The use of permanent magnets for the treatment of massive workpieces with a high-current electron beam

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Abstract. The results of experiments on the use of permanent magnets shaped as a ring or square frame for the treatment of massive (thick) workpieces with a high-current electron beam are presented. It was shown that the placing of such magnets in front of the treated workpiece eliminates the beam defocusing caused by the ejecting of pulsed guide magnetic field because of skin-effect. This method provides the beam energy density to be sufficient for reliable and uniform melting of the workpiece surface layer which is needed for improvement of its physical-chemical properties: increasing corrosion resistance, smoothing microrelief (polishing), etc.

1. Introduction
Low-energy, (up to 40 keV), high-current (up to 25 kA) electron beams of microsecond duration are widely used for surface treatment of metallic materials by pulsed melting [1-4]. As a rule, such beams are formed in the guns with plasma anode and explosive-emission cathode, and the beam transport to the target is usually performed in a guide magnetic field produced by pulsed solenoid [5-7]. However, at the treatment of massive workpieces, the beam defocusing caused by pulsed character of the solenoid magnetic field may take place. Actually, if the thickness of treated workpiece exceeds the skin depth of pulsed magnetic field penetration into the workpiece, so this magnetic field is partially ejected from it and magnetic field lines flow around the treated workpiece. This divergence of magnetic field lines means the beam defocusing, decreasing of its energy density, so the melting of the surface layer becomes impossible. But without the surface melting, it becomes impossible to improve physical-chemical properties of the workpieces, such as corrosion resistance, heat resistance, smoothing the surface. Since the skin depth decreases with the increase of material electrical conductivity, so the beam defocusing appears, first of all, for high conducting materials (copper, alumina, etc). Taking into account that for most of metals and alloys, the thermal conductivity is proportional to the electrical conductivity, it is clear that it becomes difficult to melt the surface layer.

To solve this problem, we suggest the following way. In addition to pulsed solenoid, at the electron gun output, the permanent magnet shaped as a ring or square frame is placed on the surface of the workpiece to be treated. At that, the magnetic field induction vector on the surface of magnet, \( B_{mag} \), looking to the cathode of electron gun, should be in opposite direction with the induction vector of pulsed magnetic field provided by solenoid, \( B_{sol} \). In this case, the vector of magnetic field of the permanent magnet inside the ring (frame) has a significant component coinciding with those of pulsed
solenoid and easily penetrates into a workpiece. In the present work, the results of experiments confirming the proposed idea are given.

2. Experimental arrangement and technique
Experiments were carried out on the "RITM-U" facility described in [7]. Principal experimental arrangement is given in figure 1. The electron gun of the facility consists of explosive-emission cathode 1, ring anode 2, pulsed solenoid 3, holder of the treated workpiece 4 and body 5. For the convenience in work and economy of the materials, the combined targets made of copper (melting threshold is of ~6.4 J/cm² at pulse duration of ~3 μs) and duralumin D16T (melting threshold is of ~3.5 J/cm²) were used. The target consisted of the disc 6.1 with diameter of 120 mm and thickness of 20 mm in the case of copper and 30-mm thick for duralumin and replaceable square plates 6.2 with dimensions of 120×120 mm and 1-mm thick made of material corresponding to the disc material. Beam autographs were fixed just on these plates. Pulse duration of the current through solenoid was ~20 ms, therefore, skin-layer thickness was ~9 mm for copper and ~13 mm for duralumin, e.g. significantly lower than the target thickness. Two types of the permanent magnet 7 placed in front of the target were used: a ring with dimensions of Ø130×Ø110×15 mm and square frame with dimensions of 110×90×15 mm. Material of the permanent magnets was Nd-Fe-B, and the induction on its surface was 0.3 T.

![Figure 1. Scheme of the treatment of massive workpieces. 1 – explosive-emission cathode; 2 – ring anode; 3 – pulsed solenoid; 4 – holder of the treated workpiece; 5 – body of electron gun; 6 – treated workpiece consisted of thick disc 6.1 and thin replaceable target 6.2; 7 – permanent magnet.](image-url)

