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APPLICATION OF PULSED IMPACT IN CONSUMABLE ELECTRODE GAS-SHIELDED ARC WELDING (Review)

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The paper presents the main technical means and methods of pulsed control of the process of consumable electrode gas-shielded arc welding, developed over the recent years at PWI and Admiral Makarov National University of Shipbuilding. A lot of attention is given to methods using systems of pulsed impact on the processes of electrode metal transfer, weld formation and deposited metal structure. Good prospects for application of systems with pulsed dozed feed of electrode wire are shown, and results of effective control of welding and surfacing processes are given. Methods of arc welding with pulsed feed of shielding gas and with two-jet gas shielding are considered, and problems are indicated, which prevent extensive application of these processes. The paper gives the results of some studies of the influence of external electromagnetic impact on electrode metal transfer, weld formation and crystallization, and presents some examples of effective application of this method of welding process control. Analysis of the methods of mechanical impact on the welding process using different oscillator systems was performed. The possibility is shown of combined control of electrode metal transfer, deposited bead formation and its metal structure, depending on the scheme of oscillation application and oscillation process parameters. The good prospects for this method application for surfacing operations are pointed out. 34 Ref., 2 Tables, 12 Figures.

Keywords: *welded joint, properties, control, technical means, analysis, application*

Welding and related technologies are continuously, actively and comprehensively developing. Theoretical and technological prerequisites, engineering developments for manufacturing new products are created in the traditional fields of welding production, as well as mastering other spheres of application, which were earlier considered inaccessible for a broad range of tasks, for instance, wet underwater welding [1].

A weld, or deposited layer are the result, which is achieved using mechanized or automated equipment for arc welding and surfacing. Operating (service) properties of welded, reconditioned or strengthened items (structures) depend on the structure of the deposited metal and heat-affected zone, weld surface shape, geometrical parameters of the penetration zone [2].

There exist quite a large number of techniques and methods for influencing the characteristics of the welded joint or deposited layer, including technological, technical characteristics and those related to electrode materials and shielding media. Here, we should also take into account the influence of the material being welded, conditions and media, in which the arc process is conducted.

The objective of this work is analysis and prospects for application of technical means, which are part of welding equipment systems, as well as auxiliary systems.

Developments of PWI and Adm. Makarov NUS are considered for analysis of the main technical means, used for pulsed control of parameters of the weld and deposited layer. The diversity of technical means is generalized and shown in Figure 1.

Inverter-type pulsed welding current sources became widely accepted in welding and surfacing equipment for any purpose, implementing the electric arc process using consumable electrode. The shape of output voltage pulses and their frequency depend on the problems being solved. These are mainly the problems of control of electrode metal transfer, including creation of conditions for optimum transition of molten metal drops into the liquid pool.

Widely accepted are the processes with control algorithms, where different variants of feedbacks are used [3]. As an example, let us note the process of electrode metal drop transfer at continuous feeding of electrode wire, in which the source voltage is stabilized at the stage of drop formation, and a current pulse is supplied at the stage of breaking of the neck of the drop between the electrode and the pool (Figure 2) [4].

Pulsed impact of welding current source allows to:

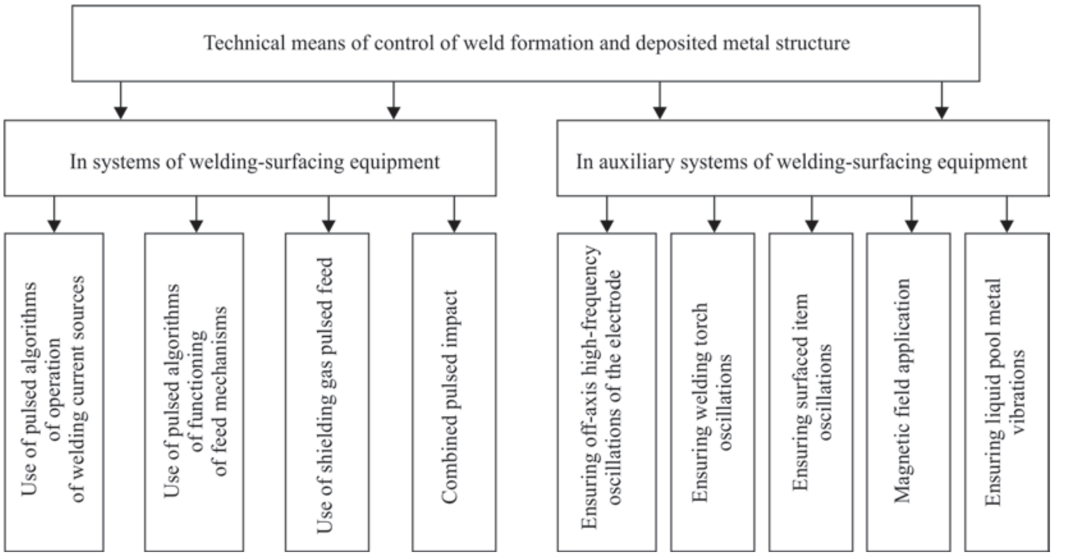


Figure 1. Technical means of influencing the properties of the weld or deposited layer

- control electrode metal transfer through drop separation and its transportation into the weld pool as the main impact of current pulse of the arc process;
- create vibrational oscillations of molten metal pool as concurrent impact of electrodynamic forces.

