INFLUENCE OF VIOLATIONS OF WELDING GUN AXIAL SYMMETRY ON FOCAL SPOT POSITION

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In addition to the known requirements to stability of heating spot position on an item specified in international standard ISO 14744-6, violations of adjustment of electron beam welding gun and procedure of their elimination are considered.

Keywords: *electron beam welding, EB gun, triode emission system, electromagnetic focusing system, violations of axial symmetry, beam crossover, focal spot, instability of dimensions and position, welding gun adjustment*

International standard ISO 14744-6 [1] contains strict limitations of instability of focal spot position — they should not exceed ±0.1 mm in the plane located at 300 mm distance from welding gun edge. This requirement cannot be satisfied in many cases, and two serious difficulties arise in practical application of EBW:

• if before welding the 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, in particular normal to the butt plane. There is the risk of beam deviation from the butt plane, particularly in its root part. Therefore, experienced operator before welding on a run-off tab (close to the weld) performs the so-called piercing with a stationary beam of nominal power. If the root part of the piecing falls on the extension of butt plane, welding can be performed;

• change of focusing current can also lead to shifting of the focal spot towards the butt. Moreover, as in this case the electron beam falls on the item at an angle, different from 90°, the arising tangential component of the recoil reaction of metal vapours disturbs the symmetry of cast metal upper part. At the same time, focal spot diameter is increased and distorted, thus reducing the penetration depth.

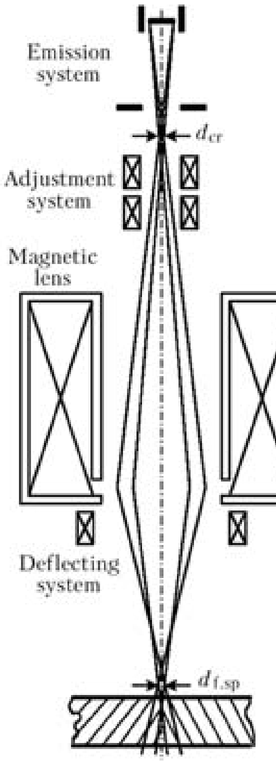

Figure 1. Schematic of welding gun electron-optical system: d_{cr} — beam crossover diameter; $d_{f.sp}$ — focal spot diameter

The cause for the mentioned difficulties is accounted for by violations of adjustment or errors (in keeping with the terminology of light and electron optics) of welding gun axial symmetry, because of inaccuracies of its fabrication and assembly, and local magnetization of gun components and item. These errors are eliminated by adjusted displacement of focusing electromagnetic lens or using two deflecting systems mounted above it and having the role of adjustment system (Figure 1). Only at combination of the axes of emission system and magnetic lens, and this should be in the entire range of welding currents, the focal spot position on item surface does not change during gun operation.

Welding gun emission system, which includes the cathode, control electrode and anode, forms the converging electron beam, the minimum cross-section of which — the crossover — is reflected using a magnetic focusing lens in the item plane as the focal spot (see Figure 1). 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 that the electron-optical system, even at a small angle of beam convergence/divergence, does not create a point image of the crossover. 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. Crossover central point is reflected in item plane in the form of a dash, transverse dimensions of the focal spot grow, and its position in item plane is disturbed.

A lot of publications are devoted to problems of violation of axial symmetry of low-current electron-optical systems of electron microscopes, TV instruments, electron accelerators (for instance, [2]). Now, this paper is devoted to errors of axial symmetry of welding gun electron-optical system, forming the electron beam in a wide range of powers from 1 up to 100 kW, mechanism of their influence on weld formation, earlier not discussed in publications.

Mechanism of disturbance of focal spot position on the item at the change of focusing and beam currents. Unlike the glass lens, the magnetic lens not only rotates the image (focal spot) relative to the item (crossover) through 180°, but additionally rotates it through certain angle ψ. At focusing, the electron beam moves in a plane, rotating about a magnetic axis, i.e. by a spiral trajectory [3].

If the electron beam is focused by a system with axial symmetry, the existence of this rotation does not affect the dimensions or position of the spot. However, if as a result of axial symmetry errors, the crossover is shifted relative to the magnetic lens axis, it is exactly beam rotation that affects the focal spot position (Figure 2).

