TENDENCIES IN DEVELOPMENT OF MECHANIZED WELDING WITH CONTROLLED TRANSFER OF ELECTRODE METAL (Review)

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Assessment of modern developments of mechanized equipment for consumable electrode welding and surfacing was performed. It is shown that modern engineering solutions involve control of electrode metal transfer as the main means of improvement of mechanized arc processes. Examples of realization of electrode metal transfer control are given.

Keywords: *welding, surfacing, pulse, source, inverter, transfer, control, feed mechanism*

Developed and commercially available semi-automatic welding and surfacing machines are being continuously improved to produce welds and deposited beads with optimum ratio of geometrical parameters and metal quality, including the near-weld zone; reducing the cost of post-weld treatment; reducing consumption of material and energy resources, lowering the influence of welding operator on welding and surfacing processes.

All the above directions were combined by the main topic of ESAB concern «Increase of efficiency» in «Welding and Cutting» Exhibition held in Essen, Germany, from September 14 to 19, 2009. In this work illustrative material from promotional brochures of leading companies-exhibitors in the exhibition was used.

The tasks of improvement of welding equipment were solved by various methods in different periods, also by developing new welding consumables, application of multicomponent mixtures of shielding gases, improvement of the main and auxiliary components and equipment as a whole.

In 1960s pulsed-arc welding process became rather widely accepted. Its essence consisted in application of pulsed algorithms for welding current source control of electrode metal transfer [1].

At present improvement of welding processes and equipment for mechanized welding proceeds, mainly, allowing for the capabilities offered by application of inverter sources of welding current and various algorithms of control of electrode metal transfer and welding cycle. This was demonstrated in the Exhibition by the majority of the participating companies-manufacturers of the respective equipment for welding steels, titanium and aluminium alloys. This equipment mainly belongs to semi-automatic machines for consumable electrode welding.

One of the first developments in the field of controllable electrode metal transfer using inverter sources of welding current were engineering solutions, proposed by KEMPPI, Finland, in the form of synergic control. The essence of this control process is known and described in [2]. KEMPPI technologies and equipment are being continuously developed and improved. As an example of such an improvement a new MIG/MAG process — FastROOT — was proposed, which is welding by a modified short arc based on digital control of arc parameters (welding current and voltage). It is applied for welding low-carbon and alloyed steels and makes the welder's work easier and faster. Welding can be performed in all positions, with good penetration and at practically complete absence of spatter. FastROOT technology ensures better weld quality, than in TIG welding at a higher efficiency. The principle of FastROOT operation is based on separation of the welding cycle into two periods: short-circuiting period and arcing period, which alternate (Figure 1). During the short-circuiting period the wire is shorted into the weld pool, the current rises abruptly and remains on the set level. At the start of the short-circuiting period, there is a short jump of welding current. During the short-circuiting period at an abrupt jump of current up to the specified

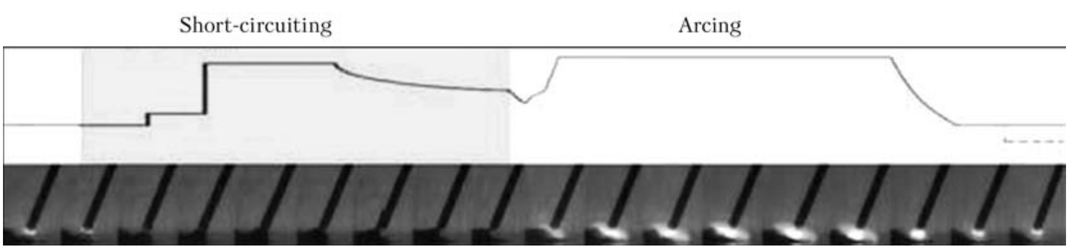

Figure 1. Graph of welding current variation in FastROOT process

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Figure 2. FastMIG Synergic semi-automatic machine

level, the electrodynamic force grows, ensuring separation of the metal drop from the welding wire tip. At a slow lowering of welding current a smooth separation of the drop takes place. At the moment of drop transfer into the weld pool the second period of current rise begins and the arc is struck. Accurate control of the time of current rise and decrease guarantees an absence of spatter at transition from short-circuiting to arcing.