Controllable transfer of electrode metal can be also obtained using pulsed feed of electrode wire. This approach is becoming more and more widely accepted that is largely determined by the capabilities for improvement of technical means and technological developments in this direction. Different designs of mechanical gearless converters of rotational movement of drive electric motor shaft into pulses of movement of wire movers can be noted [5]. Such engineering solutions allow assigning the preselected mode of electrode wire feed by the movement step and pulse duty cycle. However, the application of such designs is limited. Pulsed feed devices with quasi-wave converters are an exception [6]. As a rule, quite inexpensive d.c. commutator motors are used as drive electric motors in such devices.

Pulsed feed systems with application of brushless electric motors, namely step and valve, have been developed and their development is carried on. Their operational parameters are determined by software, based on digital control systems. Use of such electric motors implies a gearless design of wire feed mechanism that improves system response. Batch-produced sets are mainly used as electric drives with step electric motors. Such sets were used with success in the automatic machine for wet underwater welding [7] and in other types of equipment [8].

Electric drives with valve electric motors and digital control were developed in Ukraine specially for various-purpose welding equipment [9], but they became the most common in systems of electrode wire feed for implementing pulsed movement with controlled characteristics, for instance, wet welding in aqueous environment. The possibilities of pulsed feed influencing bead formation are illustrated by examples of flux-cored wire surfacing in water (Figure 3). Here, the number of nonmetallic inclusions is increased, and mechanical properties of the deposited layers are improved.

Modern valve electric drives ensure up to 50–60 Hz frequency of pulsed feed of electrode wire with controllable parameters (step, amplitude, relative pulse duty cycle) and possibility of movement reverse in feed pulse cycle. Moreover, the signal of feedback by arc process parameters can be entered into the valve electric drive regulator. A drive with current or voltage feedback, realizing dosed feed of electrode wire can be used as an example [10, 11]. Changing the parameters of dosed feed of electrode wire allows controlling the weld shape at unchanged parameters of welding or surfacing mode (average current, voltage and arc movement speed).

One of the basic effects at pulsed feed of electrode wire is also the possibility of producing a disoriented structure of the deposited metal. Detailed metallo-

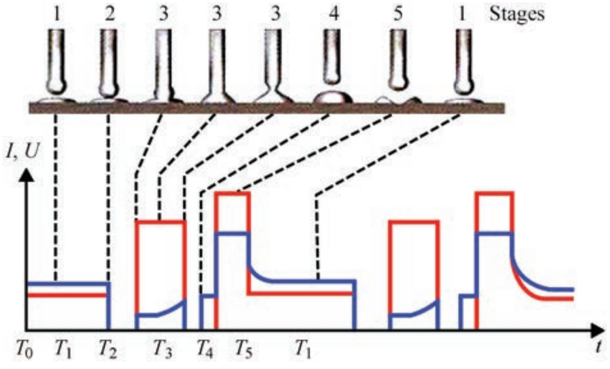


Figure 2. Algorithm of operation of control system of pulsed welding current source

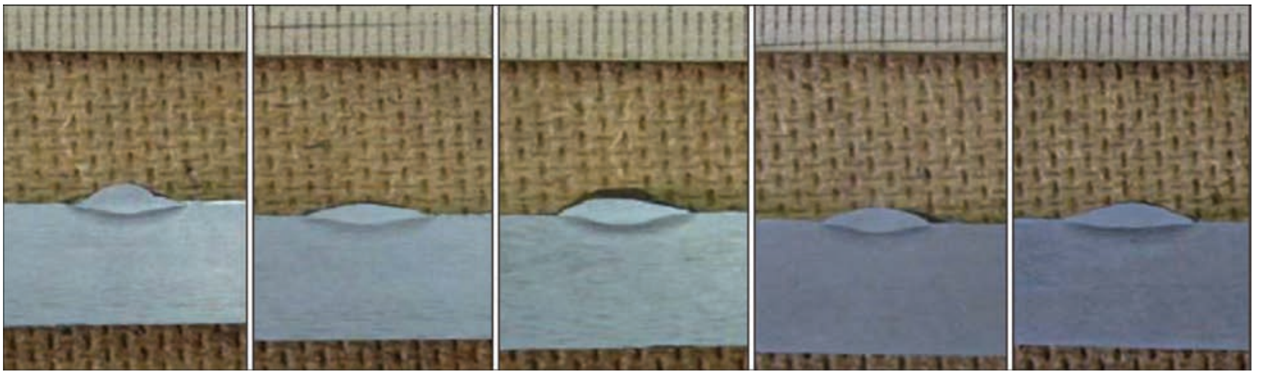


Figure 3. Microsections of beads, deposited with controlled pulses of electrode wire feed

graphic studies of samples, deposited under the same conditions and with the same energy parameters of the process, but using different methods of electrode wire feed, are indicative of significant changes in the deposited metal structure, and reduction of the quantity of nonmetallic inclusions [12].

We should also note the greater stability of the process of metal transfer at application of systems with dosed wire feed. In the oscillograms of the surfacing process performed with dosed wire feed (Figure 4), a clear regularity of the controlled electrode metal transfer is observed that eventually leads to metal structure improvement. Lowering of the degree of alloying elements burn out is observed at the same time. Welds and deposited layers produced by arc welding, also have improved mechanical properties, for instance, strength, wear resistance and toughness [13].

Results of welding (surfacing) with 1.0 mm electrode wire of 0.9 mm thick plates from an aluminium alloy can provide evidence of the effectiveness of application of dosed feed of electrode wire (Figure 5) [14]. In terms of quality indices, these joints practically do not differ from welds produced by nonconsumable electrode argon-arc welding, but as regards the efficiency the process with dosed feed of electrode wire exceeds argon-arc welding 1.5–2.0 times.