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

$$\psi \approx \frac{0.148}{\sqrt{U_{acc}\,[V]}} \int_{-\infty}^{\infty} H(z)dz. \qquad (1)$$

For instance, for magnetic lens with turn number $N = 1500$ at magnetization current $I_m = 0.66$ A and $U_{acc} = 60$ kV, beam rotation is equal to

$$\psi = 10.7\,\frac{NI_m\,[A]}{\sqrt{U_{acc}\,[V]}} \approx 43°. \qquad (2)$$

Variation of focusing current or its direction leads to a change of the angle of rotation ψ and radial shifting of focal spot on the item, respectively. Value of this shifting is maximum in the case of the change of 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°.

Violation of focal spot position at the change of focal current is manifested to the maximum degree at parallel shifting of the axes of emission and focusing systems of the welding gun. In Figure 3 axis A–A' of the emission system is shifted to distance δ relative to axis O–O' of magnetic lens and crosses the item plane in point A, and not in point O. Beam crossover is reflected by the focusing lens in points F_1 or F_2 (depending on magnetic field direction), lying on the circumference, which is circumscribed around the magnetic lens axis, circumference radius depending on lens magnification and δ value.

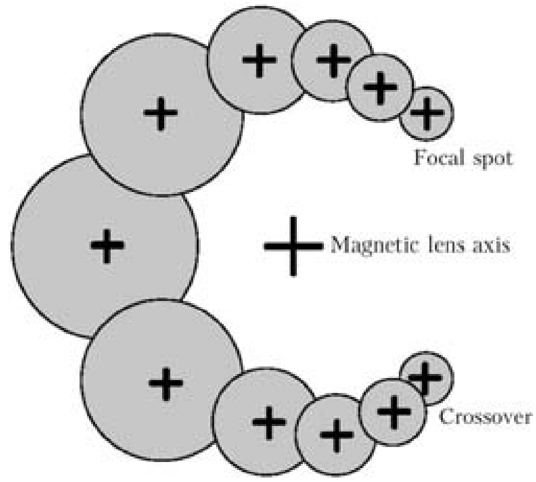

Figure 2. Projection of beam trajectory on item plane at crossover shifting relative to magnetic lens axis

In welding the polarity of power supply of the magnetic lens is certainly not switched, but focusing current can be programmed during the process, thus leading to focal spot shifting along the circumference, on which is falls. At cosmetic smoothing of the weld by deepening of the focal spot, for instance, by 100 mm, that is achieved at lowering of focal lens current by 0.050 A, angle ψ, according to expression (2), will be decreased by 3°, and at circumference radius of 5 mm beam shifting will exceed 0.1 mm and will affect both the alignment accuracy, and cast zone formation (Figure 4).

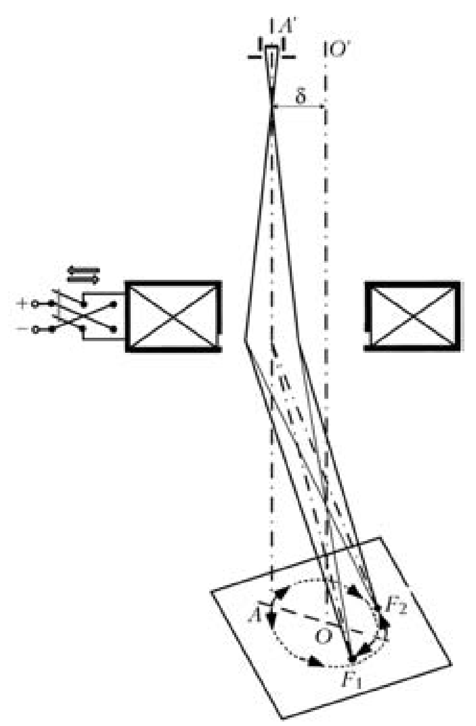

Figure 3. Schematic of influence of parallel shifting of gun emission system and magnetic lens axes on focal spot position in item plane (scale of gun reflection and beam trajectories is not observed to ensure good visual presentation; for designations see the text)

