THE USE OF THE ELECTRON BEAM FROM THE MAGNETRON GUN-BASED ACCELERATOR FOR ZIRCONIUM SURFACE MODIFICATION

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INTRODUCTION

The paper reports the results from studies on metal surface irradiation with an electron beam of the accelerator based on the secondary-emission cathode magnetron gun. Presented are the results of examination of flat zirconium sample surfaces after their irradiation with an electron beam of the accelerator having the following parameters: electron energy 70 to 80 keV, pulse length – 15 μs, pulse rate – 2 pulses/s for two regimes of energy density on the samples, namely, 10 J/cm^2 and 20 J/cm^2. Experiments have been made to explore possibilities of irradiating inner surfaces of tubular items.

EXPERIMENTAL SETUP AND METHOD OF STUDIES

To irradiate zirconium surface, we have used the electron beam of the accelerator based on the magnetron gun having a secondary-emission cathode [1, 2] of diameter 40 mm and a stainless-steel cylindrical anode with a diameter of 78 mm. The accelerator diagrammatic sketch is presented in Fig. 1.

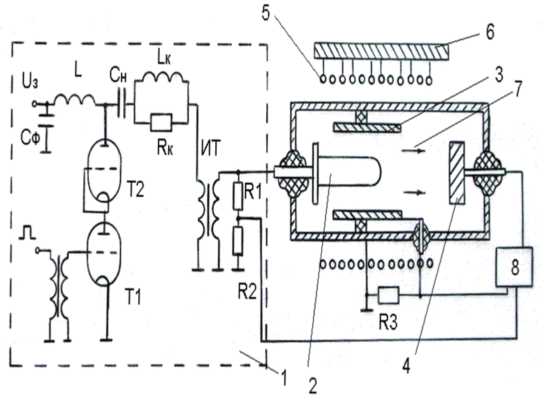

Fig. 1. Full diagram of the accelerator. 1 – impulse generator, 2 – cathode, 3 – anode, 4 – Faraday cup, 5 - solenoid, 6 - solenoid power supply, 7 – electron beam, 8 – computerized measurement system.

The accelerator consists of the following main units: an energizing high-voltage pulse generator 1; a magnetron gun with a secondary-emission cathode 2 and anode 3, located in the vacuum chamber; solenoid 5 that generates a longitudinal magnetic field; a target device with a Faraday cup (FC) 4; a computerized measurement system 8 for measuring beam parameters. The supply voltage pulse from the impulse generator 1 was applied to the magnetron gun cathode.

The impulse generator 1 provided voltage pulse shaping with a pulse overshoot amplitude of 190 kV, a pulse overshoot decay time of ~ 0.6 μs to provide the development of secondary-emission multiplication processes, and an amplitude of the voltage-pulse flat part of ~ 150 kV; the pulse length was 15 μs, the pulse-repetition rate was 2 Hz. In the impulse generator circuit, use was made of the full discharge of the storage capacitor Cs via a correcting circuit L_2R_2 to the pulse-transformer (ИТ) primary winding through two series-connected thyratrons for increasing the commutation voltage. The voltage surge was provided due to spurious inductance and capacitance of the pulse transformer.

The electron source (C – cathode, A – anode) is arranged in the vacuum chamber with an inside pressure of about 10^{-6} Torr. To produce the electron beam, the magnetron gun is used. The latter has a copper cathode (40 mm in diameter, 85 mm in length) and a stainless steel anode (78 mm in inner diameter and 140 mm in length).

The magnetic field for electron beam shaping and transport is generated by the solenoid 5 consisting of four sections, which are energized by dc sources 6. The amplitude and longitudinal distribution of the magnetic field can be controlled by varying the current value in the solenoid sections.

The measured data on the parameters of the voltage pulse, the beam current traversing the Faraday cup and their stability were processed by a computerized measuring system 9. The measurement error ranges within 1 % to 2 %. The processed data were displayed on the monitor.

EXPERIMENTAL RESULTS AND DISCUSSION

The parameters of the accelerator under discussion were investigated for the case of material surface irradiation.