During arcing period the weld pool forms and the required penetration of weld root is ensured. These two periods of current rise follow each other, and at the end of each of them the current is set and maintained at the specified level. Accurately set base current guarantees transfer of each subsequent drop during the short-circuiting period, creating the conditions for continuous separation of drops and their transfer into the weld pool practically without spatter with a guarantee of arcing stability and simplicity of welding process control.

Semi-automatic machine with realization of the considered FastMIG Synergic process is shown in Figure 2.

A direction in which attention is focused on development of systems and means of electrode metal transfer control, providing an effective solution of the problems of ensuring process quality, as well as energy- and resource-saving, continues to be intensively developed now. A confirmation of the rationality of this path of development of mechanized welding and surfacing is provided both by the entire wide range of semi-automatic machines for welding and surfacing demonstrated by numerous companies in «Welding and Cutting 2009» International Exhibition in Essen, and the package of work currently performed by PWI.

Most of the semi-automatic machines of modern design incorporate welding current sources with various algorithms of output parameter variation, allowing control of electrode metal transfer. Here SST technologies, «cold welding» technologies, their different variants and combinations of actions on the arc process (controlled formation and transfer of electrode metal drop) are used.

The widest spectrum of technological innovations was presented by known CLOSS Company, Germany. They include «cold process» (CP) realized using a semi-automatic welding machine of this company of GLC 353 QUINTO CP type, which has essential advantages compared with the usual technology, particularly in welding of thin-walled parts. Owing to a new shape of welding current pulses a lowering of thermal load on the base material (reduction of energy input) is achieved and power of welding wire melting, and, therefore, welding speed, are increased simultaneously. The cycle of electrode metal transfer occurs by the following algorithm (Figure 3):

- in the phase of positive main current base material cleaning (oxide layer breaking up) occurs, and an accurately calculated amount of thermal energy is applied to the material;
- in the pulsation phase drop separation without spatter occurs;
- in the phase of negative base current (drop formation) the arc covers the wire tip. Transfer of a certain amount of thermal energy to the welding wire takes place, the weld pool cooling down.

This provides an excellent filling of gaps between the parts being welded, accuracy and repeatability of welding result.

CP welding is optimum and effective for joining high-strength, stainless steels, coated materials, aluminium alloys, as well as for MIG brazing.

The following should be named as advantages of CP welding with the above-mentioned other algorithms of forming welding current pulses: high welding speed; increased efficiency; high welding quality;

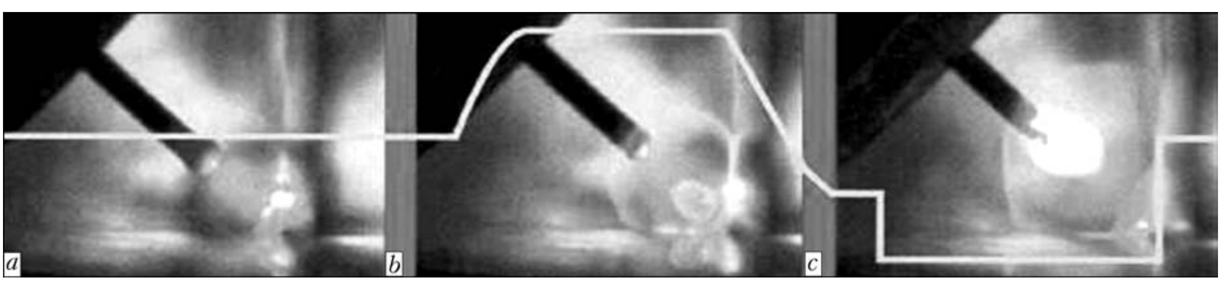

Figure 3. Process of electrode metal transfer control in the cold process: *a* — positive current phase; *b* — pulsation phase; *c* — negative current phase

lowering of thermal energy transfer into the material; reduction of thermal deformations; lowering of the risk of cracking in the weld zone because of temperature gradients; minimized molten metal spatter; no need for subsequent treatment; possibility of application of large diameter electrode wire; lowering of electrode wire costs; possibility of creating a new process — inert gas brazing (MIG brazing).