The operation of the scheme given in figure 1 is running as follows. After pumping-out of the electron gun volume and filling it with argon up to pressure of 0.03-0.06 Pa, the guide magnetic field is created with the use of solenoid 3 powered by pulsed current from the preliminary charged capacitive bank. Solenoid current rise time is 5 ms. At the maximum of solenoid current, 5-kV positive pulse is applied to the anode 2 and high-current reflective (Penning) discharge starts to burn in the space between explosive-emission cathode 1 and grounded target 6.2. Within 20-40 μs, this space is filled with plasma having density of (2÷3)×10¹² cm⁻³ [1, 5, 6]. This plasma column represents plasma anode indeed. After formation of the plasma anode, an accelerating voltage pulse with amplitude of 20-35 kV and rise-time of 10-50 ns is applied to the cathode. Then, explosive emission is...
excited on the cathode and a lot of plasma clouds (cathode spots) appear. Electrons emitted from these clouds are accelerated in the double layer between the cathode and anode plasmas and transported in the guide magnetic field of 0.1-0.15 T through anode plasma to the treated target 6.2 which serves as the beam collector simultaneously. During the transportation, the beams emitted from individual cathode spots diffuse in radial direction and mix into united high-current beam. Characteristic parameters of this beam are as follows: energy of electrons – up to 30 keV, beam current – up to 25 kA, pulse duration – 2.5-3 μs, beam energy density – up to 10 J/cm² (without focusing or defocusing).

3. Results and discussion
The beam autographs on copper plates-targets obtained for different configurations are given in figure 2. The original beam autograph (figure 2a) obtained on a thin target when the permanent magnet is absent has a brightly expressed central core about 6 cm in diameter; beam energy density (preliminary measured by calorimeter) in it was about 9.5 J/cm². It is also clear, that the placing of permanent magnet on the target surface provide rather uniform melting of the surface within diameter up to 11 cm in the case of ring magnet (figure 2c) and within square of 9×9 cm (except corners) for the square frame magnet figure 2d). On contrary, at the absence of permanent magnet, the melting is not entire but furnace, weak and nonuniform; beam diameter is enlarged and energy density is low (figure 2b). Note, that if the permanent magnet is turned so as the vector of magnetic field be in opposite direction with the induction vector of pulsed magnetic field provided by solenoid, so there is no melting because of essential deformation of the beam. Evidently, this deformation is caused by the fact that magnetic field near the target acquires "casp" configuration characteristic to the coils with opposite directed currents, e.g. created opposite directed magnetic fields. Thus, electron beam can not propagate in such magnetic field.

![Beam autographs on copper targets: without thick disc (total thickness of the target is 1 mm) and without permanent magnet – (a); with disc (total thickness of the target is 21 mm) and without permanent magnet – (b); together with disc (total thickness of the target is 21 mm also) and with the presence of a ring permanent magnet – (c); together with disc (total thickness of the target is 21 mm also) and with the presence of square frame permanent magnet – (d).](image)

Figure 2. Beam autographs on copper targets: without thick disc (total thickness of the target is 1 mm) and without permanent magnet – (a); with disc (total thickness of the target is 21 mm) and without permanent magnet – (b); together with disc (total thickness of the target is 21 mm also) and with the presence of a ring permanent magnet – (c); together with disc (total thickness of the target is 21 mm also) and with the presence of square frame permanent magnet – (d).

In figure 3, an analogues series of the beam autographs obtained for duralumin targets is presented. These autographs confirm also a positive effect from the influence of permanent magnet.

In the case of square frame permanent magnet, practically square autographs were obtained on titanium targets (figure 4). This result can be explained by low melting threshold for titanium (about 2 J/cm² at 3-μs pulse duration) which is much lower than for duralumin and copper. Thus, the corners of titanium targets were melted but for duralumin and copper targets there was not enough energy density in these corners.
Figure 3. Beam autographs on duralumin targets: without thick disc (total thickness of the target is 1 mm) and without permanent magnet – (a); with disc (total thickness of the target is 31 mm) and without permanent magnet – (b); together with disc (total thickness of the target is 31 mm also) and with the presence of square frame permanent magnet – (c).

Figure 4. Beam autograph on thin (1 mm) titanium target obtained with the use of square frame permanent magnet.

The possibility to transform of the circular electron beam into a square one with the use of square frame permanent magnet has been clearly demonstrated by thermal imaging diagnostics performed according to technique described in [8]. Figure 5 presents thermogram of the beam and corresponding energy density distribution via two mutually orthogonal cross sections.

Figure 5. Thermogram of the beam (at the left) and corresponding energy density distributions via two cross sections (at the right).
4. Conclusion
The carried out experiments have confirmed positive effect from the use of permanent magnets while surface treatment of massive metal workpieces. The ring or square frame permanent magnet placed near the treated surface eliminate the beam defocusing caused by skin-effect in relation to pulsed magnetic field created by solenoid which provides the beam transportation from the cathode to target. At that, the magnetic field induction vector on the surface of magnet looking to the cathode of electron gun, should be in opposite direction with the induction vector of pulsed magnetic field provided by solenoid. Therefore, the beam energy density becomes to be enough for effective melting of the surface layer and improvement its different physical-chemical properties.

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