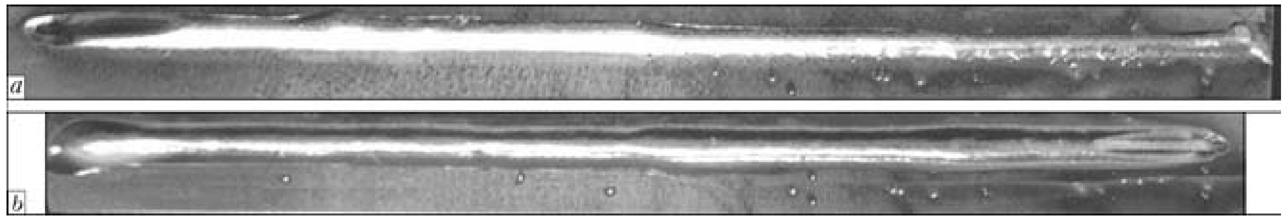

Figure 4. Asymmetrical (*a*) and symmetrical (*b*) change of weld width depending on the value of focusing lens current in a well and poorly adjusted gun, respectively

It should be noted that as follows from Figure 3 and expression (2), in the case of parallel shifting of the axes of emission system and focusing lens, the change of beam current does not affect the focal spot position in item plane.

Figure 5 shows a situation, arising at inclination of the axis of gun emission system relative to magnetic lens axis. The axis of emission system A–A' is inclined at angle θ relative to magnetic lens axis and crosses the item plane in point A, and not in point O. However, as at small beam current 1–2 mA (i.e. in probing mode), beam minimal cross-section — crossover — is located near the cathode in point *1* practically on magnetic lens axis, the crossover is reflected in item plane in point O, lying in butt plane. Now, at nominal beam current, its crossover *2* is significantly — by tens of millimeters — displaced from the previous position and turns out to be shifted to distance Δ relative to magnetic lens axis. Focusing coil reflects the crossover as focal spot in point F of the item, where the electron beam will fall, while rotating around axis O–O'. It is seen that in welding the focal spot will be shifted relatively to butt plane. At the same time, focal spot diameter is increased and distorted, thus lowering the penetration depth.

In practice, certainly, shifting and inclination of emission system axis relative to focusing coil can occur simultaneously, that makes gun adjustment still more complicated.

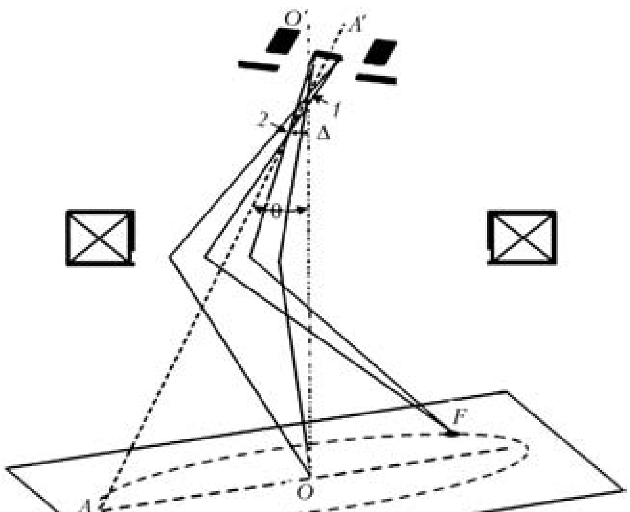

Figure 5. Schematic of influence of inclination of gun emission system axis relative to magnetic lens axis on focal spot shifting in item plane (scale of gun reflection and beam trajectories is not observed to ensure good visual presentation; for designations see the text)

Procedure of elimination of errors of welding gun axial symmetry. Before applying the system of gun electromagnetic adjustment at detection of instability of the focal spot, it is recommended to determine the gun component, responsible for this instability, and try to eliminate it by mechanical processing of parts and their demagnetization.

The most efficient is the following sequence of actions:

1. Checking the axial symmetry of electrodes of the emission system proper. Shifting of ion crater relative to cathode center (Figure 6) is an unambiguous indication of violation of axial symmetry of emission system electrodes and the need for their mechanical retrofitting.

2. Checking the alignment of the geometrical and electron-optical axes of the emission system:

• using the beam in probe mode make two surface-melted spots on the plate by switching the direction of focusing coil current;

• turn the case of the emission system relative to the initial position through an angle of 90–180°, and again make two surface-melted spots on the plate.

