CIRCUITRY OF ELECTRON
BEAM WELDING CURRENT CONTROL

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The requirements for electron welding beam current control, which are not specified by the International Standard ISO 14744-1-6 yet, were considered. The chosen principle of beam current regulation with the use of automatic bias in the emission system was substantiated. The characteristics of analog and digital beam current control are compared. Particular attention was paid to the issues of discharge suppression in the emission system, the influence of beam current value on the focus spot position, implementation of possible operation of the automatic butt weld tracking system in the real time mode.

The leaflet is intended for engineers and technicians involved in welding production, as well as institutes, specializing in the field of welding equipment.
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Beam welding techniques have been successfully applied in various fields of industry. Electron beam welding (EBW), allowing to combine metals and alloys from 0.1 to 400 mm thick in a single pass, is the most common among them. EBW refers to the techniques of welding, using the highly concentrated sources of energy and has an extensive technological options. Vacuum excludes metal contamination by harmful gases. Low volume of cast metal and short-term heating effect at EBW provide slight thermal deformations of welded parts, not exceeding the tolerances for machining in most cases. The pulse welding mode, at which heat input is additionally regulated by frequency and welding pulse duration, is widely used in butt welds, located close to glass-to-metal or ceramics-to-metal seals, in sealing of workpieces in electronics and instrumentation manufacturing industry, reactor fuel elements, etc. Electrons flow deflection in magnetic or electric fields is carried out practically without inertia. This enables to move the beam on the workpiece straight, circumferential, rectangular surface or any other surface with a complex shape, using an electromagnetic deflecting system. Besides, many problems in welding can be solved without the gun or workpiece movement and programmed relatively easy.

At EBW the working distance (the electron gun – the workpiece) can be changed considerably without changing significantly the weld parameters. The working distance is usually chosen within 50-120mm for low-voltage guns and 50-500mm for high-voltage guns. Changes in the working distance during the welding process by 1-5mm do not influence significantly the welded joint quality.

EBW provides efficient production of workpieces from refractory metals, heat-strengthened materials, when further workpieces heat treatment is not desirable, difficult or impossible after final machining if minimum welding deformations have to be provided.

EBW industrial applications in the aerospace industry, nuclear power engineering, power engineering, turbine manufacturing, electro-vacuum, instrument and relay manufacturing, automobile industry (production of gears, elements of automatic gearboxes, steering columns, reactors for exhaust gas combustion, truck rear axles, radiators), manufacture of bi-and tri-metallic stripe welded blanks for cutting tools is developed most of all.
By 2013, the world stock of industrial plants for EBW was estimated at several thousands of units at stabilized annual output of approximately 50 units, besides up to 10% of annual production is intended for replacement of morally and physically old-fashioned machines.

The main reasons, constraining the extension of industrial EBW applications, are still as follows: high cost of equipment, its complexity compared to conventional electric welding equipment, the need for qualified operating personnel, poor training of technicians and engineers in EBW, conservative designers, oriented on traditional technology. For these reasons EBW still remains rather a special process, which is used primarily where other welding methods application are impossible, as well as in cases of batch and mass production when high performance of the welding process, the possible deformation reduction, low operating costs are essential.

Noticeable changes have occurred in the list of equipment manufacturers within 50 years of application. In particular, “Sciaky” (Vitri-Seine, France), “Mitsubishi Electric” (Japan) do not perform EBW any more at all, and the British Welding Institute ceased the production of industrial equipment for EBW.

As of 2013, the major manufacturers of industrial equipment for EBW are as follows [1]:
- “Steigerwald Strahltechnik” (Munich, Germany). Specializes over the last years in: large-sized chamber machines for production of aircraft engine units; machines for electron beam perforation; machines for non-vacuum welding of car aluminum units; machines of atmosphere-vacuum-atmosphere grade for welding of bi-and tri-metallic stripe blanks;
- “PTR Prazisionstechnik” (Maintal, Germany). Specializes over the last years in: machines and lines for gear blocks of car gearboxes EBW;
- “Pro-beam” (Munich, Germany). Specializes over the last years in: lines for mass products EBW, machines for large-sized wind power plant units EBW;
- “CVE” (Cambridge, UK). Traditional specialization: machines with small-sized vacuum chambers, intended mainly for the terms of job-shops. Sometimes - large-sized chamber machines;
- E.O. Paton Electric Welding Institute of NASU (Kyiv, Ukraine) and “Techmeta” (Annecy, France) manufacture the full range of machines.
List of abbreviations

a - the distance from beam crossover to the middle of focusing lens

b - the distance from the middle of focusing lens to the minimum beam cross-section

$\Delta b$ - coordinate of the beam focusing level relative to the workpiece surface

C - capacity

e – the electron charge

f - frequency

$f_f$ - focal distance

$H$ - magnetic field strength

$h$ - the depth of penetration

$I_m$ - magnetic focusing lens current

$I_{defl}$ - the deflection coil current

$I_b, I_{beam}, I_{weld}$ - electron beam current

$r$ - the effective electron beam radius

$e$ - the emitting cathode surface radius

$r_{cr}$ - the electron beam radius at crossover

$r_{min}$ - the minimum beam cross-section radius

t - time

$U_{acc}$ - accelerating voltage

$U_w$ - voltage between the control electrode and the emission system cathode

$U_{lock}$ - locking voltage between the control electrode and the emission system cathode, at which beam current is reduced to zero

$V_w$ - welding speed

W - the number of turns

$x$ - coordinate along the welding direction

$y$ - coordinate across the beam axis and the welding direction

$z$ - coordinate along the beam axis

$a_{cr}$ - the angle of beam convergence (divergence) at crossover

$a_{con}$ - the angle of beam convergence after the magnetic lens

$\delta_m$ - thickness of welded metal

$\theta$ – the angle of beam deflection

$\tau_{puls}$ - pulse duration

$R_{f-b}$ - feedback resistor

$G = I_p / U_{acc}^{1.5}$ – full conductivity of the emission system
INTRODUCTION

As with any method of fusion welding, the welding current value at EBW is one of the main welding mode parameters, significantly effecting the weld depth and width. Basing on long-term experience of industrial EBW application, the requirements for stability and reproducibility of set current value – not worse than ± 1%, and for beam current ripples- not more than 5% (from peak to peak) are specified in the International Standard ISO 14744-1-6 [2]. The requirement for low current ripples amplitude is caused by the intention to reduce spatter formation and weld surface formation irregularities, as well as to provide high stability of the non-through penetration depth on thick metals.

Some other essential requirements for EBW current control are not specified in regulations yet, in particular:

1. Stability of presetting the adjustable, minimum beam current value.
2. The possibility of amplitude beam current modulation both for technological purposes and for operation of the secondary emission seam tracking and visualization system in real time [3];
3. The synchronism of beam current and accelerating voltage control to minimize the breakdowns and discharges consequences in the welding gun [4].

Let us consider in details the above-mentioned requirements for beam current control.

Minimum programmable increment and beam current. The value of adjustable minimum beam current, preset by an operator, should not cause the metal surface melting. As seen in Fig.1, fine-focused electron beam with energy 60keV at current 0,6mA already leaves a fused area on the specimen surface, being inadmissible for many types of manufactured products.

Therefore, both the minimum beam current and its input increment should be limited by the value less than 0,6mA in the equipment with accelerating voltage 60…120kV.
In practice, the minimum current value less than 1mA cannot be preset in the powerful supplies type ELA [5], besides its instabilities reach 100% due to the influence of electromagnetic interferences and ground leakage capacitance currents on control circuits operation.

**Current pulse shape.** The pulse welding mode, due to which the heating effect on the workpiece can be reduced, is usually carried out at pulses duration in the range of 5...20ms. It is important that accelerating voltage stability has not be deteriorated at beam pulse modulation, as shown in Fig.2.

Fig.2. Oscillograms of pulse-modulated beam current and practically unperturbed accelerating voltage in the inverter power supply ELASM-60-6 (60kV, 6kW).
At the same time, the experiments performed by us proved that at operation of some inverter power supplies, in particular, those produced by “Technix” (France) and “Universal Voltronics” (USA), inadmissible accelerating voltage instabilities occur in the pulse mode (Fig. 3). Thus, accelerating voltage increases by 8.6% at decrease of beam current to zero and has no time to be restored during the time 6 ms of missing load [6].

Particularly strict requirements are imposed on the current pulse form for the using of the seam tracking system, when welding beam periodically (usually 3 times per second) is changed over to the workpiece surface probing mode by a fine-focused beam with low power [3].

