Etching by a beam of fast argon atoms of gas dynamic grooves on the surface of ceramic substrates

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Abstract. A method of manufacturing the grooves of the end seals from high-strength dielectric materials is proposed. Uneven depth (no more than 10%) imposes a limit on the processing time. Grooves with a depth of ~5 μm in corundum substrates can be made using a source of fast argon atoms in ~1 hour with their energy of 3 keV and equivalent beam current of 1 A.

1. Introduction
Currently, gas lubricated end seals are widely used. The advantage of such seals is a high wear-resistance of friction pairs at high rotation speeds.

Technology of the end seals manufacturing is widely known [1]. Spiral grooves with a depth from one to tens of micrometers are obtained by etching the original surface of the seal part with a directional and uniform ion beam through a mask having openings of the required profile. This technology is well developed for products made of conductive material. However, the ever-increasing demands on the parts strength in conditions of ultra-high rotation speed required the use of ceramics and other non-conductive materials.

In this paper, the possibility of manufacturing spiral grooves on the surface of a non-conductive material of synthetic corundum is considered.

2. Experimental setup
A source of fast neutral argon atoms was used to etch the grooves. Its segmented hollow cathode is 21 cm in diameter and 9 cm deep. The grid and cathode electrodes are made of titanium. Segmentation is necessary to prevent the arc, as in the processing of dielectric materials, dielectric films are deposited on the cathode and the grid, stimulating the arcing.

Figure 1 shows the schematic of the experimental setup. On the left is the source of fast neutral atoms. Around the anode 2 there are 12 isolated from each other electrodes 1, forming a hollow cathode. The emissive grid consists of 6 sectors 3 with 4.6-mm-diameter holes their centers being distanced from each other at 5 mm. The distance between the edges of the holes is equal to 0.4 mm. The gap between the sectors is equal to 3 mm. Vacuum chamber 4 has a diameter of 0.5 m and a length of 0.8 m. The beam source is installed on its flange. Argon gas is admitted to the chamber, its pressure is regulated in the range from 0.01 to 1 Pa.

Plasma 10 is produced using a discharge with electrostatic confinement of electrons [2], which has already been used to produce plasma emitters of ions [3, 4]. Discharge power supply 5 is connected between segmented cathode and anode 2.
Figure 1. Schematic of the experimental setup: 1 – cathode elements of the beam source; 2 – anode; 3 – grid elements; 4 – process vacuum chamber; 5 and 8 – power supplies; 6, 7 and 9 – resistors; 10 – plasma; 11 – grid sheath; 12 – fast argon ion; 13 – slow gas atom; 14 – fast argon atom; 15 – mask; 16 – dielectric substrate.

The maximal discharge current amounts ~2A. The ion energy (~ 3 keV) is defined by a voltage of power supply 8 connected between accelerating grid 3 and anode 2. Resistors 6 with a nominal resistance of 200 Ω and resistors 9 with a nominal resistance of 2 kΩ prevent the glow discharge from transition to the arc mode. Resistor 7 with a nominal resistance of 1k Ω ensures a negative bias potential of the grid elements ~100 V relative to the chamber 4. Thus, the electrons of the secondary plasma produced in the chamber cannot penetrate into plasma emitter 10. Ions 12, extracted from the emitter and accelerated in grid layer 11 due to charge exchange collisions with argon 13 atoms turn into fast neutral atoms 14, and the slow ions produced as a result of those collisions arrive at the chamber walls.

3. Results and discussion

For argon ions with an energy of 3 keV, the charge exchange cross section is equal to $\sigma = 2.5 \times 10^{-19}$ m$^2$ [5, 6]. The distance $\lambda = 1/n\sigma$ [7], at which the ion current density decreases by a factor of 2.72, at a pressure of 0.2 Pa and a density of gas atoms $n = 5\times10^{19}$ m$^{-3}$ [8] amounts to 8 cm. Therefore, the fraction of ions in the beam of fast atoms is 10% at a distance of 20 cm and 1% at a distance of 40 cm from the grid. Thus, our substrate is bombarded only by fast neutral argon atoms. Photos of the substrate and the mask are presented in figure 2.

Figure 2. Photograph of the substrate (a); photo of the mask (b). 1–4 – profilography lines (from the center to the periphery).

At a distance of 20 cm from the source grid, there are mask 15 (figure 1) with a diameter of 54 mm and a thickness of 0.2 mm made of ASTM B 365-98 Tantalum sheet, as well as substrate 16 made of
synthetic corundum with a diameter of 40 mm and a thickness of 5 mm. They were attached to the holder rotating at a speed of 8 rpm. Rotation is necessary for uniform etching of the substrates. Without rotation, the points on the substrate surface located coaxially with the centers of the holes of the grid elements are most strongly etched. Conversely, the areas between the grid holes give a lower etching rate, creating a shadow effect.

The parameters of the etched grooves were measured using a stylus profilometer DectakXT manufactured by Bruker Nano, Inc. (USA) the stylus rounding radius amounting to 2 µm. The etching was carried out at the argon atoms energy of 3 keV, the beam current of 1 A and the gas pressure of 0.3 Pa. After each hour of processing, profilography was performed. The total etching time was equal to 4 hours.

Experiments have shown (figure 3) that the grooves are etched evenly, and their average depth was equal to 4.4 µm after 1 hour, 8.2 µm after 2 hours, 13.1 µm after 3 hours, and 17.5 µm after 4 hours. The etching rate is 4.4 µm/h and does not depend on the width of the groove. With an increase in processing time, the unevenness of the bottom of the groove also grows, which can negatively affect the laminarity of the gas flows through the grooves. The optimal depth ranges from 1 to 5 µm.

![Figure 3](image3.png)

**Figure 3.** Profilograms of grooves (numbering of curves according to figure 2(a)): (a) – depending on the processing time: 1 – 1 hour, 2 – 2 hours, 3 – 3 hours, 4 – 4 hours; (b) – after 4 hours of processing (track numbers according to figure 2(a)).

Observation with an Axiotech Vario optical microscope (Carl Zeiss, Germany) revealed etched caverns (figure 4) with a depth of 24 µm relative to the average level of the grooves. Perhaps this is due to defects in the technology of material synthesis at great depths from the surface of the product.

![Figure 4](image4.png)

**Figure 4.** Image of the groove surface at magnifications: (a) – 10 times, (b) – 100 times, (c) – 100 times, but the plane of sharpness is lower than that of (a) and (b) by 24 µm.

### 4. Conclusions

The conducted studies allow concluding about the applicability of the proposed method of manufacturing the grooves of the end seals of high-strength dielectric materials. Grooves ~5 µm deep
with uneven depth ~10% in corundum substrates can be made in ~1 hour, with energy of neutral atoms of 3 keV and an equivalent beam current of 1 A.

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