Technology and equipment for welding using STT-process developed at Lincoln Electric Company, USA, was extensively displayed in the exhibition. High-quality semi-automatic welding of root welds with back formation of the joint, welding of sheet material, and lower spatter of electrode metal, are achieved in this case.

Shapes of welding current and voltage curves in semi-automatic welding by STT method are shown in Figure 4. Considered process was realized in INVERTEC STT2 welding source which is shown in Figure 5.

The following developments of Lincoln Electric should be noted: welding current sources of Power Wave 355M type — all-purpose inverter arc power sources, also for gas-shielded pulsed-arc semi-automatic welding with synergic control of welding parameters and program control of current pulse shape. The source incorporated the latest achievements in power inverter equipment and microporcessor control with optimized software, developed at Lincoln Electric, ensuring wide capabilities of welding in combination with ease of operation. The welder just has to select one of more than 60 welding programs, depending on material type, wire diameter and shielding gas and set the welding wire feed rate. The source automatically provides the optimum shape and parameters of current pulses, maintaining control of each drop of the metal being deposited. The range of welded materials is very wide: steels, stainless steels, aluminuim, nickel alloys, etc. Equipment allows lowering the requirements to welder professional level and at the same time ensures an improved quality and efficiency of welding operations; technology of control of the shape and parameters of welding current pulses Wave Control ensures an optimum running of welding process, i.e. for each type and size of wire and material the optimum welding properties of the source are set to achieve the best welding results. The main advantages of the new technology of controlling the welding current shape are accurate control of welding process parameters, their interaction, instant response to possible deviations of arc parameters, and ease of operation.

New modes, proposed and demonstrated in the exhibition by Lincoln Electric are:

• Power mode — provides a stable smooth process in short-arc welding of thin materials;

• Pulse-in-Pulse — improves cleaning in semi-automatic welding of aluminium and forms the weld of the same appearance as in tungsten electrode welding;

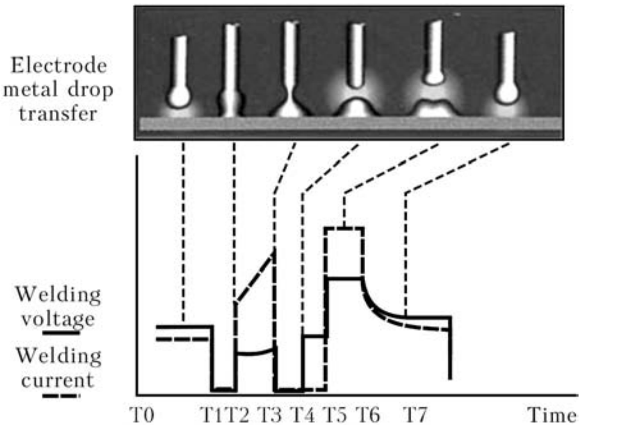

Figure 4. Diagrams of transfer of electrode metal drop at SST control

• Rapid Arc — designed for high-speed (up to 2.5 m/min — according to developer materials) semi-automatic welding of carbon steels up to 4 mm thick.

All the new developments of Lincoln Electric are based on adaptive synergic programs, i.e. have program feedbacks for correlation of arising deviations of the welding process, distinguishing the source from most of the analogs with rigidly set pulse parameters. Welding programs are constantly complemented by new ones developed by the manufacturer. Note that the user of this equipment is able to develop his own welding programs, using the acquired Wave Designer software. This, in our opinion, accounts for very broad acceptable of STT-process and its various modifications, differing from each other by some features of the pulse shape, and in some cases containing additional impacts due to the software and capabilities of modern power sources. So, STEL Company, Italy, has developed and uses in the semi-automatic machines combined control, which includes both pulsed synergic algorithms, and modulation, ensuring good labour conditions for welders, also in other positions than the horizontal one, when making short and spot welds at high and repeatable quality.