Besides:

- in order to avoid the weld formation disturbance, the time of the welding process interruption should be minimal, moreover, this time should be reduced proportionately with the increase of welding speed. The conclusion can be made herefrom on the need to minimize the transient processes duration;

- not less than 3.5 ms is required for the formation of data frame itself, i.e. the welding area image, when probing beam current is about 5mA. Perfect, but unfortunately unachievable in reality, stability of accelerating voltage and the beam current pulse shape are shown in Fig. 4.

The main factor preventing meeting the above listed requirement is the distributed capacity of the respective high-voltage cable current-carrying conductors. To prevent development of self-oscillatory processes in the high-voltage circuit, the rate of beam current variation has to be limited, this leading to increase of the current pulse front duration.

![Fig.3. Instabilities of accelerating voltage in resonance-type inverter power source 60kV, 6kW (produced by Technix) at beam current pulse modulation [6]](image_url)
Minimization of breakdown and discharge consequences in the welding gun

The development of abnormal transient processes - breakdowns and discharges - in the welding gun’s emission system is accompanied by a sharp increase in beam current up to actuation of accelerating voltage source current protection, that causes a weld defect in the form of a crater, unfilled with liquid metal. For this reason, it’s necessary first of all to minimize the weld formation disturbance means of synchronous beam current and accelerating voltage control, and then switch off the accelerating voltage source [4].

It should be noted that many aspects of EBW equipment development are considered in the well-known monographs [5] and [7]. But the issues of beam current control have not been given much attention both in these monographs and in periodicals as well. Foreign manufacturers of EBW machines order power sources with the control systems from the relevant specialized companies, in particular, “Technix”(France), “Guth”(FRG), “Genvolt”(UK), “Universal Voltronics”(USA). The listed companies do not study their power sources performance in real EBW conditions and therefore do not provide the proper publications.

E.O. Paton Electric Welding Institute developed the power sources with the control systems and carried out the whole complex of investigations in EBW conditions using its own resources. The results of these investigations formed the basis of the leaflet, offered to the reader.
Chapter 1
Formation of welding electron beam by the emission system

1.1. Beam current control and modulation characteristics of the emission system

Fig. 5 shows the circuit diagram of the welding electron gun, including the emission, focusing and deflecting systems. The emission system comprises cathode, control electrode (Wehnelt) and anode. The minimum beam cross-section at the emission system output – crossover - is displayed by the focusing system as the focal spot close to the workpiece.

The known methods of the welding guns electron beam power regulation are as follows:
- changing the cathode temperature (for instance, in the guns type EP-25 and EP-60, developed by the National Institute of Aviation Technologies/NIAT in the 60s last century),
- changing accelerating voltage, and, finally,
- changing the control electrode negative potential of the gun’s emission system.

When controlling beam current by cathode temperature regulation, the cathode does not operate in the emission current mode, limited by space charge, and the boundary conditions along the electrons flow do not remain constant. Besides, the angle of beam divergence, crossover position and dimensions substantially change. This method of beam power regulation is not applied in the state-of-the-art power-generating units for EBW any more.

In case accelerating voltage changes, power in the beam is regulated practically without changing the crossover position, since the total conductivity \( G = \frac{I_p}{U_{acc}^{1.5}} \) of the emission system remains unchanged and, consequently, the electrical conditions along the beam boundary remain unchanged as well. However, changes in accelerating voltage require to alter focusing and deflecting currents according to the established relationships \( I_{m}^2 \sim U_{acc} \) and \( I_{defl}^2 \sim U_{acc} \) to keep the focal spot dimensions and position on the workpiece. For this reason, this method of beam power regulation is not applied in the state-of-the-art power-generating units for EBW any more.

The main way of beam power regulation, stabilization of its preset value, pulse modulation, smooth reduction at stopping of the welding process is to change the control electrode negative
potential in the emission current limit mode by a space charge. When considerable negative potential is applied to the control electrode relative to the cathode, the electric field is decelerating for electrons on the entire cathode surface. The electric field nature is shown in Fig. 6a in this case.

![Figure 6a](image6a.png)

![Figure 6b](image6b.png)

![Figure 6c](image6c.png)

Fig. 6. Nature of changes in the electric field at different control electrode potentials: the emission system is locked (a), boundary state (b), the emission system is unlocked (c) [8]

The potential profile has a “saddle” in front of the cathode. The cathode is locked, beam current is zero. If to increase the modulator potential now, the “saddle” will start to move towards the cathode, and the decelerating field strength in front of the cathode will decrease. At a certain control electrode potential value, the “saddle” point will reach the cathode surface (Fig.6b). Besides, the potential gradient in the cathode middle point is already zero, but in other cathode points the field is still decelerating. The thermal electrons already leave the cathode in a small middle area due to their own initial speeds. However, the dimensions of this area are so small and the space charge limiting effect is so high, that beam current is practically still zero in this case. With further increase in the control potential in the middle of the cathode surface, the area emerges, where the electric field becomes accelerating for electrons (Fig.6c). This area will serve as the cathode working surface. At increasing the modulator potential, the cathode working surface radius and the accelerating field strength will simultaneously increase.

The dependence of beam current upon voltage between the cathode and control voltage at constant accelerating voltage is called the emission system modulation characteristics (Fig. 7), and voltage $U_{lock}$ at which beam current becomes zero, is called locking (turnoff) voltage.
At increasing negative bias on the control electrode, the distortions introduced into beam, are minimum, if the bias action comes down to the emitting surface reduction due to the limited emission from the cathode’s edges.

The beam current control channel is covered by beam current feedback in most industrial machines for EBW. But the feedback signal can be significantly noised by parasite capacitive currents of the high-voltage transformer winding and filter capacities’ overcharging currents (see in details Chapter 4). Perhaps, this is why we believe that the beam current value is set by the non-feedback control electrode potential in the machines, produced by Techmeta. Besides, it is necessary to achieve a strictly consistent emission modulation characteristic by using a set of spacer rings, mounted under the cathode holder and providing a constant distance between the cathode and the control electrode with an accuracy of 0.02 mm.

1.2. The influence of beam current on beam position relative to the gun’s axis

The International Standard ISO 14744-6 [1] contains strict limitations of focal spot position instabilities – they should not exceed ±0.1 mm in the plane, located at a distance of 300 mm from the welding gun edge. This requirement cannot be sometimes fulfilled, and two serious troubles take place in EBW practice:

• prior to welding an operator combines low power (probing) electron beam with the butt of edges being welded, then at beam current increase up to the nominal value the focal spot can shift, particularly perpendicular to the butt plane. There is the risk of beam deviation from the butt plane, especially in its root part. Therefore, prior to welding an experienced operator provides the so-
called perforation with a stationary beam of nominal power on a run-off tab (close to the weld). If the perforation root part falls on the extension of butt plane, welding can be performed;

- change of focusing current can also shift the focal spot off the butt. Besides, since the electron beam falls on the workpiece at an angle, different from 90° in this case, the arising tangential component of the metal vapour recoil reaction impairs the symmetry of cast metal upper part. At the same time, focal spot diameter is increased and distorted, thus reducing the penetration depth.

The cause for the mentioned difficulties is explained by adjustment impairment or errors (according to the terminology of light and electron optics) of welding gun axial symmetry – due to inaccuracies of its manufacture and assembly, as well as local magnetization of the gun components and workpiece. These errors are usually eliminated by adjusted displacement of the focusing electromagnetic lens or using two deflecting systems mounted successively above it (Fig.8). Only at alignment of the axes of emission system and magnetic lens, which should be in the entire range of welding currents, the focal spot position on the workpiece surface does not change during the gun operation.

![Fig.8. Schematic of welding gun electron optical system with adjustment system: $d_{cr}$ – beam crossover diameter; $d_{f.sp}$ – focal spot diameter](image)

Welding gun emission system forms the converging electron beam, the minimum cross-section of which – the crossover – is reflected using a magnetic focusing lens in the workpiece plane as the focal spot. Term «adjustment» means achievement of gun axial symmetry, i.e. symmetry of electric and magnetic field rotation.