Pulsed feed of shielding gas and two-jet gas shielding are relatively new processes of controlling the arc welding process.

During the shielding gas feed pulse, the velocity of gas outflow from the nozzle increases, gas-dynamic pressure on the drop at the electrode wire tip rises, and finer drops move into the pool, but at greater frequency [15]. Here, as a result of reduction of the time of drop transfer into the liquid pool, the intensity of alloying element burning out changes.

Among the different variants of pulsed feed of shielding gases, the main ones are the following two: with feeding one type of gas and with alternative feeding of several types of gases, the second variant being more effective. In [16] it is shown that alternative feeding of argon and helium results in a new technological process, in which the effect of pulsed impact on the weld pool arises due to pulsed change of pressure in the arc gap (because of different density and ionization potential of argon and helium). This promotes producing metal of the weld and deposited layer with fine-grained metal structure with high values of metal ductility and strength.

The appearance of welds (surface shape, ripple) depends not only on the type of shielding gas, but also on pulsed feed frequency. Gas feeding with pulse fre-

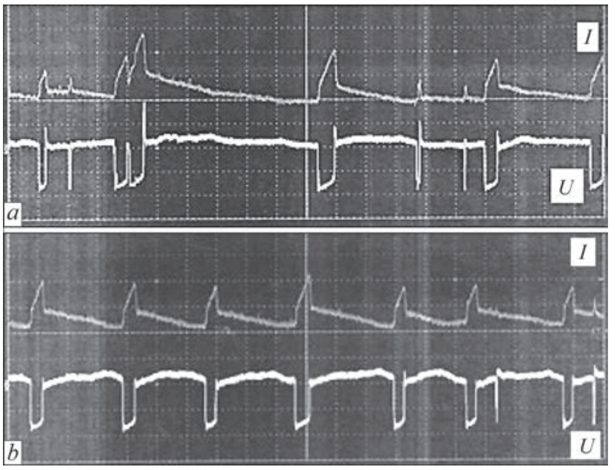


Figure 4. Oscillograms of surfacing process with electrode wire feed: *a* — discontinuous; *b* — dosed

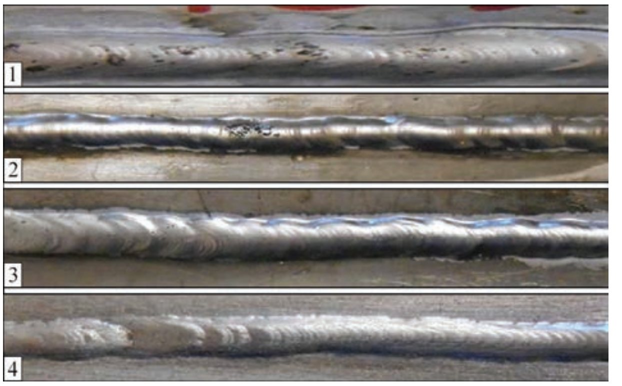


Figure 5. Appearance of beads, obtained with dosed feed of electrode wire, on sheet metal structures: 1 — surfacing with semi-automatic machine; 2, 3 — butt welding with semi-automatic machine; 4 — surfacing with automatic welding machine

quency of up to 20 Hz has a predominant effect on weld geometry [17–19].

Despite the obvious advantages of arc welding and surfacing with pulsed feed of shielding gas, wide acceptance of the method, in our opinion, is prevented by inertia of the shielding gas feed system. Here, placing the gas valve even directly at the nozzle cannot provide an effective solution of the problem. It should be also taken into account that with increase of the pulsed feed frequency, it is more difficult to ensure shielding gas feeding in individual portions without mixing.

The process of welding with two-jet gas shielding is interesting from the view point of its effect on the weld and improvement of shielding gas feed system [20]. With such a welding process, the shielding gas jet is enclosed in an outer jet, which stabilizes the inner jet, lowers its turbulence, limits air suction into the arcing zone and protects the near-weld zone. Increased gas-dynamic pressure of the inner gas jet promotes cooling of the molten electrode metal drop at its movement from the electrode tip and lowers alloying elements loss. More intensive mixing of the main and electrode metal takes place in the weld pool.

Developments of welding equipment systems with combined effects on the welding process, formation of the welded joint and deposited layer are of great interest. Engineering capabilities of application of the method of controlling electrode metal transfer at simultaneous impact of welding current source and pulsed feed mechanism with different operating algorithms on electrode wire melting were studied in [21]. Pulsed-feed mechanism with one-sided grips and electric magnets allowing synchronization of wire feed pulses with mains frequency were used for experimental studies [22].

It is found that the current pulse should always precede the pulsed movement of electrode wire. At optimum synchronization parameters controllable transfer of electrode metal is achieved in welding with short-circuiting of the arc gap, and in a number of cases controllable transfer without the short-circuiting phase with less than 3 % electrode metal losses, is possible. Use of pulsed feed allows control of welded joint formation (Figure 6).