The experiments have demonstrated that the maximum parameters of the beam were attained in a uniform magnetic field at a cathode voltage of ~ 120 kV. The magnetron gun formed an electron beam of current 125 A with a power density on the target ~ 4 MW/cm^2 at a pulse length of 10 μs.

The bandwidth of electron beam generation was determined by varying the magnetic field and was found to be $\Delta H \sim 200$ Oe. This beam generation bandwidth is of great importance in the accelerator adjustment for technological purposes.

It has been shown that at a constant cathode voltage the change in the magnetic-field amplitude and distribution results in the change of the beam current. Thus, with the use of this effect in the experiments on sample exposure to the accelerator beam, the beam current was changed by a factor of ~ 5 from 25 A to 135 A at a voltage (137±12) kV. This can be seen in Table 1, which lists the beam parameter values at target irradiation conditions.

Table 1. Beam parameters

Electron energy, keV	**Beam current, A**	**Pulse length, s**	**Target power density, MW/cm^2**	**Pulse repetition rate, Hz**
120	125	12	~ 3.5	2
125	105	12	-	2
135	80	11	-	2
140	45	11	3.0	2
150	25	10	-	2

In one of the experiments, as the uniform magnetic field was varied from ~ 1200 Oe to ~ 1400 Oe, the beam current changed from 45 A up to 120 A, i.e., by 300 %, while the cathode voltage changed only by 20%, namely, from 115 kV up to 140 kV. This enables one to control the beam energy density on the target. Notice that the sputtering of target material on the cathode surface gives its contribution to the process of current variation.

The beam parameters obtained at the accelerator under consideration are close to the parameters of the facilities-analogs that are currently used for irradiation experiments [3].

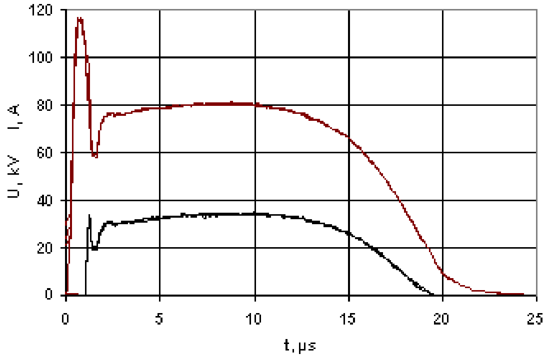

Fig. 2. Oscillograms of the cathode voltage (upper curve) and the beam current (lower curve).

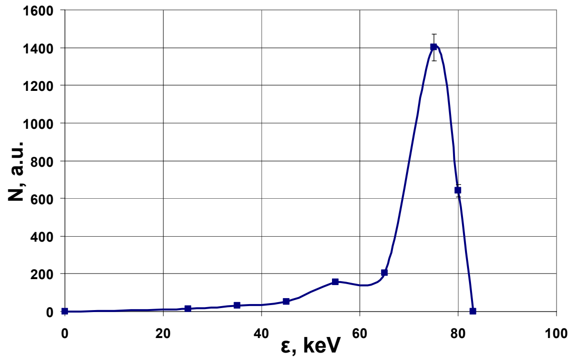

Fig. 3. Beam energy spectrum.

An important role in the experiments belongs to electron energy distribution. For this reason, based on the measurements of the beam current and the voltage amplitude we have constructed the curve of electron energy distribution in the beam. Figure 2 shows the oscillograms of the cathode voltage and the beam current, and Fig. 3 gives the beam energy spectrum in this case.

The data obtained from Fig.3 indicate that nearly 80% of particles lie in the energy range 75±10 keV (or ±10%).

The targets were irradiated at a cathode voltage of ~ 80 kV and a beam current of 85 A (the beam energy density is 20 J/cm^2) in the first case, and at ~ 70 kV and ~ 55 A (the beam energy density is 10 J/cm^2) in the second case, the number of pulses being 5. At these beam parameters the modified layer depth ranges from ~ 10 to 100 μm.