Figure 5. Welding current source INVERTEC STT2

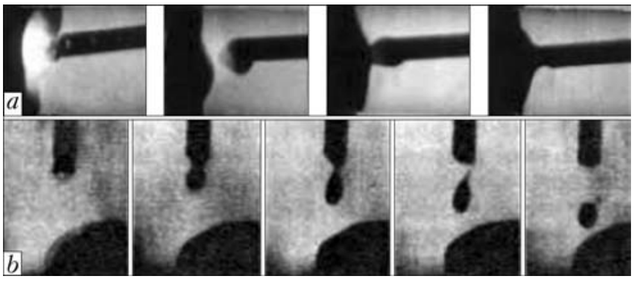

Figure 6. Filmograms of electrode metal transfer process: *a* — process with FSC; *b* — pulsed-arc process

For comparison let us consider the developments of SPA SELMA-ITS, Russia–Ukraine [3]. A new welding process was proposed, which is also a variant of semi-automatic welding with periodical short-circuiting and which was called the process of welding with forced short-circuiting — FSC. The development was based on analysis of short-comings of STT process — high cost of complex inverter welding equipment; expensive programming of welding mode parameters, if it is necessary to perform welding in a mode non-standard for this welding machine and complex maintenance; welding machine is controlled by changing the cyclogram of welding arc current, which makes it impossible to use pulsed modes, and low reliability in case of long connecting cables (more than 25 m from the power source to feed mechanism), which, in its turn, imposes serious technological limitations; lowering of welding process efficiency by at least 25 % because of shortening of free arcing time of welding arc and presence of a considerable number of short-circuits.

FSC process is based on application of welding current sources with combined external volt-ampere characteristics. The essence of the use of such characteristics consists in that, depending on the size of electrode metal drop and phase of drop transition into the weld pool (drop growth, formation of a bridge between the drop and electrode, drop transition into the pool, bridge rupture), the volt-ampere characteristic can be rigid or drooping. The power of the arc discharge at the moment of bridge rupture is limited, and open-circuit voltage after bridge rupture and drop transition into the weld pool is increased for welding process stabilization. Transfer control is performed not by current, but by arc voltage. Application of other thyristor or inverter sources (without special control algorithms) does not provide a high quality of the welded joint in mechanized welding, because of scatter of electrode metal drop sizes, chaotic transition from the process of long-arc welding to short-arc welding, considerable spatter, low welding properties at the change of electrode wire diameter and position in space.

Figure 7. Welding current source Origo Mig C3000i

During FSC process, compared to the traditional process of CO_2 welding (Figure 6) with short-circuiting of the arc gap, the time of electrode metal drop contact with the arc is considerably reduced, arcing time is shortened (by the value of short-circuiting duration) and weld pool dimensions are reduced, respectively, the process becomes more flexible and controllable in terms of technology.

Let us consider a few more engineering solutions, used by a number of leading companies-manufacturers of mechanized equipment.

QSet function is the most recent development of Swedish concern ESAB in the field of intellectual digital welding. Modern electronics allows development of software, helping welders to control MIG/MAG welding process. One-time pushing of QSet button and several seconds of trial welding are enough to automatically set all the short-arc parameters, namely an optimum ratio of arcing duration and short-cricuiting duration, at which a more efficient use of the arc is achieved at the same short-circuiting frequency. The same procedure is repeated when wire grade or diameter and/or shielding gas type are changed. The system can itself find the optimum settings. Wire feed rate can be changed at any time during the welding process or between the welding operations. If the different butt geometry, material thickness or welding positions require different feed rates, then the established optimum welding parameters guarantee a stable short arc, which provides a high welding quality. QSet function is used to set a stable process of short-arc welding at different wire extensions at the change of welded item geometry, which helps the welders. For instance, in narrow-gap welding time is also saved on scraping the welds, as ideal adjustment of the arc minimizes spattering. Figure 7 shows a source of welding current of Origo Mig C3000i type with a built-in QSet function.