On the whole, the advantages of application of a combined pulsed impact of welding current source and electrode wire feed mechanism are as follows:

● range of stable welding modes, possibility of controlling the geometrical characteristics of the welded joint and deposited layer are expanded;

● high level of control of electrode metal transfer is achieved, both in welding with short-circuiting and without it;

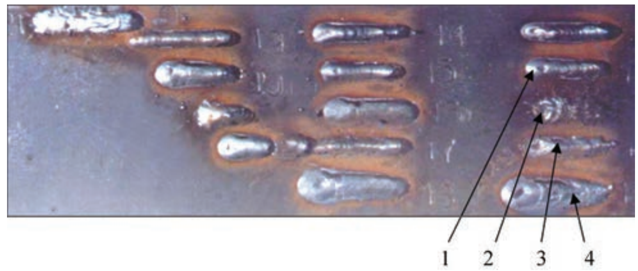


Figure 6. Beads deposited at different parameters of the process of control of electrode metal transfer due to combined effect of pulses of current source and electrode wire feed mechanism (*1–4* — ineffective pulse synchronization)

● operational conditions of pulsed feed mechanisms are facilitated, as there is no need to form pulses with high values of accelerations of wire movement in the pulse;

● problems of weld metal structuring are solved at a rather high level with reduction of crystal dimensions and respective increase of mechanical properties of the item being welded or surfaced;

● electrode metal drop stays in the zone of impact of high temperatures for a shorter time, and alloying element loss is lowered, accordingly.

The problem of combined impact on metal transfer was solved at the E.O.Paton Electric Welding Institute at development of a new method of arc mechanized and automatic welding with dosed feed of electrode wire. Here, arc feedbacks are used for feeding the current pulse from the power source at any time at the stage of impact of electrode wire feed pulse. This is a promising direction, which can be accepted in welding and surfacing of various steels and aluminium alloys, and with application of both solid and flux-cored wires.

Research work is carried on in the direction related to a combined pulsed impact from welding current source and system of shielding gas pulsed feed. Some research results [18] contain materials on two welding processes: with alternating feed of several kinds of shielding gases and pulsed-arc process with pulsed feed of shielding gas.

Combined impact on the welding process by the second method ensures formation of the weld with a high quality of the surface and has a positive influence on weld metal structure, improving its mechanical properties.

Considering the inertia of the gas feed system, complexity of selection of gas equipment, as well as certain problems in ensuring synchronization of operation of the welding current source and shielding gas feed system can be regarded as the common drawbacks of the above ingenious welding methods with a combination of pulsed impact of shielding gas and welding current source.

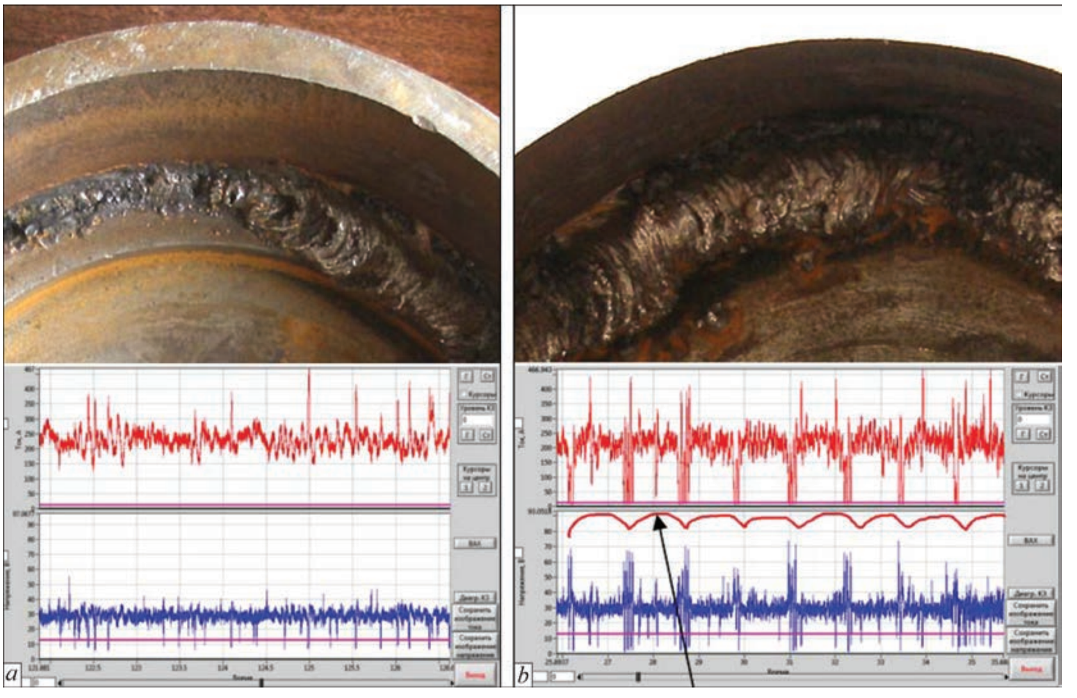


Figure 7. Appearance of welds and oscillograms of current and voltage in welding-in plugs: *a* — regular process; *b* — torch oscillations (arrow shows current supply oscillation)

Next, we will consider promising developments on control of formation of the welded joint and deposited layer, using technical means, which, as a rule, are not included into the list of the main systems of welding-surfacing equipment, but are used for a considerable increase of their effectiveness. In particular, we should note the fact that different methods of influencing the weld pool formation using technical means, realizing various pulsed or oscillatory impact, differ by the frequency spectrum of their effective impact, as part of them influences the overall volume of molten metal, and another part acts locally.

Oscillations of the torch of automated welding equipment are performed, mainly, in order to fill wide grooves or increase the deposited metal width [23]. The frequency of these oscillations is usually equal to 0.2–2.0 Hz, and it is limited by inertia properties of the torch oscillatory system. The concomitant result of operation of torch oscillators is their impact on the structure of weld metal and deposited layer. It is found that transverse oscillations of the arc allow reducing the dendritic heterogeneity of weld metal and width of heat-affected zone that promotes improvement of mechanical properties of the weld and deposited layer [24]. Transverse oscillations of the torch movement can be realized by two main methods, namely swinging of the torch or parallel displacements of the carriage with the welding torch attached to it. In the first case, the electrode wire extension is changed that also influences formation of the welded joint or deposited bead.

