Materials surface smoothing to sub-nanometer level of roughness by argon cluster ion beam

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Abstract. In this study, the influence of the accelerated argon cluster ion beam on the topography of stainless steel and optical glass surfaces has been investigated. The possibility of smoothing the material’s surface to the sub-nanometer level of roughness is shown. The dose dependencies of the root-mean-square roughness and power spectral density function are obtained. It is demonstrated that by the cluster ion treatment the effective roughness decreases at different ranges of spatial frequencies. Anisotropic structure of the treated material effects on the obtained surface roughness.

1. Introduction
To date, there are many different applications for potential technologies running on a sub-nanometer level, which, in turn, requires new parameters of materials that do not match their initial properties. The surface roughness is one of the most important physical characteristics of the material. It is assumed that thanks to the newest technologies, atomically smooth surfaces will be obtained without disturbing the structure and physicochemical contamination of the material being processed. One of the most promising methods of surface polishing is smoothing with the help of cluster ion beams formed from supersonic gas jets. Pollution of the processed surface is completely excluded due to the use of high vacuum condition and non-reactive gas, for example, argon. So-called lateral sputtering of the material occurs due to the interaction of the large number of the cluster particles with approximately the same amount of the target particles, which makes it possible to smooth out the surfaces of various materials [1, 2].

2. Surface topography evolution by cluster ions influence
2.1. Experimental details
The experiments were performed on equipment, a detailed description of which is given in [3]. In this work, we used the cluster ion beam formed from a supersonic argon jet [4]. The processing was carried out with the mean cluster ion size 1200 atoms/cluster and the cluster ion energy of 22 keV at normal angles of incidence of the cluster ions to the target. The flat samples of the stainless steel having initial mirror surface and the industrial polished optical glass were used. To observe the surface morphology before and after treatment, the atomic force microscope (AFM) Ntegra Prima HD was used. The AFM measurements were carried out at different scan sizes from $10 \times 10 \mu m$ to $40 \times 40 \mu m$ with a resolution of $1024 \times 1024$ pixels.
2.2. Stainless steel smoothing

The results of polishing by argon cluster ions of the stainless steel are illustrated in Figure 1, which shows the 3D images of surface at different treatment stage. The scan area was 20 × 20 μm, the maximum irradiation dose was $2.8 \times 10^{17}$ ion/cm$^2$. The average surface roughness $R_q$ was determined from four measurement points. There is a noticeable smoothing of surface irregularities. At each processing stage, the root-mean-square roughness $R_q$ decreases by more than 2 times.

![AFM images of the stainless steel surface before and after cluster ion polishing](image)

Figure 1. AFM images of the stainless steel surface before and after cluster ion polishing: (a) initial sample, (b) 1st treatment, (c) 2nd treatment, (d) 3rd treatment.

Figure 2 shows the dependences of the average roughness $R_q$ of the stainless steel surface on the irradiation dose for different size of the scan area. It can be seen that of the surface roughness is a significantly decreased at all scales. At scan area of less than $10 \times 10$ μm the $R_q$ roughness decreases to 0.7 nm and shows a tendency to further decrease with increasing dose. At the same time, at a characteristic size of the scan area above $10 \times 10$ μm, a restriction of the roughness $R_q$ at a level of 2-5 nm was obtained. As is known, stainless steel is an alloy of several chemical components: iron, chrome, nickel, etc. Obviously, the chemical elements are distributed in stainless steel in the form of micro-granules, have different physical hardness, respectively, different sputtering coefficients. This leads to a limitation of the decrease in roughness in the polishing of the surface of stainless steel by cluster ions at low spatial frequencies.

![Surface roughness of stainless steel as a function of the irradiation dose at different scan area](image)

Figure 2. Surface roughness of stainless steel as a function of the irradiation dose at different scan area.
More complete information about the surface roughness can be obtained by using the power spectral density (PSD) function, which describes the height distribution depending on the spatial frequency, taking into account lateral roughness values. The spatial frequency $\nu$ is defined as the reciprocal of the distance between the measurement points on the surface profile [5].

Figure 3 shows the PSD functions for stainless steel before and after treatment for scan area $20 \times 20 \mu m^2$. The sharp peaks of the original curve indicate periodically repeating values of the heights of the surface profile relative to the mean value. These peaks correspond to scratches from the previous mechanical polishing of the sample. After processing the surface roughness is reduced at all spatial frequencies: in the middle frequency region ($\nu \sim 1 \mu m^{-1}$) by 3 orders of magnitude, in the high frequency ($\nu \sim 10 \mu m^{-1}$) by 2 orders of magnitude, in the low frequency ($\nu \sim 0.1 \mu m^{-1}$) is less than 1 order. The PSD function after 3rd treatment differs little from the 2nd treatment.

![Figure 3. PSD functions of stainless steel surface roughness before and after cluster ion polishing.](image)

2.3. Optical glass smoothing

Also, the experiments were performed with samples of industrial optical glass LK having the diameter of 25 mm and the thickness of 10 mm without preliminary treatment. 3D AFM images of the optical glass surface before and after cluster ion polishing are shown in Figure 4. The scan area was $10 \times 10 \mu m$. The total height difference decreased from 20 nm to 9 nm after processing. Before processing, the surface of the optical glass had a granular structure with a characteristic size of about 1 $\mu m$, but after processing such a structure is not observed.

![Figure 4. AFM images of the optical glass surface: (a) before processing, (b) after processing.](image)

PSD functions and $R_q$ values of the optical glass surface initial and after processing by argon cluster ions are shown in Figure 5. The surface roughness of optical glass is reduced at all spatial
frequencies after processing: in the high-frequency ($\nu \sim 10 \mu m^{-1}$) range is less than 1 order, in the low-frequency ($\nu \sim 0.2-0.3 \mu m^{-1}$) by 2 orders of magnitude. The PSD function is reduced by 1 order of magnitude in the mid-frequency range ($\nu \sim 1 \mu m^{-1}$) but there is a pronounced peak on the “after treatment” curve. Presumably, this peak characterizes the frequency of periodic low-dimensional scratches, which remained from preliminary mechanical polishing of the sample. Comparing Figure 3 and Figure 5, it can be noted that the PSD function of the glass decreases by 2 orders of magnitude after one treatment, whereas the PSD function of the steel decreases by 1 order after 2-3 treatments only.

![PSD functions of optical glass surface before and after cluster ion polishing.](image)

**Figure 5.** PSD functions of optical glass surface before and after cluster ion polishing.

### 3. Summary

The influence of accelerated argon cluster ion beam on the surface topography of stainless steel and optical glass was studied. The root-mean-square roughness $R_q$ of stainless steel is reduced by 5.4 times, and the optical glass – 4.5 times to the sub-nanometer level. For the stainless steel surface, the roughness is maximally reduced at medium and high spatial frequencies, while for the glass surface roughness decrease at low spatial frequencies. It has been found that the limiting surface roughness obtained by cluster ions treatment can be restricted by the anisotropic structure of the material being processed.

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