A very interesting solution realized in ESAB equipment, is pulsed control algorithm, which allows controlling in a broad range the «arcing–short-circuiting» time at the same transfer frequency (Figure 8). It is also possible to change the frequency of short-circuiting of the arc gap by changing the choke inductance. Here, short-circuiting frequency decreases with increase of choke inductance. All this is achieved by

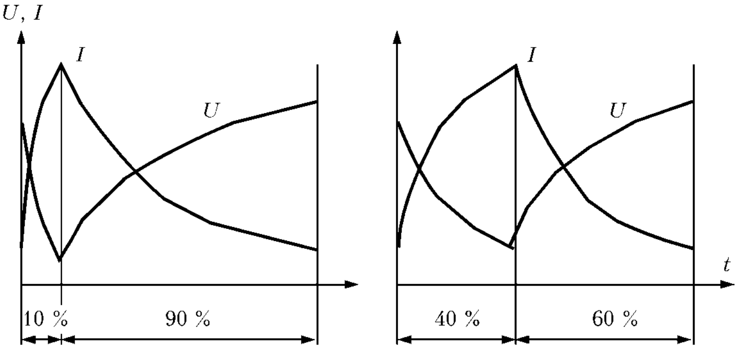

Figure 8. Capabilities of control of short-circuit and arcing time

QSet function. Settings of choke inductance, welding voltage and electrode wire feed rate, in addition to ensuring the process stability, also essentially influence the heat input. At greater inductance arcing time is increased, short-circuiting frequency is decreased and heat input is increased.

Let us consider the method of control of forceArc process developed by EWM, Germany. In mechanized gas-shielded welding (inert gas or mixture of gases with high argon content) jet process of electrode metal transfer by fine drops without short-circuiting is often used. This is possible at relatively long arc with high value of welding voltage, which is not always effective in practice, as the arc can be deflected because of magnetic blow, and, in addition, undercuts or pores can occur, as well as loss of alloying elements. At arc shortening as a result of welding voltage lowering, duration of short-circuiting phases is increased and spatter is enhanced.

Appearance of inverter machines and modern digital control systems enabled at a very short arc with long short-circuiting phases to quickly «intervene» into the adjustment process. At arc excitation current is lowered until programmed arc voltage has been reached. As a result, short-circuiting duration is markedly reduced, and spattering is minimum. Electrode metal transition into the weld is of a jet nature with finest drops and practically without short-circuiting. At further lowering of voltage the arc length will decrease. The arc runs in molten metal depression, forming under the pressure of plasma flow. Size of metal drops moving into the pool, changes from fine to medium drops. Frequency of the drops following each other increases to such a state when their sequence forms a short-time contact with the melt, leading to short-circuiting with increased metal spatter. Such a transfer is influenced by control algorithm of inverter current sources. In this case the inductance is adjusted using an electronic system. At short-circuiting it can be completely switched off (just the welding wire inductance remains). Therefore, current increase and lowering in the short-circuiting phase and at arc excitation can be adjusted very quickly. Spattering is very low.

Voltage drop and rise are used as setting parameters for the adjustment process. Voltage is measured continuously and each voltage change is recorded appropriately (highly dynamic adjustment of instantaneous values).

Such a type of control ensuring jet transfer during welding is called EWM-forceArc. Current and voltage change can be ensured without any significant spatter.

Fast adjustment of the process allows welding to be performed with a long wire extension, which is favourable for the weld at limited access to it (difficult access to the welding site). In this case, however, sufficient flow rate of shielding gas must be ensured.

High-speed filming frames in Figure 9 demonstrate arcing and electrode metal transfer during the EWM-forceArc process.

PHOENIX 500 EXPERT PULS semi-automatic machine, in which control of MIG/MAG process of forceArc welding is realized, is shown in Figure 10.

Application of forceArc process can lead to the following results: increased penetration due to high pressure of plasma in the arc; absence of undercuts