Adjustment errors (in other words, first order aberrations or axial astigmatism) are manifested, first of all, in the fact that electron optical system, even at a small angle of beam convergence/divergence, does not create the crossover point image. Central beam electrons, the initial speeds of which lie in different meridional planes, experience different action of the refracting medium, and do not cross the axis in one point. The crossover central point is reflected in the workpiece plane in the form of a dash, transverse dimensions of the focal spot grow, and its position in the workpiece plane is disturbed.
A lot of publications are devoted to the problems of impairment of axial symmetry of low-current electron optical systems of electron microscopes, TV instruments, electron accelerators (see, for instance, [9]). Errors of axial symmetry of the welding gun electron-optical system, forming the electron beam in a wide range of powers from 1 up to 100kW, the mechanism of their influence on welds formation, were not discussed in the past.

Unlike the glass lens, the magnetic lens not only rotates the image (focal spot) relative to the crossover through 180°, but additionally rotates it through certain angle $\Psi$. Therefore, at focusing the electron beam moves in a plane, rotating around the magnetic axis, i.e. along a spiral trajectory [10].

If the electron beam is focused by the system with axial symmetry, then the existing turn does not affect the dimensions and position of the spot. But, if the crossover is shifted relative to the magnetic lens axis due to axial symmetry errors, it is exactly the beam rotation that influences the focal spot position (Fig.9).

Angle of rotation $\Psi$ depends on magnetic field intensity in the focusing lens, its configuration $H(z)$ and accelerating voltage $U_{acc}$:

$$\Psi \approx \frac{0,148}{\sqrt{U_{acc} [V]}} \int H(z) \, dz \quad \text{.................. (1)}$$

For instance, for magnetic lens with a number of turns $N = 1500$ at magnetizing current $I_m = 0,66$ A and accelerating voltage 60 kV, the beam rotation value, measured in degrees,

$$\Psi = 10,7 \frac{NI_m[A]}{\sqrt{U_{acc} [V]}} \approx 43^0 \quad \text{.................. (2)}$$

Variation of focusing current or its direction leads to changes in the angle of rotation $\Psi$ and radial shifting of the focal spot on the workpiece, respectively. The value of this shifting is maximum
in case of changes in focusing current direction and is also equal to 43°, but in the opposite direction. Thus, at switching of magnetization current polarity, the shift between two melting points will be equal to almost 90°.

The focal spot position impairment at changes in focusing current is manifested to the maximum at parallel shifting of the axes of the welding gun emission and focusing system. In Fig. 10 axis $A-A'$ of the emission system is shifted a distance $\delta$ relative to axis $O-O'$ of magnetic lens and crosses the workpiece plane in point $A$, but not in point $O$. The beam crossover is reflected by the focusing lens in points $F_1$ or $F_2$ (depending on magnetic field direction), laying on the circumference, which is circumscribed around the magnetic lens axis, besides, circumference radius depends on the lens magnification and $\delta$ value.

![Fig.10. Schematic of influence of parallel shifting of gun emission system and magnetic lens axes on focal spot position in workpiece plane (scale of gun reflection and beam trajectories is not observed to ensure good visual presentation)](image)

At welding the magnetic lens power source polarity is certainly not switched, but focusing current can be programmed during the process, thus leading to the focal spot shifting along the circumference, on which is falls. At cosmetic smoothing of the weld by of the focal spot deepening, for instance, by 100mm, that is achieved at lowering focal lens current by 0.05A, angle $\Psi$, according to expression (2), will be decreased by 3°, and at circumference radius of 5mm beam shifting will exceed 0.1mm and will effect both the alignment accuracy, and cast zone formation (Fig. 11).
It should be noted that according to Fig. 10 and expression (2), in the absence of parallel shifting of the emission system and focusing lens axes, changes in beam current does not effect the focal spot position in the workpiece plane.

Fig.12 represents a situation, arising at tilting of the gun emission system axis relative to the magnetic lens axis. The emission system $A-A'$ axis is inclined at angle $\theta$ relative to the magnetic lens axis and crosses the workpiece plane in point $A$, and not in point $O$. But since at small beam current 1—5mA (i.e. in probing mode), the beam minimal cross-section – crossover – is located close to the cathode in point $I$ practically on the magnetic lens axis, the crossover is reflected in the workpiece plane in point $O$, laying in the butt plane. Now, at nominal beam current, its crossover 2 is significantly – by tens of millimetres – displaced from the previous position and turns out to be shifted at distance $\Delta$ relative to the magnetic lens axis. The focusing coil reflects the crossover as the focal spot in point $F$ of the workpiece, where the electron beam will fall, while rotating around axis $O-O'$. It can be seen that at welding the focal spot will be shifted relatively to the butt plane. At the same time, the focal spot diameter is increased and distorted, thus lowering the penetration depth.
Of course, in practice, shifting and tilting of the emission system axis relative to the focusing coil may occur simultaneously, that makes the gun adjustment more complicated.

Prior to using the gun electromagnetic adjustment system at detection of the focal spot position instability, it is recommended to determine the gun part, responsible for this instability, and try to eliminate it by mechanical processing of parts and their demagnetization. The following sequence of actions shall be most effective [11]:

1. Checking the axial symmetry of electrodes of the emission system. Available shifting of ion crater relative to the cathode centre (Fig.13) indicates unambiguously of impairment of emission system electrodes axial symmetry and the necessity of their additional machining.

![Fig.13. Shifting of ion crater relative to cathode center](image)

2. Checking the alignment of the geometrical and electron optical axes of the emission system:
   • using beam in the probe mode obtain two melted spots on the plate by switching the focusing coil current direction;
   • turn the emission system case relative to the initial position at angle 90—180°, and again obtain two melted spots on the plate. If the case rotation did not influence the distance between the melted spots and their spatial orientation, then it is indicative of the alignment of the geometrical and electron-optical axes of the emission system.

3. Checking the alignment of the geometrical and magnetic axes of the focusing system:
   • use beam to obtain in the probe mode two melted spots on a plate by switching the focusing coil current direction;
   • turn the focusing lens case relative to the initial position at angle 90—180° and again obtain two melted spots on the plate for two directions of the focusing lens current. If rotation of the focusing lens case did not influence the distance between the melted spots and their spatial orientation, this is indicative of the alignment of the geometrical and magnetic axes of the focusing lens.

4. If after fulfilment of the above mentioned operations it was not possible to eliminate shifting of the focal spot at changing beam current or focusing current, the axes of the emission and magnetic systems should be aligned. In case of parallel shifting of the above mentioned axes, as shown in Fig.10, changes in beam current will not effect the focal spot position. The welding beam asymmetry will only cause shifting and asymmetry of the cast zone at the changing of focusing current.

Now, if the emission system axis is inclined relative to the magnetic axis, then, as shown in Fig.12, changes in the beam current value will cause a noticeable shifting of the focal spot.
At this final stage the alignment of axes of the emission and focusing systems is performed using a double electromagnetic deflecting system (Fig.14). Application of one out of two algorithms of the alignment process is possible: either step-by-step approximation of two melted spots on the workpiece, made at nominal and minimum beam current, or displacement of any of these melted spots to the reference point $O$ of the magnetic lens axis. The result of this operation is the coincidence of the probing beam trajectory with the middle of the cast zone, made at nominal beam current in two mutually perpendicular planes (Fig.15).

![Fig.14. Principle of straightening of axes of emission system and focusing lens using two deflecting systems](image1)

![Fig.15. Accurate alignment of probing beam trajectory with the middle of welds made in orthogonal directions](image2)
Chapter 2

Transient processes in high-voltage circuits at welding current pulse modulation and non-steady processes in the load

At electron beam current control of changes in the control electrode potential of the emission system two control voltage formation circuits are applied (Fig.16):

- using an independent voltage source, besides the accelerating voltage source minus is connected to the emission system cathode;
- using automatic bias [12], when the grid-controlled tube is connected to the emission system cathode circuit. In this case the accelerating voltage source minus is connected to the emission system control electrode.

Fig.16. Simplified diagrams of electron beam current control using self-sufficient voltage source (a) and self-biased configuration employing an automatic bias (b); 1 - anode, 2 - control electrode, 3 - cathode, 4 - HV cable, 5 - control voltage supply, 6 - control tube; R1 - feedback resistor in beam current stabilization circuit; R2, R3 – resistance of HV divider arms; $U_{acc}$ - accelerating voltage supply; arrows show the main location of the spark discharge of the accelerating gap; for other designation see the text.

