Calculation features of the magnetic and temperature fields of planar magnetron system when sputtering magnetic targets

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Abstract. Mathematical model for temperature fields calculation in targets of magnetron sputtering systems is described. The paper shows the main ways in which the power supplied to the discharge is removed. The results of numerical simulation of the spatial temperature distribution of a magnetic target are presented. The paper also shows the results of numerical simulation, which allow to link the input power and the shape of the target with the distribution of its temperature. For the obtained temperature distributions magnetic induction distributions are calculated taking into account the loss of magnetic properties of a material when its temperature exceeds the Curie point.

1. Introduction
Magnetron sputtering systems (MSS) are widely used in various fields of technology [1, 2]. These systems allow to deposit thin films of various materials with good adhesion strength. The adhesion of films is largely defined by the processes that occur in a magnetron discharge. The nature of these processes is determined by the presence of a region of crossed electric (EF) and magnetic fields (MF) near the surface of the cathode. The magnetic induction must be within certain limits [3]. Crossed electric and magnetic fields create a so-called “magnetic trap”. Once in this trap, the electron cannot escape until it gives up its energy to the molecules, thereby ionizing them. This condition imposes an upper limit on the magnetic induction. The lower limit is associated with the possibility of an electron leaving the magnetic trap without colliding with molecules.

Thus, a magnetron discharge exists only in case of the magnetic induction component presence of at least 0.03-0.1 T above the target surface [3]. At the same time, this magnetic induction should be perpendicular to the EF strength. That is particularly important in the case of designing MSS with magnetic targets [4]. At the same time, in order to use targets with a thickness of more than 1-2 mm, it is necessary to preheat the target area above the Curie temperature [5] and limit the heat sink from the target. The most accessible method of limiting heat sink is to use shaped targets in which contact with the copper cooled plate is only on a small part of the internal surface of the target. In this case, the value and configuration of the magnetic induction can be determined only by using numerical experiments on a mathematical model that takes into account the spatial temperature distribution of the target and the dependence of the magnetic properties of target material on temperature. This paper is devoted to the creation of a mathematical model for the joint calculation of target temperatures and the magnetic induction of the system.
2. Description of mathematical models for calculating the temperature and magnetic induction in MSS

Mathematical models were created for calculations in a planar magnetron (figure 1). Magnetic induction in this magnetron is created by samarium-cobalt magnets (1). Lines of magnetic field induction are closed through the magnetic core made of steel R18 (2). When calculating, the most interesting component is the magnetic induction, directed along the target surface (Br). Therefore, it is convenient to consider the calculated values of magnetic induction (3) as the sum of the vectors of the longitudinal (Br) and transverse (Bz) components.

\[ \text{Figure 1. Geometry of the study area.} \]

There is a copper water-cooled plate (5) with a thickness of 2 mm at a distance of 2 mm from the surface of the magnetic core. The inner, shaped surface of the nickel target (4) contacts the copper plate. Taking into account the high thermal conductivity of copper, its surface temperature is constant and depends on the input power and water flow rate.

In such a statement problem can be solved in a cylindrical coordinate system in a two-dimensional formulation. However, further in this model it is planned to conduct numerical experiments with a complex geometry of the magnetic system. Therefore, we created particularly the 3-dimensional model.

To calculate the temperature distribution in a shaped nickel target (figure 2) of the MSS, a mathematical model was created based on solving the stationary heat equation:

\[ \text{div}(\lambda \text{grad} T) = Q \]  

(1)

where \( \lambda \) – is thermal conductivity, \( Q \) – is the specific power released at a given point.

Equation (1) was solved in the three-dimensional approximation in a cylindrical coordinate system. The dependence of thermal conductivity on temperature was taken into account. The specific power was released in a thin surface layer, which looked like a ring (1 in figure 2). The following boundary conditions were used in the solution:

- The temperature value on the surfaces of the target that are in contact with the copper water-cooled plate is \( T = 3300 \text{ K} \) (2 and 3 in figure 2),
- The heat flux from heated surfaces (4 in figure 2) was determined on the basis of the Stefan-Boltzmann law, taking into account the emissivity of nickel, which is 0.6.

The spatial distribution of the magnetic induction in the system was determined by solving the equation:

\[ \text{div} \mathbf{B} = 0 \]  

(2)

The magnetic induction was assumed to be zero at all boundaries at a considerable distance from the studied area. Samarium cobalt magnets are magnetized along the \( 0_z \) axis. The real magnetization curve for steel P18 and for nickel was used in calculations.
The tasks of calculating the temperature distribution and magnetic induction were solved numerically using two created mathematical models in the ANSYS program. The adequacy of the obtained results of the calculation of magnetic induction was estimated by comparing it with the data obtained in a physical experiment [5]. The adequacy of the numerical simulation results of the temperature distribution was estimated by comparison it with the well-known analytical solution for the nonstationary temperature distribution of a point source in the case of a semi-infinite medium. These comparisons made it possible to determine the necessary and sufficient splitting of the calculation area. Further this splitting of areas was used during the calculations.