If the case rotation did not influence the distance between the surface-melted spots, or their spatial orientation, it is an indication of 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:

Figure 6. Shifting of ion crater relative to cathode center

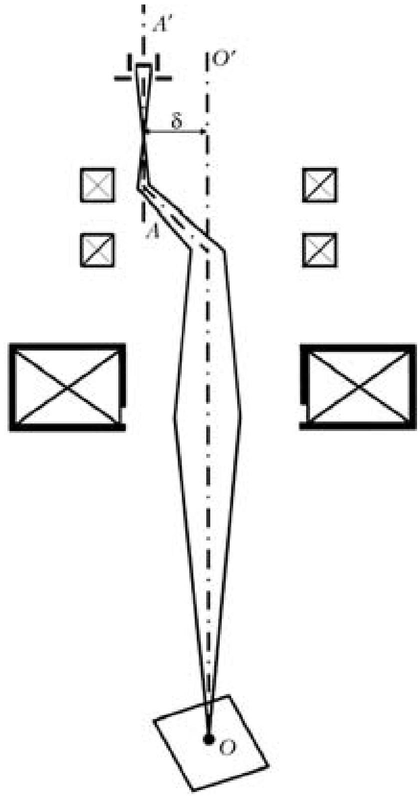

Figure 7. Principle of straightening of axes of emission system and focusing lens using two deflecting systems

- use the beam to produce in the probe mode two surface-melted spots on a plate by switching the direction of focusing coil current;
- turn the focusing lens case relative to the initial position through an angle of 90–180° and again obtain two surface-melted spots on the plate for two directions of focusing lens current.

If rotation of focusing lens case has not affected the distance between the surface-melted spots or their spatial orientation, this is indicative of alignment of the geometrical and magnetic axes of focusing lens.

4. If after fulfillment of the above operations it was not possible to eliminate shifting of the focal spot at the change of beam current or focusing current, the axes of the emission and magnetic systems should be superposed. In the case of parallel shifting of the above axes, as follows from Figure 3, change of beam current will not affect the focal spot position. Asymmetry of the welding beam only will cause shifting and asymmetry of the cast zone at the change of focusing current. Now, if the emission system axis is inclined relative to magnetic axis, then, as follows from Figure 5, change of beam current will cause a noticeable shifting of the focal spot.

At this final stage alignment of the axes of emission and focusing systems is performed using two electromagnetic deflecting systems (Figure 7). Application of one or two algorithms of the alignment process is possible: either step-by-step drawing together of two

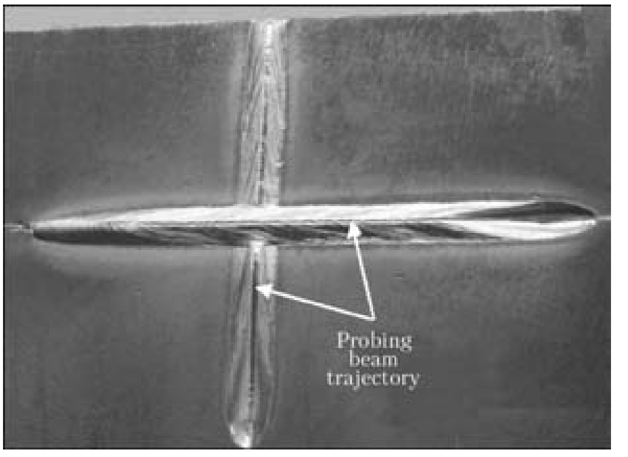

Figure 8. Accurate alignment of probing beam trajectory with the middle of welds made in orthogonal directions

surface-melted spots on the item, made at nominal and minimal beam current, or displacement of any of these surface-melted spots to calculation point *O* of magnetic lens axis.

Result of this operation is coincidence of the trajectory of probing beam with the middle of the cast zone, produced at beam nominal current in two mutually normal planes (Figure 8).

CONCLUSIONS

1. The main indication of satisfactory axial symmetry of electron-optical system of the welding gun is coincidence of probing pulse trajectory with the middle of cast zone produced at nominal beam current in orthogonal directions.

2. Procedure of variation of focusing beam current can be used as a convenient express method of preliminary checking of the quality of gun adjustment, as a rule, in the mode of low beam currents.

3. Indications of satisfactory axial symmetry of gun emission system proper are absence of shifting of ion crater relative to the cathode center and constant position of the focal spot on the item at turning of the emission block around its axis through an angle of 90–180°.

4. Axial symmetry of focusing lens is confirmed by unchanged position of the focal spot on the item at turning of the lens around its axis through an angle of 90–180°.

5. A final stage of gun adjustment is straightening of the axes of emission system and focusing lens using two deflecting systems sequentially located below the anode.

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