat conduction and convective heat exchange to space).
The action of heat processes in electrode on speed of electrode melting and amount of transferred molten metal, the nature of formation and transfer of every electrode metal droplet, and the state of the arc gap on the level of instantaneous values in limits of mathematical model (Saraev & Shpigunova, 1993) have been investigated.
There is most difference in temperature distribution, melting speed and sizes of transferred electrode metal droplet from paper (Saraev & Shpigunova, 1993) near the melting front or in time moment $t = t^0 + t_{s.c.}$.

The area of a solution existence for the proposed model is bigger than for model (Saraev & Shpigunova, 1993).

The developed approach permits on the basis of numerical realization of developed models to solve the inverse problem - to design optimum algorithms of control over the system "power source – arc – weld pool" in pulsed welding process, to determine optimum complex of values of regulated parameters depending on solving of technological problem, such as: decreasing of molten metal sputtering, improvement dynamic properties of power sources, the formation of weld with preset sizes and service properties.

This set of pulsed process parameters can be optimizing at the stage of technological preparation of production, in order to produce a sound welded joint operable under different types of loading.

The results of researching of the developed mathematical models of melting and metal transfer with systematic short-circuiting of the arc gap during the pulsed welding process, using a computer experiments, permits: to evaluate the influence of technological and energetic parameters complex of the process on the penetration of the weld metal, the shape and sizes of the weld and heat-affected zone.

Using these mathematical models permit to reduce the volume of experiments, aimed at developing pulsed conditions and to predict the strength properties, quality, reliability and operating longevity of welded joints.

Physics-mechanical and chemical processes of the formation of primary crystalline structure of weld and HAZ are multiple and difficult to simulation. There are a large number of accompanying factors which in particular cases may be a cause for control over welded joint strength in welding technology. The thermo-capillary convection applies to this class of phenomena. It leads to effect of irregular distribution of impurity concentration in melt that entails a change of crystallization front and affects the formation of structure of welded joint. Also it is necessary to examine the diffusive mechanism of impurity migration and the kinetics of polymorphous transformation.

The developed methodology of computer aided design of advanced technologies, which suppose the creation of integral model of adaptive pulsed process of welding and hard-facing; modeling; original software; adaptive algorithms of pulsed control and special equipment are most effectively used for defectless welding of root joints with the formation of the reversed bead in all spatial positions without any additional backing strip and welding on the reverse side by electrodes of different types.

The use of specialized equipment for developed pulsed methods of welding makes it possible to stabilize the welding processes as a result of fine-droplet transfer of electrode metal into the weld pool with the minimum (2 - 3%) splashing of electrode metal in the range 70-200 A in mechanized and automatic welding with electrode wires with a diameter of 0.8 – 1.2 mm; ensure guaranteed high-strength properties of important welded joints to be subjected to 100% inspection; simplifies welding technology in all spatial positions in the presence of large variations of the gap between the welded edges; increases 3 – 4 times the productivity of welding operations as a result of ensuring the possibility of downhill welding.

The regions of application of advanced pulsed welding technologies are: the welding of root, filling and facing layers of ship structures in different spatial positions and butt joints in the processing and transmission pipelines with a diameter of 32 – 1420 mm; boiler and power equipment for important applications, welding robotic technological systems for engineering companies.

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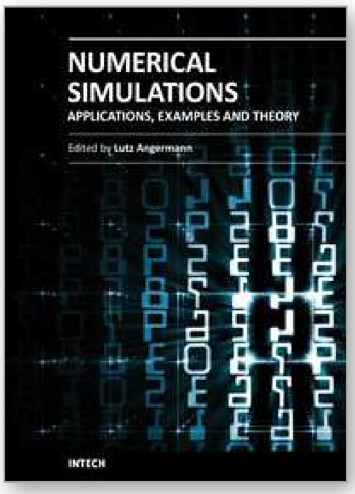

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This book will interest researchers, scientists, engineers and graduate students in many disciplines, who make use of mathematical modeling and computer simulation. Although it represents only a small sample of the research activity on numerical simulations, the book will certainly serve as a valuable tool for researchers interested in getting involved in this multidisciplinary ï¬eld. It will be useful to encourage further experimental and theoretical researches in the above mentioned areas of numerical simulation.