In the steady-state operation mode of the emission system electron beam current and its modulation are successfully controlled, when using any above mentioned schematics. However, in practice, of an independent voltage source application may be observed considerable disturbances of welds formation in sheet metals, arising after spark breakdowns in the emission system, which are followed by a discharge of the high-voltage circuit capacitances in fractions of a microsecond [13]. Already in the initial stage of breakdown, the control electrode negative potential is de-energized and the emission system is thereafter turns out to be completely unlocked, as a result of this all current, emitted by the cathode, reaches the workpiece.
As breakdown develops, the control electrode potential may rise practically to the anode potential, until a breakdown occurs between the control electrode and the cathode, and the beam current on workpiece may exceed many times as large the preset value and the workpiece burnout shall be inevitable. Besides, the welding process is not interrupted, since the safety device does not disconnect the power source so quickly, but the crater is formed in the weld (Fig. 17) or the workpiece burnout may occur.

When self-biased configuration employing an automatic bias is used, such defects are absent and this fact needs to be cleared up.

The studies showed that the value of beam energy, necessary for the formation of such defect, is approximately 300 J. For this reason, the formation of defect can not be explained only by release of the power source stored energy, because its value is less than 1 J/kW. At the same time, when welding thick metals such malfunction practically does not effect the weld formation.

Spark breakdown of vacuum insulation practically always occurs in accelerating gap anode - control electrode, besides discharge current is maintained by discharge of the distributed cable capacity C2 and the total filter capacity C3, as well as the distributed capacities of the accelerating voltage source $U_{\text{acc}}$. During spark discharge of the emission system, the control electrode turns out to be connected practically short to the ground. It is noteworthy that in case of using self-sufficient control voltage source (Fig. 16,a), discharge of the capacity C3 will take place via the distributed capacity C1 of the cable and the filter C4 capacity of the control voltage source, but not via the control voltage source itself, as its internal resistance is rather high.

At operation with automatic bias (Fig. 16,b) discharge current of capacity C3 does not run in the control voltage formation circuits, which reduces the risk of their damage. After discharge of capacities, spark discharge ceases, the vacuum insulation restored, the high-voltage circuit capacities are charged during the time, depending upon the source internal resistance, the capacities themselves and the current-carrying circuit parameters.

How the beam current potential difference between the control electrode and the cathode change during discharge and after it still remains unknown. It is rather difficult to directly record the
fast transient processes during the spark breakdown of the emission system with electronic devices, as the studied circuits are immersed into transformer oil and are at a high potential. In addition, at the measuring circuits themselves are exposed to powerful electromagnetic interferences, essentially distorting the pattern of the recorded processes. Therefore, we have applied [14] computer simulation of high-voltage circuits of the beam current control using one of the known programs OrCAD PCB Designer with Pspice (developed by “Cadence Design Systems”).

At simulation of the diagrams, we assumed that in both cases similar high-voltage cables, emission systems, as well as 60 kV accelerating voltage sources with power 30 kW and internal resistance 5 kOhm were used. Modulation characteristics of the emission systems are given in Fig.7. They can be used to preset the control voltage and internal resistance values of the emission system, corresponding to the selected value of steady-state beam current. The high-voltage cable 50 m long has three current-conducting wires for powering the cathode and its heater (spiral). The wires are enclosed into braiding, which is connected to gun control electrode. Distributed capacitance between the wires is 50pF/m, and 150pF/m - between the braiding and external grounded shield. Distributed inductance of the braiding and each of the wires is equal to 1.5uH/m, internal resistance of the control voltage source is 30kOhm.

Fig.18 shows the graphic windows of the computer mathematical simulator of high-voltage circuits of beam current control with an independent control voltage source (Fig.18,a) and automatic bias (Fig.18,b) at steady-state beam current of 60mA and other preset parameters. Electron conduction of the welding gun corresponding to current 60mA is emulated by the resistor with resistance 1mOhm, connected into the circuit between the ground and current lead to the cathode. Current lead to the control electrode is connected to the contactor emulator, closing the control electrode to the ground for 0.5us with delay 100us after initiation of the emulation process. Presentation of the high-voltage cable as one pair of concentrated elements, namely capacitance and inductance, did not fully reveal the resonating circuit nature. Therefore, the cable is considered as a long line and is simulated by four links, besides further increase of the number of links does not change the nature of transient processes, which are revealed by emulation.
Fig. 19 gives time changes of the control electrode and cathode potentials after a spark breakdown of the emission system with independent control voltage source. It can be seen that prior to breakdown the emission system forms electrons beam with current 60mA, and control voltage is 1.6 kV (Fig. 19,c). After breakdown the potentials of both the control electrode and the cathode become equal to that of the ground (Fig. 19,b). After that the cathode potential starts changing immediately, and that of the control electrode starts changing with the frequency of about 1 MHz and amplitude of +60…-160kV with a delay for the time of available short-circuit (0.5us) as a result of attenuated self-excited oscillations. Self-excited oscillations cease in approximately 10us; the total time of the circuit steady state recovery is about 10ms. During this time, the control electrode is under positive potential for 3 ms relative to the cathode (section A in Fig.19,c), i.e. the emission system operates in the cathode complete current take-off mode.

During this time beam energy of up to 200J can be released by the workpiece. From the time of equalizing the control electrode and cathode potentials and up to establishment of the initial stationary potential difference -1.6kV (section B in Fig.19,c) beam energy not less than 100J is additionally released. In total energy up to 300J will be released by the workpiece during the period of the high-voltage circuit steady-state condition recovery, which explains the formation of a crater in the weld (see Fig. 17).
Fig. 19. Change of potentials $U$ of the control electrode (solid curves) and the cathode (dot–dash lines) after breakdown of the emission system with self-sufficient source of control voltage: a – general pattern picture, b,c – spread scales of time and potentials, respectively.
At breakdown of the vacuum gap of the emission system, operating in the mode of automatic bias, the nature of transient processes differs (Fig.20) significantly from the one considered above:

- the control electrode potential remains negative relative to the cathode potential, that excludes the workpiece damage by excessive current;
- the time of the high-voltage circuit steady-state condition recovery is just 1 ms, i.e. is by an order of magnitude lower;
- amplitude of overvoltages is smaller by almost 25%, which somewhat lowers the risk of damage of the high-voltage circuit elements.

The results of computer simulation of high-voltage circuits of welding current control agree well with the experience of their practical application and provide strong evidence in favor of beam current control by automatic bias.
Chapter 3

Peculiarities of beam current control channel

In modern EBW machines, the beam current control channel is integrated with the common welding process computer control system based on the CNC system, realizing multi-axial welding movements [15]. Beam current is one of the virtual CNC system axes and its instantaneous value is strictly synchronized with movements. The type and location of the relevant interface CNC module impose restrictions on the structure and characteristics of the beam current control channel as a whole.

Fig. 21 shows two versions of beam current control, using the following similar decisions:
- control signal, setting the required beam current, is a digital code formed by CNC (1),
- decoupling of the control channel parts at different potentials is performed using fiber-optic pairs 2, located on air - transformer oil boundary in a high-voltage tank of the accelerating voltage source,
- control voltage of the welding gun emission system is formed by the beam current stabilizer 4, and the beam current feedback signal is read from the resistor \( R_{fb} \),
- the maximum value of the negative potential of the emission system control electrode is set by the resistors R1 and R2.

Differences in the circuits of beam current control consist in the first case (Fig. 21a) in application of a standard digital-analog converter (DAC) of Sinumerik 840D system, and in the second case (Fig. 21, b) — incorporation of the converter with digital output (DO), developed by the Paton Electric Welding Institute, into this system.

In the circuit, shown in Figure 21a, the digital value of preset beam current:
- is converted by DAC into analog signal,
- then is converted into frequency signal (since Sinumerik 840D system does not contain the modules, capable of direct code-to-frequency conversion),
- is transmitted through a fiber - optic communication line,
- then is converted from the frequency (using F—V converter) back into analog signal,
- is filtered through the low-pass filter (LPF) and is applied to the beam current stabilizer.

In the circuit shown in Figure 21b, the digital value of the preset beam current is converted into analog signal already in the high-voltage tank, directly before the front of the beam current stabilizer inlet. The microprocessor 3 with its own DAC is used for this purpose.
If not to consider the characteristics of the beam current stabilizer (since this unit is similar for both circuits), it can be seen that in the first case at least three links affecting the reliability of control signal transmission, are available:

Fig.21. Block-diagram of analog (a) and digital (b) control of beam current: 1 - CNC; 2 - fiber-optic decoupling from high voltage; 3 - microprocessor (MP); 4 - beam current stabilizer (DAC — digital-analog converter; ADC — analog-digital converter; D/O — digital interface module; V—F -voltage—frequency converter; LPF— low-frequency filter; $U_{acc}$— minus of accelerating voltage source; $R_{fb}$ — resistor of beam current transducer)
• analog communication channel between the hardware cabinet accommodating the CNC system and the accelerating voltage source, up to 10 m long is exposed to the influence of electromagnetic fields;
• “voltage—frequency” and “frequency—voltage” converters (≤ 0.1 % non-linearity at frequency of 1 MHz, temperature instability of ± 0.015 %/deg at the frequency of 100 kHz, setting time is 11us at frequency 100 kHz);
• the low-pass filter.