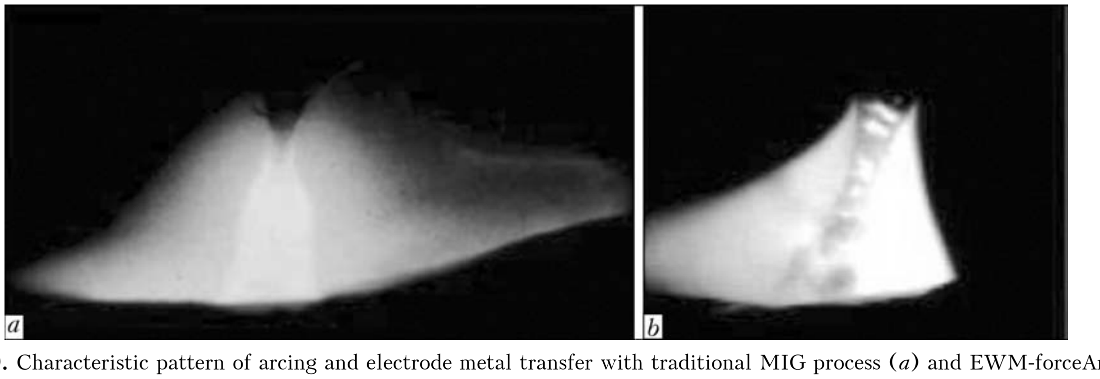

Figure 9. Characteristic pattern of arcing and electrode metal transfer with traditional MIG process (*a*) and EWM-forceArc (*b*)

Figure 10. Semi-automatic machine PHOENIX 500 EXPERT PLUS

due to a very short arc; high cost-effectiveness owing to a high welding speed; better weld quality as regards the heating zone and distortion due to slight heating.

The well-known Fronius Company, Austria, has essentially widened the capabilities of CP-process, developing CMT — cold metal transfer. The novelty of this control process consists in the method of drop separation, in which, in addition to other features, metal transfer is relatively cold compared to conventional processes. Not only wire feeding in weld pool direction is used, but also a reverse motion, i.e. electrode wire is fed forward and in a certain phase of drop transfer it is reversed, promoting electrode metal transition into the weld pool. An inverter welding current source is used, the control algorithm of which is conjugated with electrode wire motion. The main moments of electrode metal transfer cycle provided by reverse motion of electrode wire, are shown in Figure 11.

Achieving CMT with programmable operation of feed mechanism leads to a process with new characteristics. Performance of welds and braze seams practically without spatter becomes possible, which allows avoiding subsequent expensive and time-consuming machining. The feature of CMT process compared to traditional arc welding processes consists in that metal transfer occurs at almost zero current. At regular submerged-arc welding the current rises considerably in the short-circuiting phase, and in CMT process current value remains low in this phase. Here, despite a very low current value in the short-circuiting phase, drop separation is still possible, as this is promoted by reverse motion of the wire, which is attributable to surface tension of liquid metal by analogy with SST-process, obtained through control of welding current source parameters.

Weld formation quality (appearance, possibility of gravity welding without backing, small heat-affected zone, etc.) in sheet metal welding in CMT-process is given in Figure 12.

The process allows controlling heat input, which, in its turn, influences weld geometry. A combination of CMT process and pulsed arc is applied, if it is necessary to eliminate the lack-of-penetration in the weld, or increase welding speed. CMT-process also has advantages at arc excitation.

It should be noted that a number of companies use pulsed movement of wire at sufficiently high frequencies (for instance, MEGATRONIC, Denmark) — frequency of tens of Hertz. This, however, is true only for cases of application of filler wires.

Use of pulsed feed of electrode wire in welding and surfacing equipment displayed in the Essen exhibition, was limited to the above-described developments of Fronius, the essence of which consists in that the usual algorithm of electrode wire motion with a specified speed, providing an integral value of its melting speed, is interrupted at the required time by reverse motion of the electrode away from the item.

Having analyzed the considered algorithms of electrode metal transfer control by the type of SST and CMT one can come to the conclusion that such technologies practically do not actively control the transfer, as, for instance, this is done in the pulsed-arc process [1], but just create optimum (soft) transfer conditions. They, however, cannot be widely accepted, for instance in flux-cored electrode wire welding and surfacing.

A number of algorithms of control of electrode metal transfer with specified parameters were pro-

