Cleaning substrates and subsequent deposition of coatings with coaxial magnetron discharge

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Abstract. The created experimental magnetron sputtering system allows preliminary cleaning of the substrate surface and subsequent deposition of coatings on long cylindrical products within a single system using a coaxial magnetron discharge at a working gas pressure of 150 mTorr. The coating discharge has reverse electrodes polarity relative to the cleaning discharge. A theoretical calculation of the discharge parameters has been carried out.

1. Introduction
The creation of an effective technology for the deposition of high-quality and reproducible thin-film coatings is an urgent task of modern industry. In particular, an important task for the nuclear industry is to create an accident tolerant fuel. One of the possibilities for creating such a fuel is the modification of the fuel elements cladding surface by applying a protective coating. This coating can limit the interaction of zirconium with water vapor in an emergency situation [1, 2].

The application of corrosion- and wear-resistant multilayer coatings on lengthy products using well-known CVD and PVD technologies is an expensive and time-consuming process.

Today magnetron sputtering is the main method of coating large-area substrates. Long magnetron sputtering system designs can be divided into planar and coaxial. The use of coaxial magnetron discharge systems makes it possible to increase target utilization rate, coatings properties uniformity, and also to combine the processes of preliminary substrate treatment and deposition of coatings.

The aim of this work is to create a technology for applying protective coatings to fuel rod cladding (4 meters length) using a coaxial magnetron sputtering system. One of the tasks is to create a model and analyze the theoretical calculation results to select the optimal system parameters.

2. Functional diagram and design features of the system
The functional diagram of the magnetron sputtering system is shown in figure 1. The system includes a vacuum chamber (1) in the form of a cylindrical tube with an internal diameter of 48 mm (external -50 mm) sealed with flanges (5, 6). A sputtered fuel rod cladding (2) is installed along the chamber axis using dielectric supports (3). Pumping is carried out using a vacuum system consisting of a backing pump (9) with a shut-off valve (10) and a turbomolecular pump (8) providing a pressure in the chamber of 1x10\(^{-5}\) Torr. The configuration of the magnetic field required to create a magnetron discharge is formed by the magnetic system (4). The discharge is powered by an adjustable high-voltage source (7), which can operate in three stabilization modes: current, voltage, or power. Visual
control and monitoring of the process inside the chamber is carried out using windows (12) on the flange (6).

The following electrode polarity has been used for cleaning: the fuel rod cladding has been served as a target and cathode.

![Image](image1.png)

**Figure 1.** Block diagram of a long magnetron sputtering system prototype.

The created experimental magnetron sputtering system allowed to obtain the discharges for two processes preliminary cleaning of the substrate surface and subsequent deposition of coatings. The photos of the discharges are shown in figure 3.

![Image](image2.png)

**Figure 2.** The structure of the magnetic field at the end of the system.

3. **Description of results and discussion**

The created experimental magnetron sputtering system has been performed using the Comsol Multphysics software package. The numerical solution of Maxwell's equations for the electric and magnetic potential has been carried out using a ready-made implementation of Newton's method with a damping factor. The electrons motion trajectories in electromagnetic field have been built to study the processes of gas ionization. The electron motion parameters have been found as a numerical solution of the particle motion differential equations using the field structure from the calculations performed earlier. The numerical solution has been carried out using a ready-made implementation of the BDF method, which is a special case of the Adams finite-difference multistep method.
Figure 3. Photographs of discharges for (a) cleaning the surface (b) applying coatings.

It is necessary to minimize the loss of electrons to create an efficient sputtering system. The magnetic system forms a magnetic trap, which bends the trajectories of electrons due to the Lorentz force. This effect makes it possible to increase the ionization efficiency and the ion current density on the target. Thus, the sputtering rate increases at low working gas pressures.

The magnetic and electric fields configurations are different for the processes of cleaning the substrate and subsequent coating. It leads to different electrons trajectories and plasma discharge patterns for these two processes. As shown in [3, 4] the magnetron sputtering system with inverted electrodes polarity (negative potential on the substrate) can be used as an ion source. Such electrodes inverse connection has been used in this work to carry out surface cleaning. The magnetic system forms an open magnetic trap - a magnetic mirror. The electrons oscillate from one electrode to another in such a trap. This increases the ionizing collisions number and the ion current density on the substrate. Thus, the cleaning efficiency with the use of a magnetic mirror system is higher than for a glow discharge without a magnetic system. In direct electrodes connection (negative potential on the target) electrons drift along the cathode and form a closed oval track.

The electron trajectories have been obtained in a field configuration that corresponds to a real experimental magnetron sputtering system (figure 4). The electrons motion picture has been coincided with real discharges in the indicated field configurations.

Figure 4. Electron motion models with (a) inverted electrodes polarity and (b) direct electrodes polarity.

4. Conclusions

   Based on the experiments and theoretical calculations, a conclusion has been made about the effectiveness of the presented method for conducting preliminary surface cleaning relative to existing methods. The electrons motion in various electromagnetic fields configurations has been analyzed. The collisions influence of electrons with working gas ions have been taken into account. The developed technology makes it possible to clean the surface and apply coatings within a single technological cycle.
References
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