Although temperature instabilities of “voltage—frequency” and “frequency—voltage” converters exceed the similar DAC parameters, nonetheless, they do not go beyond the maximum admissible values, effecting the welding current parameters. The analog communication channel is the link, being the most susceptible to electromagnetic noise influence. Therefore, experimental studies [16] showed the need for application of the low-pass filter with the maximum setting time not less than 0.4 ms, that essentially limits both the dynamic capabilities of the beam current control channel, and the stability of the low beam currents (see table below). The negative influence of the low-pass filter cannot be compensated by application of the known techniques.

In the digital channel of beam current control only one link, which effects the reliability of control signal transmission — i.e. DAC, incorporated into the microprocessor (see Fig.21,b) is available. The microprocessor performs only linear operations, and the constants stored in its memory, are independent on time (time spent by the microprocessor for performance of any operations with the input signal is negligibly short).

The microprocessor has the following functions:
• conversion of the digital setting code into analog signal of the beam current stabilizer control using DAC1;
• implementation of the second adjustment contour in the low current mode, using DAC2;
• forcing the process of the required beam current adjustment.

Analog signal of the DAC1 converter is applied to the main input of the beam current stabilizer and provides the current setting discreteness of 250uA with performance accuracy of ±125uA for maximum current 1A. If setting was realized by the beam current stabilizer without errors, such accuracy would be quite reasonable for most welding purposes. However, the stabilizer, despite the fact that it is covered by the analog feedback loop, introduces its own errors and instabilities, dependent on temperature and time, particularly at the initial section of its characteristic. For their elimination, the second feedback loop, which is realized in the digital form as follows, is included into the control system.
The resistor \( R_{fb} \) feedback voltage in the current stabilizer tube cathode is measured by DAC of the microprocessor, designed so that the bit capacity of conversion in the low signal range is equal to 16, i.e. the discreteness is equal to several tens of microamperes. The code of the beam current value measured on the feedback resistor, is compared to the setting code, received by the microprocessor DAC, and then the corrective action on the control signal is taken, which corresponds to the measurement channel accuracy. Besides, summing up of the main and correction setting signals allows, if required, switching to finer setting discreteness, than can be provided by the main DAC1 converter. Moreover, the latter generates the control signal in a coarse grid, and DAC2 corrects it to the nearest fine grid value.

The microprocessor application allowed improving beam current controllability due to the broad capabilities of the pre-distortion method [17], when in order to control the knowingly “slow” cascade, pre-distortions compensating the insufficient cascade dynamics, are introduced into the control signal to obtain acceptable dynamic characteristics.

In the case under consideration:
- in order to cut off beam current, the current stabilizer is switched off by a special discrete pulse and a higher negative potential is applied to the electron tube control electrode than the one required for complete blocking of the emission system;
- short time of going out from the repeated blocking mode to the required current level is achieved by restoring the current stabilization mode with simultaneous feeding to the stabilizer input of a pulse, accelerating the process of setting the required current level.

Let us compare the oscillograms, characterizing operation of the channels under consideration at current sudden change (Fig. 22 a, b).

It can be seen in case of analog control (Fig. 22 a) that:
- probing current pulse in fact does not have a flat top. As a result, considerable instability of probing current affects the weld zone display accuracy;
- by the time of probing process start-up and its interruption, welding current does not drop to the zero value, corresponding to the scale 2. This impedes the timely beam scanning generator start-up and its interruption. Therefore, it is difficult to avoid the workpiece surface fusion during the rise \((\sim 0.5 \text{ ms})\) and drop \((\sim 0.1 \text{ ms})\) of line sweep amplitude;
- it fails to reduce duration of the welding process interruption less than 6 ms.

In case of digital control:
- probing current pulse has a flat top, thereby errors, relating to probing current instabilities, are missing at display of the weld zone;
- by the time of probing process start-up and its interruption, welding current drops to the zero value, corresponding to the scale 2. It is at the moments of beam current zero values that the beam
scanning generator start-up or interruption occurs, that excludes the workpiece surface fusion during the rise and drop of line sweep amplitude;
- duration of the welding process interruption is reduced to 5 ms;

It is important to note, for the case with the digital microprocessor channel, considerable single-order reduction of beam current instabilities in the range of low adjusting currents – 0.1...1 mA, as well as fourfold increase of beam current control speed as compared to the case of analog control.

![Oscillograms characterizing the operation of analog (a) and microprocessor(b) control of beam current $I_b$ at operation of the system of automatic guidance of the beam to the butt in real time mode. For case a: 1— synchronizing pulse; 2— scale of zero current 3 — beam frame scan current; 4— beam line scan current; and for case b: 1— beam line scan current; 2— scale of zero current; 3— scale of zero current setting; 4— synchronizing pulse](image)

The table below summarizes the major parameters of electron beam control, when using the considered channels [18].
Table. Comparison of characteristics of analog and microprocessor welding beam current control

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Analog channel</th>
<th>Digital channel with pre-distortion function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linearity, %</td>
<td>0,2</td>
<td>0,05</td>
</tr>
<tr>
<td>Temperature coefficient, %/degrees</td>
<td>0,07</td>
<td>0,0025</td>
</tr>
<tr>
<td>Current setting resolution, uA</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Minimum beam current, uA</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Beam current instabilities in the following ranges, %</td>
<td>±100</td>
<td>±10</td>
</tr>
<tr>
<td>—0,1...1mA</td>
<td>±1</td>
<td>±1</td>
</tr>
<tr>
<td>—1...1000mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum rate of beam current adjustment, mA/ms</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>Duration of interruption of welding process at tracking the weld, ms</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig.23 gives an overall view of the welding gun’s beam current and cathode heating control unit. High-frequency source mains conversion allowed to significantly decreasing the mass and dimensions of this unit.

Fig. 23. Overall view of welding gun’s beam current and cathode heating control unit, disposed under high potential in transformer oil.
Chapter 4

Beam current ripples

The most reliable measurements of electron beam current are performed using the Faraday cup, when electron beam is directed into a deep hole, drilled in the massive target, grounded via the measuring resistor. Knowing the resistor voltage drop value and its resistance, the beam current value can be obtained [2]. But directly at EBW it’s impossible to use this method of beam current measurement for stabilization circuit feedback closing and beam current control. The peculiarity of the vast majority of accelerating voltage sources to power electron welding guns is the application of thermally-stable resistive current sensors, connected to the current flow circuit. Voltage drop on the thermally stable resistor is used as a feedback beam current control channel signal. The sensor position substantially influences the friendly signal-to-noise ratio (S/N ratio).

4.1. Influence of sensor position on the beam current ripples

The simplest step is to connect the measuring resistor between the ground and ”plus” terminal of the accelerating voltage source. In this case no problems of the control circuits decoupling from a high potential are encountered. But numerous attempts to mount the resistive sensor in the “plus” circuit of the conventional power sources, generating rectified voltage directly from the mains with frequency \( f = 50 \text{Hz} \) without frequency transformation, failed, as the feedback signal is quite noisy, because of parasitic capacitive currents of the high-voltage transformer windings and currents of filter capacities recharging, that flow in this circuit. Fig.24,a gives the current oscillogram in the “plus” circuit of the source ELA-60, the high-voltage rectifier of which is assembled by the “Larionov star-triangle” connection diagram. Up to 30—50 % of the total current value, particularly in the range of low current (from one to several percent of rated current) make up low-frequency \((f = 50—600 \text{Hz})\) variable components, for which the results of Fourier analysis are given in Fig.24, b. Suppression of these noises requires application of filters with cut-off frequency \(f_{\text{cutoff}} < 10 \text{ Hz} \). For first order filters, in which \(f_{\text{cutoff}} = (2\pi/RC)^{-1} \), the time constant will be not less than 100 ms [19], respectively. As a result, it becomes impossible to achieve the required fast beam current control for welding with beam current pulse modulation, or apply secondary-electron systems of tracking the welded edges butt in real time, when it is necessary to set and stabilize beam current during 5 ms pulse. When the resistive current sensor is mounted in the high-voltage circuit of these power sources, the feedback signal has a low noise level, the is no need in its filtration, and fast beam current control becomes possible. The tubes are used as bias adjustable resistance and beam current is controlled by changing...
their conductivity. Such a solution, however, makes the equipment more complicated and less reliable [14].