An example of original and effective application of torch oscillations to solve the problem of welding over a larger gap is development of a device for welding-in plugs inside a pipe of 157 mm diameter with 10 mm wall thickness by wet method in a liquid medium at more than 200 m depth, performed by PWI [25]. Torch oscillations are realized from the electrode wire feed mechanism by special eccentric mechanism, allowing adjustment of oscillation amplitude. Special features and results of welding with application of the developed torch oscillator are illustrated by Figure 7.

In particular, the oscillogram (Figure 7, *b*) clearly shows the arc process current pulses, resulting from the change of electrode extension in the extreme points of oscillations. Such pulses are close to current pulses in welding with mode modulation and have the respective effect on weld characteristics.

Let us briefly consider the known systems of welding process control and formation of welded joint and deposited layer, using the magnetic fields [26]. Quite often the complexity of application of these engineering systems limits their mounting in systems of automatic equipment for welding and surfacing. In a number of cases, however, their use is necessary and has prospects for application in the future.

The effectiveness of controlling the above processes, using external pulsed magnetic fields was proved experimentally [27]. It is found that application of axial pulsed fields allows not only controlling the frequency of transfer and dimensions of electrode metal drops, but also changing the transfer type, for instance, from globular to jet transfer. Losses of electrode wire metal for spattering become smaller with increase of electromagnetic pulse frequency. Con-

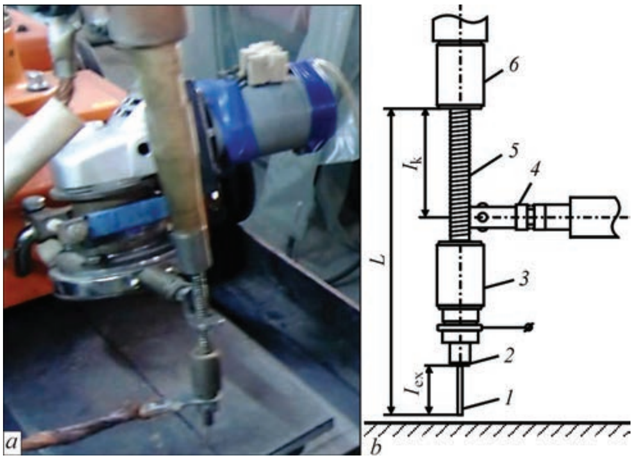


Figure 8. General view (*a*) and scheme of inducing high-frequency oscillations of electrode wire (*b*): *1* — electrode wire; *2* — current supply; *3*, *6* — current supply fastening components; *4* — vibration component of mechanical oscillator; *5* — flexible spiral; *L* — length of mobile (elastically fastened) part of current supply with the electrode; l_k — arm of application of the force from mechanical oscillator; l_{ex} — electrode extension

trolled electromagnetic field, acting on weld pool liquid metal enables changing the weld geometry and thereby serves as a means of increasing the hot cracking resistance of the metal.

In order to obtain the required structure and geometry of the deposited layer at surfacing operations, different methods are used, which are based on adjustment of the heat input into the processed metal and physicochemical impact on the arc and weld pool [13, 28]. Control of the structure ensures the required mechanical characteristics of the deposit metal, and control of penetration dimensions promotes increase of surfacing process efficiency and reducing the fraction of base metal in the deposited layer.

Work associated with development of high-frequency direct (without additional converters) oscillator of electrode wire using new engineering means and original application of a number of physical effects is aimed at solving this range of problems [29, 30]. Mechanical generator of high-frequency electrode oscillations provides a combined impact, at which the conditions of simultaneous control of metal transfer through the arc and of deposited layer geometry at automatic submerged-arc surfacing are realized.

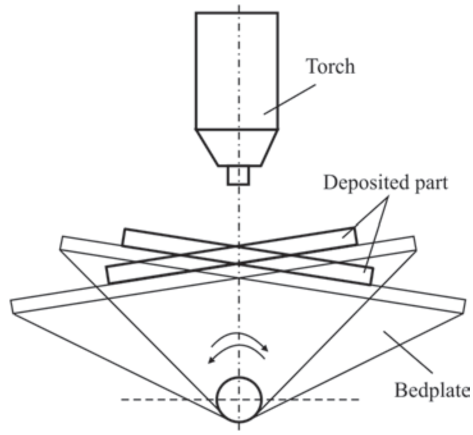


Figure 9. Scheme of weld pool harmonic oscillations

The generator features the capability of creating high-frequency electrode oscillations, consisting of two harmonics with the required values of frequency and amplitude. The harmonics with a higher frequency provides an increase of electrode melting stability, and that with a lower frequency, but greater amplitude, promotes increase of deposited bead width and reduction of base metal penetration depth. Improved design of mechanical oscillator (Figure 8), allows, unlike previous developments, inducing electrode oscillations along or across the deposited bead and adjusting their amplitude, irrespective of the length of electrode extension, required by the technology [31].

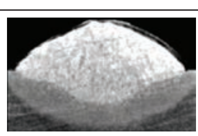
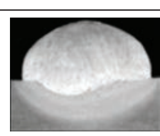
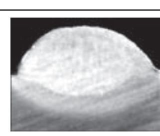
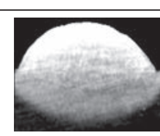
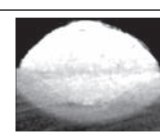
Mounting the mechanical oscillator on standard equipment for automatic welding allows achieving the following results, depending on amplitude-frequency characteristics of induced oscillations:

- ensuring microdrop transfer of metal as a result of gravitation-capillary dispersion;
- controlling metal transfer;
- controlling deposited layer geometry due to heat flux dispersion.