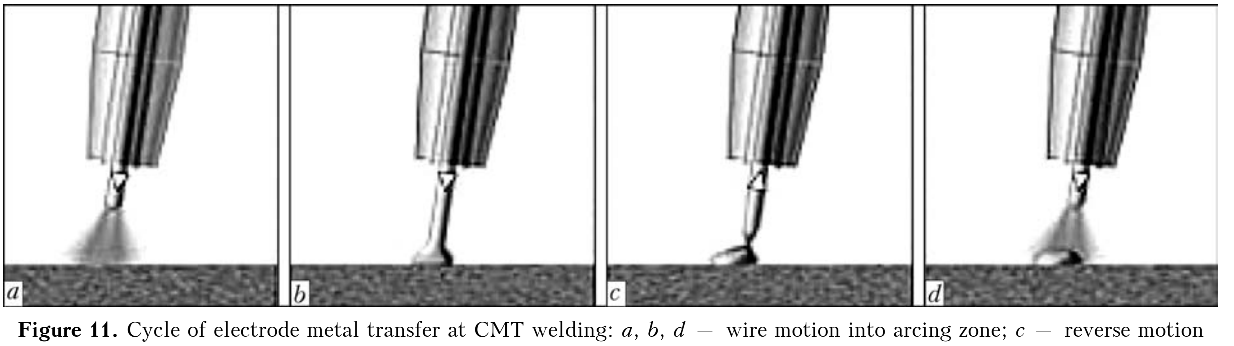

Figure 11. Cycle of electrode metal transfer at CMT welding: *a*, *b*, *d* — wire motion into arcing zone; *c* — reverse motion

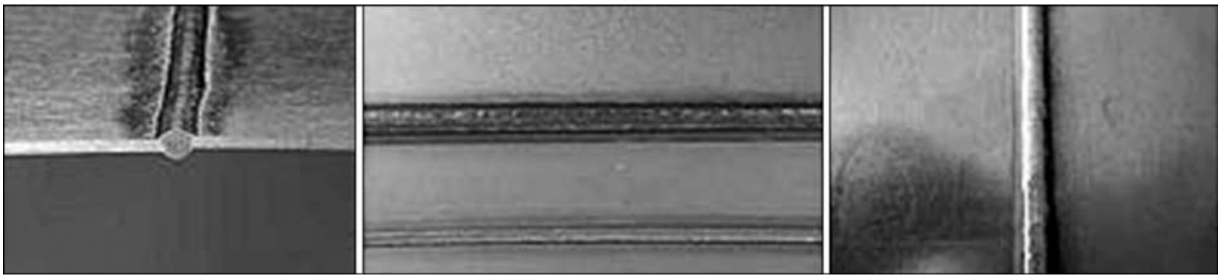

Figure 12. Appearance of welds when CMT process is used

posed by Russian researchers [4]. Technical realization of such algorithms is quite complicated and no real solutions were proposed, which could be the basis for commercial equipment in this direction, although quite interesting and promising results on real control of electrode metal transfer were indeed obtained during investigations. An exception is the feed mechanism with electromagnetic drive and drivers — one-sided grips. Such a feed system is difficult to adjust and is limited both as to operation period (unreliable designs of one-sided grips), and as to electrode wire types (flux-cored wire cannot be fed).

Adjustment of pulsed feed parameters can be regarded as the main objective, which is considered in [5] in all its aspects.

PWI of the NAS of Ukraine also pays a lot of attention to pulsed feed systems with one-sided grips with electric motors and electric magnets. Certain results have been achieved. A number of experimental semi-automatic machines have been developed, however, the work has not yet been taken to the stage of commercial introduction. At present, having a sufficiently large scope of the required theoretical studies on the possibilities of pulsed feed of electrode wire [6], a concept has been developed of design of pulsed feed mechanisms, which is based on application of electric motors in the two main directions:

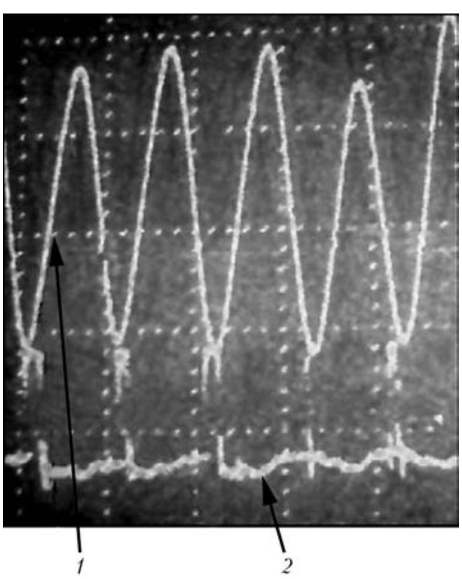

Figure 13. Oscillograms of wire feed rate *1* and voltage *2* in steel welding (1.2 mm Sv-08G2 wire, welding voltage of 21–22 V, welding current of 120 A)

- with application of special converters of rotary motion of electric motor shaft into pulsed motion of feed rollers and electrode wire;
- with application of special high-speed electric motors and feed roller mounting directly on the electric motor shaft.