In inverter power supplies with high-frequency transformation of mains voltage, location of current feedback resistor in the “plus” circuit of the power source is applicable due to the fact that the current variable component frequencies lie mainly in the high frequency range \(f = 20—30\text{kHz}\) (Fig. 25a, b). Filters with cut-off frequency 2—3kHz can be applied for filtering these components, that corresponds to the time constant \(t < 0.2\text{ms}\).

![Fig.24. Oscillogram of voltage drop \(U_R\) on resistive current sensor with resistance \(R = 10\text{ Ohm}\) mounted in the plus circuit of accelerating voltage source ELA-60 (a), and spectrum of its variable component at load current 50mA (b): \(A\) – voltage amplitude](image)

![Fig.25. Oscillogram of voltage drop \(U_R\) across resistor with resistance \(R = 10\text{ Ohm}\) of current feedback in the plus circuit of inverter source of accelerating voltage ELASM-120/18 (a), and spectrum of its variable component at 50mA load current (b)](image)

Thus, the current feedback resistor in electron beam sources of accelerating voltage operating at industrial frequency should be mounted in the rectifier high voltage circuit, and in inverter power sources with high-frequency transformation of mains voltage, it is rational to place it in the rectifier plus circuit.
4.2. Influence of bombardment current ripples on beam current ripples

Despite the high-usage pulse modulation of the electron beam current with a depth of 100%, it is important that in the steady-state operation mode the peak-to-peak amplitude of the beam current ripples be no more than 5% (ripples factor 0.05), which is specified by international standard EN ISO 14744-1 [2]. As mentioned above, this requirement is caused, in particular, by the need to ensure a high consistency of the non-through penetration depth in heavy metal sections.

In the majority of cases the high-power (60—120kW) welding electron guns use massive cathodes heated by electron bombardment, and the most efficient control of the beam current is provided by automatic bias [12], where an electronic valve with grid control is connected to the emission system cathode circuit. In this case, minus of the accelerating voltage source is connected to the modulator (control electrode) of the emission system of the gun.

In the former USSR the guns of this type were equipped with coaxial high-voltage four-core cables of the 4KVEL-60 or 4KVEL-165 grades, and there were no problems with the welding current ripples. But now, because the coaxial cables with the required electric strength between the cores are no longer produced, the use is made of the four separate cables (Techmeta, France) or multi-core cables (E.O. Paton Electric Welding Institute). With these cables it is necessary to thoroughly filter the cathode bombardment current to avoid ripples of the welding current, which involves some difficulties associated with placement and reliability of electronic elements at a high potential in the oil bath. The bombardment current usually amounts to 100mA at voltage of 1.5—5.0kV. When changing from mains power source to source with frequency of 20—50kHz, the effect the cathode bombardment current ripples becomes much more pronounced. Thus, under other equal conditions, the beam current ripples factor using the bombardment current source with ripples frequency of

Fig.26. High-voltage cables used in welding guns with cathodes heated by electron bombardment and their parasitic capacitances $C_p$: a – coaxial cable, $C_p(1—2) = 300$, $C_p(2—3) = 400$, $C_p(3—4) = 500$, $C_p(4—5) = 100$ pF/m; b – four separate single-core cables, $C_p = 70$ pF/m; c – multi-core cable with conductors in current-conducting screen 4 used as a current conductor to the modulator, $C_p(1—2) = 150$, $C_p(2—3) = 70$, $C_p(1, 2—4) = 210$, $C_p(3—4) = 70$, $C_p(4—5) = 130$ pF/m; 1, 2 – current conductors to heater spiral; 3 – current conductor to cathode; 5 – external grounded screen
100Hz is approximately 30 times lower compared to the bombardment current source with ripples frequency of 20 kHz [20].

The final causes of ripples of the welding electron beam current in the guns considered may be ripples of the accelerating voltage and potential of the modulator (control electrode) of the emission system. As according to the requirements of international standard EN ISO 14744-1 the mean level of the accelerating voltage ripples should not exceed 2 % (in practice it is lower by an order of magnitude), allowing for dependence $I_b \sim U_{acc}^{3/2}$ the value of the beam current ripples for the above reasons should be not higher than 3 %. The reason of powerful beam current ripples should be sought in ripples of the control electrode potential of the welding gun emission system.

The high-voltage cables under investigation are shown in Fig.26. When changing the coaxial cable by other types, the emergence of beam current ripples, which disappear after a sudden interruption of the cathode bombardment current, is observed (Fig. 27).

![Fig. 27. Oscillogram of the beam current ripples (a) (time axis scale – one cell = 10 µs) and its termination (b) (one cell = 1 s) from the time point of shutoff of the bombardment current when using the multi-core cable. Frequency and ripples factor 50 kHz and 0.28, respectively; time point of shutoff of the bombardment current is marked by an arrow; beam current 12.5mA; bombardment current 60 mA; bombardment voltage 1.5kV; oscillograph Tektronix TDS-2002](image)

As the cathode cools down, beam current gradually falls to zero without any ripples. This result explicitly confirms that beam current ripples are caused by the cathode bombardment current ripples, but it doesn’t give a clearer insight into the mechanism and quantitative evaluations of this influence.
For this reason computer mathematical simulation of the beam current control circuits was used for three types of the high-voltage cables. The preset length of each cable is 10 m. Graphic windows of the computer mathematical simulator [21] are shown in Fig. 28.

Fig.28. Graphic windows of the computer mathematical simulator of beam current control circuits for coaxial cable (a), four separate cables (b) and multi-core cable (c): VI – heat source for spiral; V2 – source of direct bombardment voltage; V3 – source of alternating voltage; V4 – source of bias voltage; V5 – stabilised source of accelerating voltage; X5 – model of 60 kV, 60 kW welding gun; X6 – simplified model of tetrode GMI-27

They are made so that it could be possible to reveal quantitative relationships and main ways of flowing of an alternating component of the cathode bombardment current via the cable parasitic capacitances. The bombardment voltage source is presented here in the form of two series-connected sources: direct voltage source V2 = 1500 V and alternating voltage source V3 = 1.5—150 V with frequency ranging from 50 Hz to 50 kHz, which is used to set the ripples factor values within the range of interest, i.e. 0.005—0.1. The vacuum diode (heater cathode) is represented by the resistor R2 = 20 kOhm = \( U_{\text{bomb}}/I_{\text{bomb}} = 1500 \text{ V}/0.075 \text{ A} \), which is justified by the given load constancy. Models of the welding gun and valve GMI-27 were made on the basis of study [22]. Model X5 of the welding gun ELA-60-60 complies with its modulation

Fig.29. Certificate anode characteristic of tube GMI-27
characteristic (Fig.7), and the tube model X6 – with the anode characteristic of the electronic tube GMI-27 (Fig.29).

In case of using the coaxial cable (see Fig.26, a) the alternating component of bombardment current is closed by the filament-cathode circuit and parasitic capacitance C2, thus, exerting no effect on the cathode—modulator potential difference and, hence, beam current ripples. Therefore, in this case there is no need to place the ripples eliminating filter(smoothing filter) at output of the cathode bombardment current source. It is enough just to rectify bombardment current, as at frequency of 20—50 kHz the losses in the cable are inadmissibly high. In case of four separate cables (see Fig.26, b) the alternating component of the cathode bombardment current is closed both by the filament—cathode circuit and by the accelerating voltage source—ground—parasitic capacitances C1 and C2 circuit marked by the dashed line, where alternating voltage drop is formed at the tube X6 and resistor R5 connected in parallel. The latter causes the corresponding beam current ripples. When using the multi-core cable (see Fig. 26, c), the alternating component of the cathode bombardment current also causes alternating voltage drop at the electronic tube X6 and resistor R5, as there is the circuit of closing the alternating component of the cathode bombardment current via parasitic capacitances C2—C4.

Fig. 30, a, b show the results of computer simulation of the beam current effect on the amplitude of control voltage and beam current ripples for the same cables at three different bombardment current ripple factors. The character of dependencies and, hence, the mechanism of emergence of beam current ripples are identical for both types of the cables, although when using four separate cables the ripples are a bit lower.

