INTRODUCTION

Trends in the development of modern nuclear power engineering require an increase in the efficiency of using nuclear fuel, placing new demands on the already strict conditions for the materials employed in nuclear technology [1]. The shells of fuel elements are some of the most important elements of a reactor zone. The material capabilities of the shells directly affect the operational efficiency and safety of the nuclear reactor. A whole set of demands is imposed on the shells of fuel elements, e.g., high specific strength (shell thickness, <1 mm; length, up to 4 m), resistance to wear, high heat transfer, compatibility with nuclear fuel, and resistance to corrosion in the flow of heat carrier. The possibilities of traditional treatments for improving the characteristics of shell material, e.g., bulk doping, mechanical treatment, and mechanical–thermal treatment, are now virtually exhausted. One possible solution to the problem of improving the industrial properties of fuel element shells would be to introduce ion-beam treatment to finish the outer surfaces of fuel element tubes via cleaning and polishing, instead of resorting to power-consuming mechanical grinding [2]. This technology is environmentally friendly and requires no physical contact with the tubes. The geometry of the tubes remains virtually the same and can be easily transformed for additional doping of the near-surface layers of shell material in the ion-mixing mode and the controlled oxidation of the surface.

EXPERIMENTAL

As samples for our investigations, we used plant tubes (length, 500 mm; outer diameter, 9.15 mm; wall thickness, 0.65 mm) made of E110 zirconium alloy, that are used in the nuclear power industry as the shells of fuel elements. Analysis of the samples shows that surfaces can be cleaned and polished via ion-beam treatment, and roughness $R_a$ can be reduced from $2.0 \pm 0.5 \mu m$ to $0.6 \pm 0.1 \mu m$.

**Table 1.** Elemental composition of E110 alloy

<table>
<thead>
<tr>
<th>Element</th>
<th>Nb</th>
<th>Al</th>
<th>Ni</th>
<th>Cu</th>
<th>Fe</th>
<th>Cr</th>
<th>Mo</th>
<th>O</th>
<th>C</th>
<th>N</th>
<th>Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content, %</td>
<td>1.0</td>
<td>0.008</td>
<td>0.02</td>
<td>0.005</td>
<td>0.05</td>
<td>0.02</td>
<td>0.005</td>
<td>0.1</td>
<td>0.02</td>
<td>0.006</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
these conditions, the electron mobility transverse to the magnetic field (Fig. 2, 4) is strictly limited, and the electric field mainly operates over the ions, accelerating them in the specified direction.

The treated tubes were fastened in a vertical casing and rotated around their axes during irradiation, ensuring uniform treatment of the sample surface. Control of the treatment process is completely automated with the exception of loading and unloading, which was done using a computer programmed with specially developed software.

The form of the topography is mainly determined via the sputtering of material by the Ar beam in the investigated temperature range. The rate of sample thinning is virtually constant over time at sputtered layer thicknesses of up to 10 μm [4, 5] and is determined mainly by the formula

\[ V_{\text{thin}} = S_p(E) \times \Phi/\rho_{\text{at}}, \text{ cm s}^{-1} \]

where \( S_p(E) \) at./ion is the coefficient of material sputtering by an Ar beam with energy \( E \); \( \Phi \), ion cm\(^{-2}\) s\(^{-1}\) is the density of the particle flow; and \( \rho_{\text{at}} \), at./cm\(^3\) is the atomic density of the treated material.

It is known that the angular dependence of the sputtering coefficient for most metals has a character-

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**Fig. 1.** Schematic diagram of the KVK-10 installation: (1) vacuum chamber, (2) working holder for six samples; (3, 4) ions sources, (5, 6, 7) planar magnetrons, (8) array of optical pyrometers, (9) port for gas ion implanter, (10) working gas supply system, (11) vacuum pump, (12) turbomolecular pump, (13) vacuum pressure sensor, (14) valve for air inflow, (15) computer, (16) low-voltage supply and control unit, and (17) high-voltage supply and control unit.

**Fig. 2.** Schematic diagram of a wide-aperture ion source based on gas discharge with closed electron drift: (1) anode, (2) cathode (magnetic conductor), (3) constant magnet, (4) magnetic field force line, and (5) region of working gas ionization.

**Fig. 3.** Dependence of the normalized coefficient of Zr–1% Nb alloy sputtering by 400-eV Ar\(^+\) ions (calculations performed using the SRIM-2012 software code).