The solution of the thermal task is carried out according to a given value of the input power and a predetermined geometry of its distribution, which is given by the ring radii R1 and R2 (Figure 2). The result of this solution, the temperature distribution, makes it possible to determine the limits of variation in the magnetic properties of the target material. For nickel, this limit is TK = 631K. The value of the relative magnetic permeability is assumed to be 1 in the region where the calculated value of the temperature is higher than the Curie point. Taking into account the change in the magnetic parameters of the MSS, the problem of determining the magnetic induction is solved. The area on the target surface, in which the longitudinal component of the magnetic induction exceeds the value of 0.07 T, determines the boundaries of the discharge existence. Consequently, it also determines the boundaries of the area to which the power contribution is made (R1 and R2 in Figure 2). Taking into account these new boundaries of power contribution, the thermal task is recalculated. The iterative process of recalculating thermal and magnetic tasks is considered steady in the case when the radii R1 and R2 in the two subsequent solutions differ by less than 5%.

3. Calculation results

Figure 3 shows the calculations results of the temperature distribution of nickel target with such geometry: diameter 135 mm, thickness 4 mm, diameter of area 3 (Figure 2) - 10 mm, internal diameter of area 3 (Figure 2) - 119 mm, thickness of the last two areas - 8 mm. The input power of 2 kW is distributed over the ring with R1 = 35 mm and R2 = 45 mm. The performed calculations show that in the ring area with a width of K = 17 mm, the temperature is higher than the Curie point over the entire thickness of the target. Thus, in this area there will be a loss of the magnetic properties of the target and the distribution of the magnetic induction will differ from the case with a fully magnetic target.

Figure 4a shows the results of calculations of the magnetic induction distribution for magnetron with a nickel target. The temperature at all points remains below the Curie point. Obviously, almost the entire magnetic flux closes in the target volume.

A tentative numerical calculation of the thermal task with an input power of 2 kW made it possible to obtain the temperature distribution of the target and the boundaries in which the magnetic permeability of nickel is equal to 1. Figure 4b shows the results of calculations of the magnetic...
induction, taking into account the distribution of the magnetic permeability of the target, obtained during the numerical calculation of the thermal task.

Figure 3. The temperature distribution in the cross section of the target when input power is 2 kW.

The vector distribution of magnetic induction is purely illustrative. In the calculations, we were primarily interested in the longitudinal component change of the magnetic induction on the target surface. Figure 5 shows the results of calculations of magnetic induction for the case of titanium (a), nickel completely magnetic target (b) and nickel target, the distribution of magnetic permeability for which is obtained by calculating the temperature distribution in the following cases: c - P = 2 kW, d - P = 2.5 kW (in this case, the width of the annular region with a temperature above the Curie point was K = 32 mm). Clearly, these results are significantly different from each other. Magnetic induction on the surface of a magnetic material target does not exceed 0.005 T. This induction value is not enough for the magnetron discharge existence. In the case of P = 2 and 2.5 kW above the target surface there is a region, in which the longitudinal component of the magnetic induction is sufficient for the magnetron discharge existence.

The solution of the thermal task allows us to determine the main ways of power removal from the target heating zone. The obtained results, namely, the energy fluxes in the zones in which the boundary conditions were specified, can be used to optimize the design of the MSS. Table 1 shows the results of calculations of the energy loss distribution for the studied structure of the MSS. The maximum heat flux P1 (about 80% of the input value) is carried out in the annular water-cooled zone (2 in figure 2). In the central water-cooled area P2 (3 in figure 2), the heat flux does not exceed 10% of the input power. Approximately the same amount removed by radiation P3.

4. Conclusions
1. The accuracy of calculations of the temperature and magnetic fields parameters distribution depends on the partitioning of individual elements of the system.
Figure 5. The distribution of the tangent component of the magnetic induction on the target surface.

Table 1. The calculations results of the energy loss distribution.

| P, W  | P₁, W | P₂, W | P₃, W |
|-------|-------|-------|-------|
| 2000  | 1704  | 192   | 103   |
| 2500  | 2104  | 235   | 161   |

2. The required value of the longitudinal component of magnetic induction using permanent magnets and a 4 mm nickel target thickness can be achieved only by heating its ring region above the Curie temperature.

3. The required power and geometry of a nickel shaped target can be determined only by jointly solving thermal and magnetostatic tasks.

4. The minimum value of the power invested in the nickel target in the studied geometry was 2 kW.

References
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