Possibilities of combined control of surfacing process characteristics using high-frequency transverse mechanical oscillations of the electrode can be assessed by the results presented in Table 1 [32]. Oscillations with frequencies close to the resonance ones have an especially significant effect.

Considering the good technological results (metal structure, geometrical parameters of deposited lay-

Table 1. Influence of the frequency of electrode oscillations on surfacing characteristics

Oscillation frequency, Hz	0	680 (resonance)	1295	3820 (resonance)	5800
Deposited bead macrosection					
Base metal share in deposited bead	0.36	0.13	0.30	0.22	0.25
Electrode melting coefficient, g/(A·h)	15.0–15,2 15.1	16.5–17.2 16.9	15.1–15.5 15.3	18.0–18.9 18.6	15.8–16.3 161.1

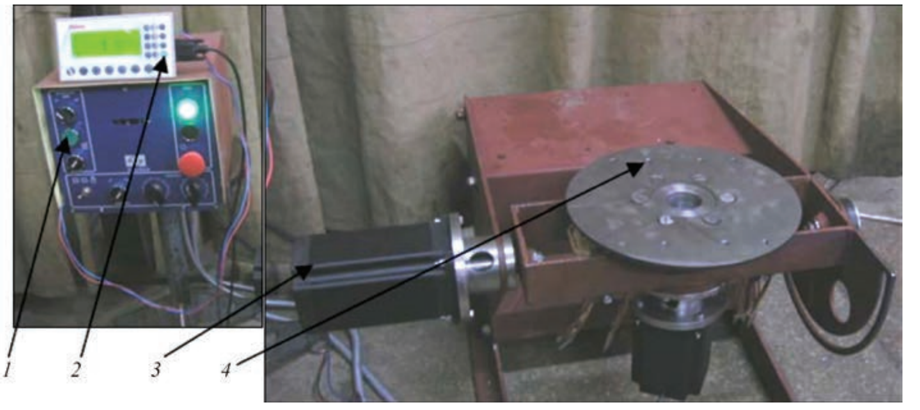


Figure 10. Unit for transverse oscillations of the surfaced item: *1* — control module; *2* — oscillation parameter regulator; *3* — oscillation drive electric motor; *4* — work table

ers), produced at surfacing with high-frequency controlled oscillations of electrode wire, we believe it is expedient to apply them also in other processes using a consumable electrode.

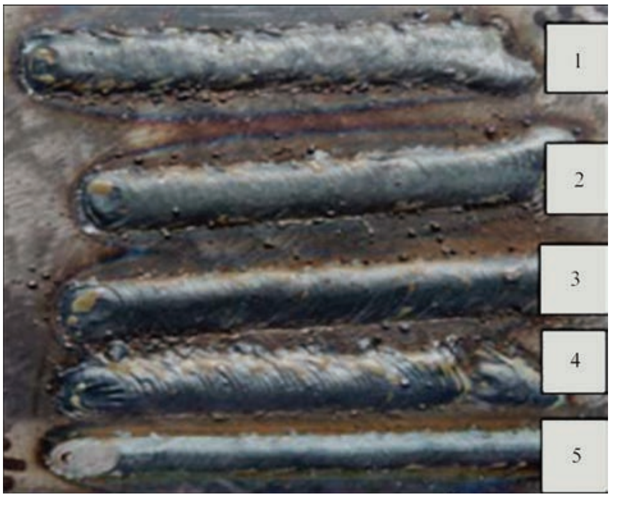


Figure 11. Beads deposited with oscillations of unit work table with frequency, Hz: 1 — 4.67; 2 — 4.0; 3 — 3.0; 4 — 2.0; 5 — without oscillations

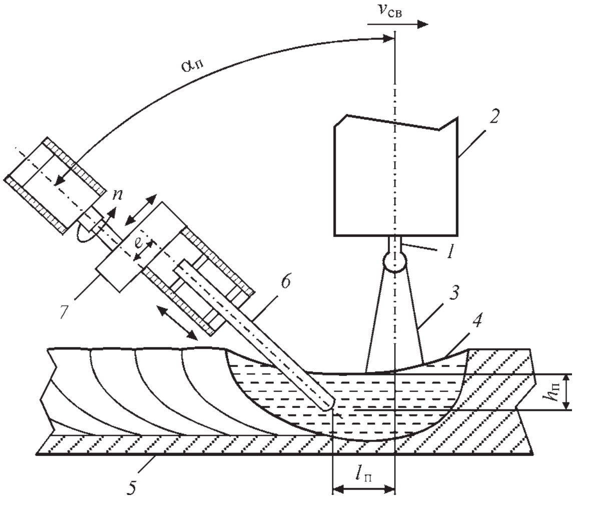


Figure 12. Scheme of welding-surfacing process using mechanical vibrator of the weld pool: *1* — electrode wire; *2* — torch; *3* — welding arc; *4* — weld pool; *5* — item; *6* — vibrator waveguide; *7* — generator; *n* — waveguide rotation frequency; *e* — half-amplitude of waveguide oscillations

PWI is working on application of other oscillatory processes, also at lower frequency. It was noted above that weld pool vibrations lead to a change of the structure of weld metal or deposited layer. Plane or plane-parallel movements of vibrators in the form of vibrating tables of different design are usually applied to excite oscillations of molten metal of the pool.