Based on the simulation results, the effect of bombardment current ripples increases with decrease of beam current, and at beam current of 1mA and the cathode bombardment current ripples of 10 % the amplitude of beam current ripples with frequency of 20kHz approximates to 100 %, which makes functioning of the secondary-electron observation and welded edge butt tracking system impossible. Based on these results it appears that in order to decrease beam current ripples factor to 0.05 (the maximum permissible value specified by international standard EN ISO 14744-1) it is necessary to limit the cathode bombardment ripples factor, formed by the power source at frequency of 20kHz, to the same value. Switching an extra capacitance to the circuit between the cathode and modulator effectively decreases the beam current ripple amplitude, although it deteriorates, accordingly, the dynamic characteristics of the beam current control system.
Fig. 30. Dependence of the control voltage ripples amplitude \((a)\) and beam current ripples factor \((b)\) on the beam current when using four separate cables (dashed lines) and multi-core cable (solid lines); bombardment current ripples factor 0.1 (1), 0.05 (2) and 0.005 (3); cathode bombardment current ripples frequency 20kHz.
5.1. Transient processes restriction in the power sources

Development of abnormal non-stationary processes in the welding gun, to which electric discharges relate due to vacuum insulation impairment, can result not only in violation of the weld formation but also cause damage of a number of the power unit assemblies, such as the high-voltage insulator of the welding gun and the high-voltage cable (Fig. 31), as well as the limiting resistor. Since the mentioned assemblies can withstand test voltage, twice exceeding the operating voltage without fracture, available overvoltages at least twice exceeding operating voltage can be assumed [23].

Fig. 31. High-voltage insulator of high alumina ceramics (a) and high-voltage cable (b), withstood the test voltage of 120 kV but destroyed in the process of operation of standard power unit ELA-60 (rated voltage of 60 kV)

Overvoltages were revealed after discharge in welding gun as early as at the beginning application of EBW, but measuring by instruments of rapidly running processes under high potential relatively to the earth is extremely complicated [24,25]. It partially explains the missing publications on the problems of overvoltages prevention after discharge in the welding gun. They managed experimentally to fix only current overloads of accelerating voltage sources.
Using the control electron tube as a linear element prevents intensive current surges in the power source after discharge in welding gun. However, it was stated that, for example, in equipment with accelerating voltage of 60kV after discharge in the gun the control tube voltage increases up to 130kV, which may cause almost simultaneously the discharge in control tube. For this emergency case the source of accelerating voltage should be equipped, besides the maximum protection, with an additional protective system. The limiting resistors, connected in series to load, are frequently used for this purpose. The resistor resistance value is limited by power, dissipated in it, and minimizing of the source load characteristic. Therefore, for instance, it is offered in the work [26] to use the high-voltage inductance, shunted by the reverse biased diode or just by the resistor, in series with the high-voltage power source output as a tool of its dynamic protection. Unfortunately, overvoltages in the source—high-voltage cable—insulator system were not considered here.

The limiting resistors can be designed both as bulk and wire-wounded. The latter are characterized by pronounced self-inductance, which reduces the power source current rise speed during discharge, but causes the oscillatory process in the high-voltage cable and resistor itself. The optimum relationship between the resistance and self-inductance values was not formerly discussed as well. In order to choose the optimal parameters of overvoltage protection, the results of non-stationary and emergency situations simulation in the accelerating voltage source-high-voltage cable-welding gun system are considered below.

At simulation of transition processes after discharge in the welding gun, a few simplifying assumptions can be made for the standard power unit ELA-60 (Fig. 32).

Fig.32. Simplified schematic diagram of standard power unit ELA-60 with elements for simulation of transition processes (for explanations see the text)
In the simulation scheme (Fig.33) the gun X1 itself and high voltage cable, presented by an electric link with concentrated capacitance, inductance and resistance, are excluded. Some errors of such presentation affects only the high-frequency components of the transition process.

Since it has been established that the load current value does not influence the characteristics of transition processes, emerging at discharge in the gun, load current was preset by the arbitrary value of 300mA. The accelerating voltage source is presented by the voltage source V1 with the diode D1. Capacitors C3 and C4 take into account for all capacitances relatively to the earth, connected to positive and negative terminals of the source. Resistor R4 = 60kOhm, simulating the control electron tube X2 in the mode of 300mA current flow, is connected in series to the accelerating voltage source V1 in its plus circuit. Discharges in the welding gun and tube are simulated by the switches S1 and S2, respectively, which are controlled by the pulse voltage sources V2 and V3. Resistance of breakdown simulator S1 contacts in open state is 200kOhm, which corresponds to flowing of stationary current 300mA, resistance of the closed contact S1 at discharge simulation is 0.01Ohm. Resistance of contacts of the switch S2 in open state is 100MOhm, and in closed state is 0.01Ohm. Short-circuit duration is preset by a longer time (5µs), which corresponds to two discharge stages:
breakdown and spark [27]. The limiting resistor R2 with its own inductance L2 is used for protection. The high-voltage cable is 10m long.

Time diagrams of transition processes are presented in Fig.34. Time diagrams contain the following designations:

- \(v(C1)\) – potential in the junction of cable connection to gun control electrode;
- \(v(4.2)\) – voltage drop on the limiting resistor;
- \(I(7.8)\) – current of the accelerating voltage source;
- \(v(V2)\) and \(v(V3)\) – presetting of available discharge time.

Fig.34. Time diagrams of transition processes: 

- \(a\) – discharge only in gun, \(R_{\text{limit}} = 200\) Ohm, \(L = 2\) mH;
- \(b\) – successive discharge in gun and control tube, \(R_{\text{limit}} = 200\) Ohm, \(L = 2\) mH;
- \(c\) – successive discharge in gun and control tube, \(R_{\text{limit}} = 1200\) Ohm, \(L = 6\) mH;
- \(d\) – successive discharge in gun and control tube, \(R_{\text{limit}} = 1200\) Ohm, \(L = 6\) mH, shunting diode is switched on.
Based on the time diagram, given in Fig.34,a, during discharge only in the gun the control electrode potential drops to zero, and after discharge termination the rated accelerating voltage value is restored aperiodically without dangerous overvoltages. The amplitude of voltage oscillation in the limiting resistor is changed in the range of $\pm U_{\text{acc}}$, and amplitude of current flowing via the power source, does not exceed 12 A. Such progress of events is quite acceptable and is not considered as an emergency situation.

But successive discharge in the gun and control tube (Fig.34, b) has already created the emergency situation: the potential of control electrode reaches minus 150kV, the amplitude of voltage oscillations in the limiting resistor is $\pm 240$kV, power source current during available discharge succeeds to rise up to 125A. Therefore, in order to prevent this emergency situation, it is necessary to increase resistance of the limiting resistor up to the value acceptable regarding minimizing of load characteristics of the power source, dissipation of heat evolved in the oil tank and losses of effective power of the electron beam. Normally, this value may change for each specific source. For instance, for the power sources with load current of about 1 A the optimal resistance value is 1000—1200 Ohm. As it follows from obtained time diagrams of transition processes at simultaneous discharges in welding gun and control tube using $R_{\text{limit}} = 1200$ Ohm with self-inductance $L = 6$mH (Fig.34, c), after termination of discharge the overvoltage in the in the junction of cable connection to the gun control electrode decreased down to $-75$kV and the amplitude of current, flowing via power source, does not exceed 30A. But the potential oscillations in the limiting resistor circuit remain considerable (from $+90$kV to $-120$kV).

The next step in overcoming overvoltages is shunting of the limiting resistor by the diode (practically by a circuit of connected in series diodes, withstanding the voltage drop to 1.5$U_{\text{acc}}$), as expected, leads to complete oscillating process suppression. Due to this overvoltage in the cable is missing, voltage drop in the limiting resistor is only 80 kV (Fig.34, d).

Though numeric values, obtained during simulation of transition processes can not be completely valid, nevertheless, the general regularities of protection parameters influence of on character of these transition processes seem to be convincing. Confirmation of efficient increase in resistance of the limiting resistor and its shunting by the chain of reverse biased diodes is the fact that after application of these recommendations, breakdowns of the high-voltage cables main insulation, destruction of the limiting resistor and the high-voltage insulators of welding guns did not occur in our practice.

The similar protection also provides an accident free operation of the powerful units of inverter type with high-frequency transformation of the mains frequency, where control tube is not used. The limiting resistor value can be respectively increased in less powerful units, thus increasing the protection system efficiency from overvoltages even more and decreasing the source current during the gun discharge.
5.2. Peculiarities of current protection of power sources for EBW.