Below we give the results of metallographic examination of Zr 1%Nb samples cut out from fuel claddings and of pure zirconium samples after their exposure to a tubular electron beam of the accelerator based on the magnetron gun with a cold copper second-emission cathode. The results obtained have demonstrated that zirconium surface irradiation with electrons causes essential changes in the subsurface layer structure. Figure 4 shows the boundary surfaces of the irradiated and non-irradiated areas of zirconium materials. It is obvious that electron irradiation of zirconium surfaces causes noticeable changes in their subsurface layer. Thus, the surface texture variation caused by surface fusion and intense evaporation is clearly seen. The irradiation leads to a substantial planarization of surface roughness, the surface has become smoother and mirrored. In some cases, at an energy density of 20 J/cm^2, the areas within the irradiated region show (even at a low magnification of x100) the crater formation, the latter being due to the material expulsion as well as to gas and lightest constituents emission from the sub-surface layer (see Fig. 4 d). Microhardness tests of irradiated and nonirradiated surfaces of zirconium samples have shown changes in the microhardness values of irradiated areas, namely, the microhardness of the

Zr1%Nb alloy has changed by ~ 20 % and ~ 35 % of its initial value (19-20 MPa) at electron energy densities of 10 J/cm2 and 20 J/cm^2, respectively. This may be due to different amounts of energy imparted to the irradiated surface.

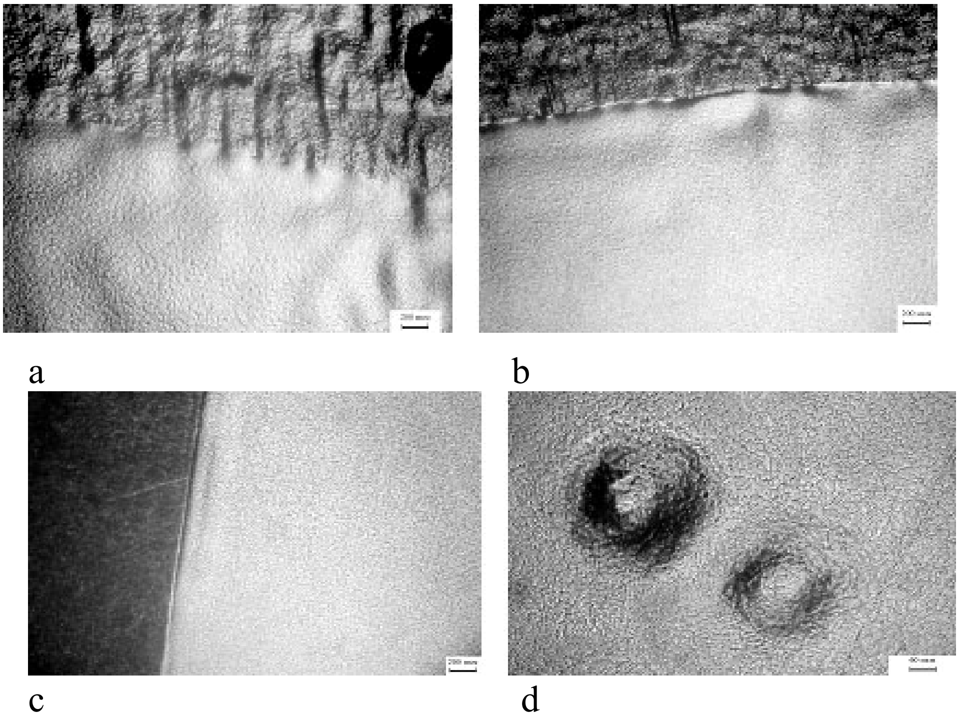

Fig. 4. Boundaries between nonirradiated and electron-irradiated Zr1 %Nb (a, b) and Zr (c) surfaces (×50), as well as irradiated Zr surface area (d) (×160), the electron beam energy density being 10 J/cm^2 (a) and 20 J/cm^2 (b, c, d). At the bottom right of the figures the mark, 200 μm in length, is shown.

The electron beam of the magnetron gun is strongly "magnetized". This enables one to increase the beam diameter as the magnetic field falls off along the beam propagation, and to provide a sufficiently precise beam entry into tubular products thereby ensuring the electron bombardment of their inner surfaces. By varying the type of falling-off magnetic field distribution it appears possible to shift the irradiation zone along the tube length.

CONCLUSION

Thus, the undertaken studies have demonstrated the possibility of using the secondary-emission-cathode magnetron gun-based accelerator for modifying planar and cylindrical surfaces.

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