Both these directions are effective for adjustment of feed pulse parameters, although in the first case the system has certain gaps, but it is sufficiently inexpensive (less expensive than the regular reduction gear feed systems). The system in the second direction is perfect, controllable (up to 70 Hz now, more than 100 Hz in the near-term). Such systems can indeed provide a controllable electrode metal transfer when using wires of various designs and in a rather broad range of processes and modes of arc welding and surfacing. PWI developed an arc welding process with pulsed feed, realization of which practically guarantees control of transfer with a short-circuiting phase, at which the level of electrode metal losses and power costs are lowered with production of welds of a good shape and appearance.

Figure 13 shows characteristic oscillograms of electrode wire pulsed feed rate and voltage for steel welding. Each drop transfer corresponds to a feed pulse at correctly selected parameters of pulsed motion of electrode wire, and the above transfer is performed in different pulse phases for the processes of welding steels and aluminium.

Figure 14 shows deposited beads of metal of aluminium alloys produced by the conventional mechanized process and process with pulsed feed of electrode wire. Absence of undercuts, regular bead formation at visual absence of inclusions, when pulsed feed process is used, are obvious. Possibility of obtaining a

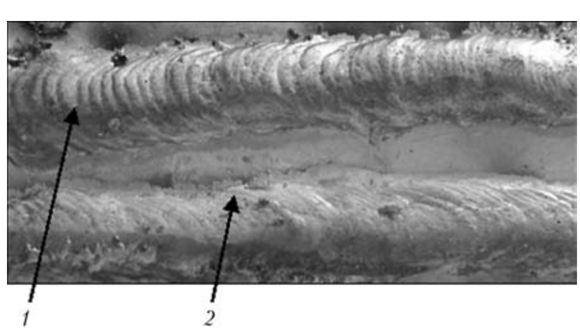

Figure 14. Deposition on plates from aluminium alloys with pulsed *1* and regular *2* electrode wire feed

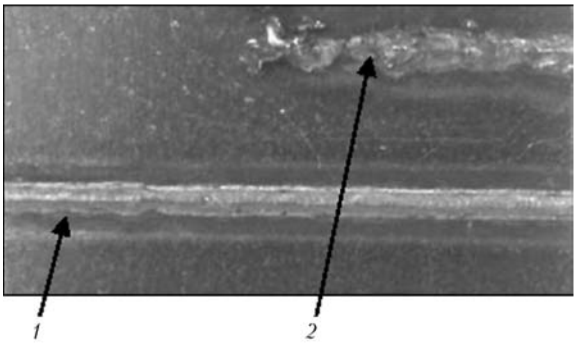

Figure 15. Bead deposition on steel sheet 1.2 mm thick with pulsed *1* and regular *2* electrode wire feed

sound metal bead at deposition on sheet metal is shown in Figure 15.

Revealing the features of electrode metal transfer in welding with pulsed feed allows defining the requirements to one more controlled transfer process, namely that with simultaneous use of pulsed feed mechanism and pulsed source of welding current. This direction was implemented in practice at PWI [7]. Such a method of forced control of transfer yields very good results at small energy consumption for pulse formation from a pulsed source (3–5 times lower than in pulsed-arc process in aluminium welding). However, up to now this process was difficult to implement because of a number of special requirements to the pulsed feed mechanism. PWI development of a new type of completely controllable pulsed feed mechanisms based on special designs of computerized valve electric motors enables commercial implementation of transfer control with action on the drop of two pulsed impact sources operating by a certain algorithm.

In conclusion it can be stated that one of the main directions in improvement of equipment for mechanized welding and surfacing processes is ensuring the possibility of effective controllable transfer of electrode metal. The highest effect can be achieved using advanced inverter-type welding current sources with computerized control and adjustment systems (Lincoln Electric, Fronius, CLOOS, etc.), as well as results of theoretical investigations and developments of systems of pulsed feed of electrode wire, conducted in Ukraine and Russia.

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