Based on achievements of modern mechanotronics with computerized control of drive systems, new engineering solutions and techniques are proposed for making an impact on the weld pool with controlled oscillations parameters, such as frequency, amplitude, and shape. Figure 9 gives the scheme of inducing oscillations of the surfaced item, which are transverse relative to the weld, Figure 10 is a fragment of an experimental unit, and Figure 11 shows the deposited bead appearance.

A step motor with gearless transmission of movement directly to the work table was used as the drive for transverse oscillations. The unit was applied to perform experimental verification of the developed mathematical model of the surfacing process with item oscillations [33], which showed satisfactory convergence of results (Table 2).

An essential increase of the deposited bead width at accordingly reduced height as a result of weld pool oscillations is indicative of higher efficiency of this surfacing process, compared to the conventional

Table 2. Results of checking the adequacy of the mathematical model

Experiment number	Oscillation frequency, Hz	Deposited bead width, mm		Error, %
		calculation	experiment	
1	4.67	15.4	14.0	10
2	4.0	13.6	13.0	4.6
3	3.0	12.0	14.0	14.3
4	2.0	11	14.0	21.4
5	0	–	8.0	–

method, performed under the conditions of stationarity of the surfaced item. Moreover, improved structure of the deposited metal provides higher service characteristics of the surface layer [34].

Results of the performed studies give ground to believe that the technology with item oscillations should be developed in the direction of application of other parameters of the oscillatory process. The considered surfacing process can be used at manufacture or repair of parts of agricultural machinery, components of stamping or metal-cutting tools [34], etc.

Recently, a method of welding-surfacing with addition of mechanical oscillations into the weld pool, using an additional vibrator, was proposed (Figure 12).

When performing the welding or surfacing processes, the vibrator waveguide, immersed into the liquid metal of the weld pool behind the arc, moves together with it at speed V_w. The position of the waveguide working end (distance from welding arc l_{im}, immersion depth h_{im}, angle of inclination α_{im}) is determined by weld pool dimensions, and oscillatory process parameters (frequency and amplitude) are set by oscillatory mechanism generator. The effect of mechanical mixing of the weld pool consists in structuring the deposited metal and, as a consequence, in improvement of mechanical properties of the joint or deposited layer.

Conclusions

1. At great diversity of methods and techniques of controlling the welded joint operating properties, correct selection of welding method and modes is the determinant factor to produce a joint with the required mechanical and special characteristics. However, a versatile welding process, which, allowing for various external conditions of conducting the process, ensures absolutely equal strength and quality of the joints, has not been developed yet.

2. The main directions of effective improvement of welded joint quality are rational application of the methods of pulsed and vibrational impact on the welding process, using welding equipment systems proper, as well as auxiliary systems, allowing control of the deposited metal properties.

3. The results of mechanical impact on the characteristics of welded joint or deposited layer can be significantly enhanced by application of different methods of combined impact, selecting the most effective of them, taking into account their cost-effectiveness.

1. Paton, B.E. (2003) Current trends of research and development in the field of welding and strength of structures. *The Paton Welding J.*, **10–11**, 5–11.
2. Makovetskaya, O.K. (2012) Main tendencies at the market of welding technologies in 2008–2011 and forecast of its development (Review). *Ibid*., **6**, 32–38.
3. Mironov, S. (2003) Inverter power sources for arc welding. Svarochn. Proizvodstvo, **4**, 41–43 [in Russian].
4. Saraev, Yu.N., Bezborodov, V.P., Grigorieva, A.A. et al. (2015) Control of structure and properties of welded joints of critical technical systems by methods of adaptive pulsed arc welding. *Voprosy Materialovedeniya*, **1**, 127–131 [in Russian].
5. Paton, B.E., Lebedev, V.A., Poloskov, S.I., Lendel, I.V. (2013) Application of mechanical pulses for control of processes of automatic and mechanized consumable electrode welding. *Svarka i Diagnostika*, **6**, 16–20 [in Russian].
6. Paton, B.E., Lebedev, V.A., Pichak, V.G., Poloskov, S.I. (2009) Evolution of systems of pulsed wire feed for welding and surfacing. *Ibid*., **3**, 46–51 [in Russian].
7. Maksimov, S.Yu., Lebedev, V.A., Lendel, I.V. (2015) Sealing of heat exchanger pipes by «wet» welding at depth of 200 m. *Voprosy Materialovedeniya*, **1**, 199–204 [in Russian].
8. Lebedev, V.A., Dragan, S.V., Trunin, K.K. (2016) Automatic submerged-arc welding with pulsed electrode wire feed by step motor. *Svarochn. Proizvodstvo*, **2**, 27–34 [in Russian].
9. Lebedev, V.A., Guly, M.V. (2014) Fast valve electric drive for mechanized arc welding equipment. *Mekhatronika. Avtomatizatsiya. Upravlenie*, **6**, 47–51 [in Russian].
10. Lebedev, V.A., Zhuk, G.V. (2017) Control of electrode metal transfer based on pulse algorithms of systems functioning with dosed electrode wire feed during mechanized arc welding. *Tyazholoe Mashinostroenie*, **6**, 27–32 [in Russian].
11. Lebedev, V.A. (2016) Mechanized synergic welding with pulsed electrode wire feed. *Naukoyomkie Tekhnologii v Mashinostroenii*, **2**, 19–24 [in Russian].
12. Lebedev, V., Reisgen, U., Lendel, I. (2016) Study of technological opportunities of GMA welding and surfacing with pulse electrode wire feed. *Welding in the World, February*, 9–14.
13. Paton, B.E., Lebedev, V.A., Zhuk, G.V., Dragan, S.V. (2017) Mechanical pulse and vibration effects in equipment and technologies of mechanized welding and surfacing. In: *Proc. of 16th Intern. Sci.-Techn. Conf. on Vibrations in Engineering and Technologies (Ukraine, Vinnytsya, 26–27 October 2017)*, 10–16.
14. Lebedev, V.A., Zhuk, G.V. (2017) Solution of problems of mechanized welding of thin sheet aluminium alloys based on application of programmable feed mechanism electric drives. *Montazhnye i Spec. Raboty v Stroitelstve*, **9**, 21–24 [in Russian].
15. Denisov, L.S., Barsukov, I.V., Apolonik, S.A. (1998) Development and analysis of equipment for welding with alternate gas supply. In: *Proc. of Sci. Conf. on Advanced Engineering and Technology of Machine Building, Instrument Making and Welding Production*. Kiev, Vol. 4, 310–313 [in Russian].
16. Tarasov, N.M., Tulin, V.M. (1982) Control of electrode metal transfer by short-time increase of the rate of shielding gas flow. *Svarochn. Proizvodstvo*, **8**, 23–25 [in Russian].
17. Zhernosekov, A.M. (2012) Tendencies in development of control of metal transfer processes in shielding gases (Review). *The Paton Welding J.*, **1**, 29–33.
18. Zhernosekov, A.M., Sidorets, V.N., Shevchuk, S.A. (2013) Combined pulsed action of shielding gases and welding current in consumable electrode welding. *Svarochn. Proizvodstvo*, **12**, 9–13 [in Russian].
19. Kitsch, M. (2006) Metall-Inert Gas Schweissen von Aluminium mitgepulster Schutzgaszufuhr. *Schweissen und Schneiden*, 58(**1**), 19–22 [in German].