Breakdowns can develop in vacuum insulation between the control electrode and the anode in the welding gun emission system. The gap between the control electrode and the cathode is frequently overlapped by drops of molten metal from the weld pool. Electrical insulation disturbance between the high-voltage cable conductors, connected to the cathode and the control electrode is also possible. An uncontrolled beam current rise, disturbing the weld formation, occurs in all these cases.

Abrupt switching off of the accelerating voltage source at operation of the maximum current protection is highly undesirable, as it causes a serious weld defect in the form of a through crater, unfilled with liquid metal. Therefore, first of all it is necessary to minimize the weld formation impairment, and then disconnect the accelerating voltage source. If the source was switched off, then in case of its asynchronous restarting current protection operation is inadmissible, because of the power source starting current, substantially exceeding dynamic current, due to magnetization current surge of the power source [28], charging the high-voltage cable and output filter capacitances. Exactly these currents at automatic restarting of the source, even in the mode of the so-called soft, i.e. delayed start, may cause false operation of current protection, if its time delay is absent and too low operation threshold is set.

The high-voltage inverter power source with power 6 kW and accelerating voltage 60 kV, developed as a result of teams cooperation of E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine (NASU) and “Torsion” Co. Ltd., Kharkov, was used in the experimental study of algorithms. At load currents up to 0.1A the source operates in the mode of accelerating voltage stabilization. Because of the available current sensor in the load circuit, the voltage stabilizer may go into current stabilization mode at short circuits, thus limiting the load current. The ballast resistor, limiting the maximum current amplitude via the output high-voltage rectifier at short circuit in the load and preventing development of parasitic resonance processes in the output cable [23], is switched on at the high-voltage filter output.

Random nature of vacuum breakdown emergence makes it difficult to record its electric and time parameters to compare them with the weld formation impairments. Therefore, normally-open shorting plug of the control electrode—cathode circuit and discharger with adjustable inter-electrode gap were temporarily integrated into the high-voltage power source between the core, connected to the control electrode and the ground (Fig. 35).
Fig. 35. Schematic of experimental set-up: 1 – anode; 2 – control electrode; 3 – cathode; 4 – high-voltage cable; 5 – short-circuiting plug of control electrode—cathode circuit; 6 – beam current regulator; 7 – discharger with adjustable inter-electrode distance; $U_{\text{acc}}$ – accelerating voltage source; $C_1$—$C_4$ – distributed capacitances of cable conductors relative to the ground; $C_5$ – filter capacitance

This allows directly in the process of specimen welding to close any of the circuits, record the oscillograms of load current and accelerating voltage at specific time, and compare them with the weld formation impairment that occurred. The digital electronic oscillograph Tektronix TDS-2014 with the bandwidth of 100 MHz and sampling rate of 1 Gsamp/s was used as a recorder.

Experimental studies revealed the necessity for different approaches to operating algorithms of the power source current protection, in order to enable performance of EBW at breakdowns simulation in the gun and at short circuit of control electrode—cathode circuit (diode mode of the gun operation).

Fig. 36 gives the oscillograms of beam current and accelerating voltage at electric breakdown simulation between the gun’s control electrode and the anode directly in the process of welding. The accelerating voltage source is forcibly switched into the mode of automatic restarting, in order to prevent any serious impairment of the weld formation and the source malfunction [29].
Duration of accelerating voltage fronts cutting off and respective load current surge is about 0.1 ms. Accelerating voltage is missing for 7.5 ms, that allows recovering electric strength of vacuum gap of the gun emission system. Then accelerating voltage is recovered slowly enough – in 2.5 ms – according to the linear law. Accelerating voltage may recover much faster, but then metal splashing from the weld pool may occur due to the respective increase of beam current rise speed. Moreover, soft accelerating voltage startup decreases the source starting current, as well as slows down charging of the filter and high-voltage cable capacitances, that enables a certain reduction of requirements to the power source maximum current. Nonetheless, as shown in Fig.36, the value of load current surge at the moment of accelerating voltage restarting reaches 0.35 A, i.e. it exceeds the maximum operating current of the source (0.1 A), at least 3—4 times as much. If the threshold of admissible current excess is lowered for sure, then even if electric strength of the vacuum gap has already been recovered, false operations of the source protection will be occurring for an unlimited time, and the welding process will not be able to recover. It should be noted that at missing accelerating voltage the oscillogram records running of certain load current, in all probability, between the cathode, being under residual negative potential, and the control electrode. At increase of accelerating voltage transient current rises, its value being affected by the beam current stabilization circuit. If serious malfunctions of instrumentation are missing, then total duration of equipment normal operation recovery is not more than fractions of a second and in the worst case, repair welding pass through the area of the weld formation impairment is required.
In the considered case, switching the accelerating voltage source into the mode of automatic re-starting is much more efficient than forced switching of the accelerating voltage source into the current source mode, as current flowing results in maintaining of ionization processes in the vacuum gap, which prevent recovery of its electric strength.

On the contrary, as is shown below, at switching of the emission system into the diode mode, forced switching of the accelerating voltage source into the current source mode turns out to be useful because of short circuit of the control electrode — cathode circuit. At closing of this circuit, current rises up to the level, corresponding to completely unlocked emission system. Cutting off accelerating voltage at this moment leads to defect formation in the form of a deep crater unfilled with liquid metal and having numerous shrinkage cracks (Fig. 37, a).

Switching the accelerating voltage source into the current source mode with respective decrease of accelerating voltage allows avoiding the defect formation (Fig. 37, b).

Fig. 37. Appearance of welds interrupted at the moment of short-circuiting in control electrode—cathode circuit:  
a – formation of defect in the form of crater at cutting off of accelerating voltage by maximum current protection;  
b – defect free completion of weld owing to source going from accelerating voltage stabilization mode into beam current stabilization mode

Fig. 38 gives the oscillograms of beam current and accelerating voltage at electric breakdown simulation between the gun’s control electrode and the cathode. At the moment of short circuit of the control electrode and the cathode, when the emission system goes into the diode mode, beam current rises from the preset value of 0.1 up to 0.25A. In 3—5ms current protection operates, the programmed threshold of which is 0.13A, i.e. is by 30% higher than beam current setting, and the voltage supply goes into the current stabilization mode of this value. In order to maintain such current, the supply
generates voltage of about 30kV. Thus, beam power decreases from 6 to 3.9kW, and, most importantly, at decrease of accelerating voltage the beam is refocused significantly (the focal spot rises relative to the workpiece surface), that results in a considerable reduction of the molten metal volume. A defect-free completion of the weld formation without the crater fixation takes place, after which the source can be switched off to take the required remedial actions.

Fig.38. Dynamics of variation of beam current $I_{\text{beam}}$ and accelerating voltage $U_{\text{acc}}$ at simulation of short-circuiting of control electrode to cathode directly during EBW

The Table gives optimum characteristics of current protection of accelerating voltage sources

<table>
<thead>
<tr>
<th>Welding mode disturbance</th>
<th>Cause of disturbance</th>
<th>Algorithm of current protection operation</th>
<th>Operating time, ms</th>
</tr>
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<tbody>
<tr>
<td>Beam current 3…4 times exceed maximum load current of the source</td>
<td>Electric breakdown between the control electrode and the cathode</td>
<td>Forced switching of accelerating voltage source into the mode of its automatic restarting</td>
<td>~ 0.1</td>
</tr>
<tr>
<td>Beam current reached the value corresponding to diode mode of gun emission system</td>
<td>Short-circuiting in control electrode-cathode circuit</td>
<td>Forced switching of the source from voltage stabilization mode into current stabilization mode</td>
<td>2…5</td>
</tr>
</tbody>
</table>
CONCLUSION

The electron beam current control circuitry has undergone some significant changes during a half-century history of EBW development and industrial application.

In particular:
- in the 60’s of the last century, there was a transition to a solid element base instead of the tubes;
- at the end of the last century the time of computer and numeric control came;
- at the beginning of this century an extensive application of the frequency network conversion in accelerating voltage sources and the welding gun emission systems’ power source has begun;

The priority tasks of further development of the electron beam current control circuitry are as follows:
- bringing the tetrode emission systems, generating electron beams with the angle of convergence, independent of beam current, to industrial application. This emission system will permit to substantially simplify the welding operator activity and increase the reproducibility of geometric dimensions and welds quality;
- application of magnetometric methods for contact-free beam current measurement under high-voltage potential, which will improve the accuracy, quick response and reliability of the control system.
References

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