System of inverted magnetrons for the formation of multilayer composites on axisymmetric small-sized substrates

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Abstract. The article presents a system of 3 consecutively installed inverted magnetrons for applying coatings on axisymmetric substrates and one conventional cylindrical magnetron for cleaning substrates. The circuit of the inverted magnetron and its characteristics are shown. The modes of formation of Mo-Nb multilayer composites on cylindrical substrates are given.

1. Introduction
Multilayer composite coatings of alternating metal and/or ceramic layers are attracting increasing attention because of their excellent mechanical properties, such as high hardness, adhesive strength and wear resistance, and relatively low level of residual stresses. The layered composition turns out to be very effective when used for various types of heat-shielding coatings obtained by vacuum deposition methods. In addition, the use of vacuum deposition allows you to create thin-walled small-sized axisymmetric shell structures, for example – tubular products with a different surface profile. The process is implemented by deposition of a multilayer composite on the mandrel, which is then etched.

Previously, we carried out work on the creation and research of a similar product [3]. For this, we used the method of vacuum-arc deposition of Nb and Mo layers (the number of layers ~ 230). As a result, a layered composite with a wall thickness of ~1000 μm was obtained. However, the method had low productivity, and in the composite there were large residual stresses leading to its destruction during mechanical processing. Therefore, for further research on the creation of multilayer shell structures, the method of deposition of layers by magnetron sputtering was chosen.

Currently, magnetron sputtering is increasingly used in many industries to obtain coatings with special properties on various types of substrates. The method allows to obtain films of both pure metals and their chemical compounds (borides, nitrides, etc.).

To solve the problem of the formation of thin-walled compact axisymmetric shell structures, inverted magnetrons are most effective. Inverted magnetrons were invented in the 1960–70s [4, 5] and later various versions of their designs were developed [6, 7]. Inverted magnetrons spray material from the inner surfaces of cylindrical targets. They have a high deposition rate on the substrate, efficient use of the target material (more than 90 %), uniform distribution of the sprayed material flow and the absence (unlike vacuum arc spraying) of droplets in the deposited flow. Therefore, they proved to be very useful for solving task of work.
2. Design and study of the magnetron system

For the deposition of multilayer coatings, a system was created of 3 consecutively installed inverted magnetrons and one conventional cylindrical magnetron used for cleaning substrates. A general view of the magnetron system is shown in figure 1. The holes in the anodes along the ends of the magnetrons and the mechanism of the longitudinal movement of the holder with the substrate made it possible to freely direct the substrate into the desired magnetron and deposition the desired layer composition.

The circuit of the inverted magnetron is shown in figure 2. The anode was held at ground potential and negative high voltage was applied to the cathode. By design, our magnetron is similar to that presented in the article of D A Glocker [7]. However, there are significant differences, which are as follows (see figure 2):

– in this magnetron, in contrast to [7], the cathode has no wings that are energized by the target and are used to reflect electrons back into the trap;
– in order to restrain the discharge in the cylinder [8] and to exclude the breakdown to the anode, a screen is used in the design, which is at a floating potential.

The anode and screen are made of titanium. The inner diameter of the cathode is 37 mm, height - 24 mm. Deposition coating on longer substrates was provided by their continuous longitudinal movement.

Magnetrons showed high reliability and efficiency in operation. The deposition rate of magnetron coatings for different cathode materials was determined at the following sputtering mode: \( I_{\text{cathode}} \) – 1 A; \( U_{\text{cathode}} \) – Ta (300 V); W (345 V); Nb (240 V); Ir (350 V); \( U_{\text{substrate}} \) – 0 V; \( P_{\text{Ar}} \) – 0.2 Pa; \( t_{\text{deposition}} \) – 60 min.
The values of the deposition rates of metals on a cylindrical substrate, obtained with the developed magnetron, are presented in table 1.

| Metal      | Deposition rates, µm/h |
|------------|------------------------|
| Tantalum   | 24                     |
| Tungsten   | 30                     |
| Niobium    | 20                     |
| Iridium    | 30                     |

The operation of magnetrons for the formation of a layered Nb-Mo composite was tested at the deposition regimes of the layers Nb and Mo presented in table 2.

| Mode of sputtering Niobium | Mode of sputtering Molybdenum |
|---------------------------|-----------------------------|
| $I_{\text{cathode}}$, A  | $I_{\text{cathode}}$, A   |
| $U_{\text{cathode}}$, V  | $U_{\text{cathode}}$, V    |
| $U_{\text{substrate}}$, V| $U_{\text{substrate}}$, V  |
| $P_{\text{Ar}}$, Pa     | $P_{\text{Ar}}$, Pa        |
| 0.5                      | 0.5                        |
| 260                      | 260                        |
| 200                      | 0                           |
| 0.2                      | 0.2                        |

The absence of a bias voltage on the substrate during the deposition of Mo is caused by both about 1.5 times the larger Mo sputtering coefficient compared to Nb, and the expected significant change in morphology of the surface of the layers, as well as possible high residual stresses.

The deposition of layers of a multilayer Nb-Mo coating on a cylindrical substrate using this magnetron system was carried out under conditions of continuous displacement of the substrate along the axis of the magnetrons at a speed of 40 cm/s.

Continuous operation at the formation of Nb-Mo multilayer composite was 24 hours. The magnetron sputtering system showed stable operation in the formation of the multilayer Nb-Mo composite.

The stresses in the sputtered thin films depend on a large number of factors, including the pressure of the working gas, the magnitude of the bias voltage on the substrate, the temperature of the substrate, the angle of incidence of the sputtered atoms on the substrate, etc. This magnetron system, by moving the substrate along the axis of the magnetrons, makes it possible to spray coatings onto substrates whose length is much longer than the length of the cathode. This ability of the system at the same time provides the same angular conditions for the incidence of particles on each elementary area of a cylindrical substrate, and also reduces the end effects (reducing the deposition rate of the coating at the edges of the cathode).

According to the data of [9], the thickness of the previously deposited layer of a multilayer coating obtained by deposition at a large angle can strongly influence the stress profile of the rest of the coating. Therefore, the above property of the system to provide the same coating deposition conditions for the entire substrate surface is very important for the purposes of work, namely, reducing the stresses in the coating. At given cathode sizes, the maximum deposition angle of the sprayed particle will be 60 degrees, which refers to deposition at a large angle. However, a cosine or close to it angular distribution of the intensity of a stream of sputtered particles reduces the negative impact of this effect.

In connection with the above, the need to optimize the operating modes of the magnetron system for the formation of a thin-walled small-sized axisymmetric shell structure made of Nb-Mo laminated composite is obvious. In addition to the discharge parameters, the most important optimization parameters are the bias voltage and the substrate temperature.

3. Conclusions
The magnetron coating system presented in the article, created on the basis of inverted magnetrons, as a result of the first tests showed stable operation and made it possible to apply a multi-layer Nb-Mo composite coating on a cylindrical substrate. Further work will be carried out in the direction of
optimizing the operating parameters of the magnetron system in order to reduce stresses in multilayer composites.

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