20. Chinakhov, D.A. (2009) Effect of double-jet gas shielding on performance of welded joints on GL-E36 shipbuilding steel. *The Paton Welding J*., **9**, 29–32.
21. Paton, B.E., Lebedev, V.A., Mikitin, Ya.I. (2006) Method of combined control of electrode metal transfer process in mechanized arc welding. *Svarochn. Proizvodstvo*, **8**, 27–32 [in Russian].
22. Fedko, V.T., Solodsky, S.A., Kryukov, A.V. (2004) Pulsed welding wire feed with controlled transfer of electrode metal. In: *Proc. of Sci.-Techn. Conf. on Science-Education-Production. Nizhny Tagil*, Vol. 2, 100–103 [in Russian].
23. Makara, A.M., Kushnerenko, B.N. (1967) Transverse arc movements as the factor of improvement of structure and properties of welded joints. *Avtomatich. Svarka*, **1**, 31–35 [in Russian].
24. Boldyrev, A.M. (1976) On mechanism of formation of weld metal structure at low-frequency oscillations in weld pool. *Svarochn. Proizvodstvo*, **2**, 1–3 [in Russian].
25. Lebedev, V.A. (2019) Automatic underwater welding in increased gap. *Remont. Vosstanovlenie. Modernizatsiya*, **3**, 16–20 [in Russian].
26. Sidorenko, P.Yu., Ryzhov, R.N. (2010) Application of pulse electromagnetic effects to control the process of electrode metal transfer in arc welding. *The Paton Welding J*., **6**, 44–45.
27. Ryzhov, R.N. (2007) Influence of pulse electromagnetic actions on formation and solidification of welds. *Ibid*., **2**, 49–50.
28. Lebedev, V.A., Tishchenko, V.A., Loj, S.A. (2019) Technical-technological effects in mechanized surfacing with modulation of modes. In: *Proc. of 19th Int. Sci. and Techn. Seminar on Modern Question of Production and Repair in Industry and Transport (Slovak Republik, Kosice, February 18–23)*, 106–109.
29. Goloborodko, Zh.G., Dragan, S.V., Simutenkov, I.V. (2013) Automatic submerged-arc surfacing of structural steels with transverse high-frequency movements of electrode. *The Paton Welding J*., **6**, 34–37.
30. Simutenkov, I.V., Dragan, S.V., Yaros, Yu.A. (2014) Stability of arc process in automatic submerged-arc surfacing with high-frequency electrode oscillations. *Zb. Nauk. Prats NUK*, **4**, 43–48 [in Russian].
31. Simutenkov, I.V., Yaros, Yu.O., Dragan, S.V., Gal, A.F. (2015) *Device for automatic submerged-arc surfacing*. Ukraine Pat. 10288, Int. Cl. B23K 9/00, No. u 201504821 [in Ukrainian].
32. Dragan, S.V., Simutenkov, I.V., Ignatenkov, O.V. (2012) Procedure for determination of parameters of electrode high-frequency mechanical oscillations in automatic submergedarc surfacing. *Visnyk Derzh. Mashynobudivnoi Akademii*, 3(**28**), 124–129 [in Russian].
33. Lebedev, V.A., Novikov, S.V., Zhuk, G.V. et al. (2018) Mathematical modeling of arc surfacing process with controlled variations of arc gap length. *Tekhnologiya Mashinostroyeniya*, **3**, 56–62 [in Russian].
34. Lebedev, V.A., Solomichuk, T.G., Novykov, S.V. (2019) Study if a welding harmonic oscillation influences on the welded metal hardness and weld bead width. *J. of Eng. Sci*., **6**, 16–21.

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