

Two-ply anode X-ray tube for computed tomography scanner

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Abstract. This report presents a method of the formation of tungsten layer on the graphite surface. The described method can be used to create the anode of powerful x-ray tubes for medical purposes, in particular, a computer tomograph (CT). The thermal properties of the graphite base and the deposited tungsten coating, as well as the strength of the resulting coating were studied. Thermal fields in the CT-anode with a power of 100 kW were calculated.

1. Introduction

One of the major factors determining the progress of the development of medical X-ray equipment is increasing the power of X-ray sources. This is especially important for the X-ray tube of CT. It is known that the X-ray tube is a thermal device in which more than 90% of input energy is converted into heat. Also, the focal track in tubes with a rotating anode for CT scanners is exposed to considerable temperature fluctuations (up to 1000°C per 1 mm) during a single shot. These fluctuations are repeated during the rotation of the anode. Rapidly changing stresses appear as a result of temperature changes that are accompanied by the appearance of micro-cracks on the anode surface, metal melting and evaporation. This is accompanied by degradation of the anode surface, which reduces the X-ray intensity by the absorption of radiation by protruding surface irregularities.

One of the possible effective methods of heat removal and, as a consequence, reduction of thermal and mechanical stresses is the selection of anode material and the technology of its manufacture.

The anode material must provide:

1. A thermal stability of the target made of refractory material, as the local overheating of the focal spot of the anode reaches 2500°C.
2. A high thermal capacity of the anode disk. The maximum value of the thermal capacity anode is an important parameter for the X-ray tube. The higher the value of the thermal capacity of the anode base material, the more the number of switching the tube without its overheating during the operation of CT is allowed. In addition, the high heat capacity makes it possible to minimize the size of the anode disc.
3. A high heat exchange coefficient between its components and the use of materials with a high coefficient of thermal conductivity.
4. A high emissivity of the anode surface.
5. A high atomic number of the material, because it determines the integrated intensity of radiation;
6. A coherence of thermal expansion of anode materials and the focal track material working in conditions of thermal cyclic loads.



7. A mechanical strength of the anode disc with the lowest possible moment of inertia.
8. A purity of the X-ray (no diffusion escape of the substrate material on the surface of the anode).
9. The joint of the target material with the substrate must be durable, continuous, and able to provide effective heat dissipation from the focal track of the combined anode.

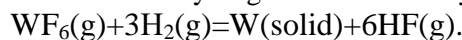
Tungsten satisfies all of these requirements. However, a disadvantage of tungsten is that it is very fragile, therefore uncomfortable to handle. In addition, the high specific weight also imposes limitations. Therefore, in modern designs of anodes, tungsten and tungsten-rhenium alloys are used as a thin target layer formed on the anode substrate having a high heat capacity.

This work is dedicated to the optimization of the method of forming a tungsten layer on the surface of the graphite substrate having high operating properties (a high specific heat, a low density and a high emissivity). The method used in this paper can be applied to create anodes of powerful x-ray tubes for medical purposes, in particular for computed tomography and angiography.

2. Experimental data

The formation of a tungsten layer on the graphite surface was performed by CVD (chemical vapor deposition). The main advantage of crystallization from the gas phase is that the deposition takes place at the atomic level. This allows getting a refractory material with a density close to the theoretical value. The coating may be applied to any form of the product. The starting material for the coating is tungsten hexafluoride.

The reaction of tungsten hexafluoride with hydrogen is described by the overall equation:



The anode is a product that works in conditions of thermal cycling. For successful operation of the anode, equal or similar coefficients of linear thermal expansion of the constituent materials are required. For that, the thermal linear expansion coefficients of a deposited tungsten coating and graphite in various directions of its compression were identified by dilatometry (Figure 1). Graphite can have two directions of the compaction: the press direction is coincident with the axis of symmetry of the anode (α_{\parallel}) and the press direction perpendicular to the axis of symmetry of the anode (α_{\perp}).

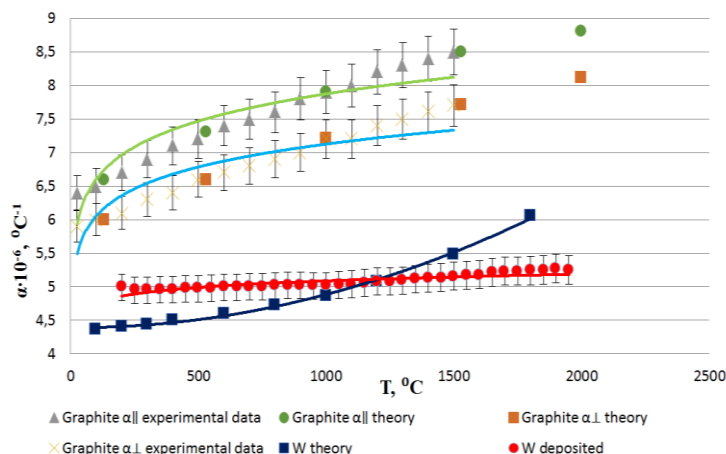


Figure 1. Coefficients of linear thermal expansion of the anode materials.

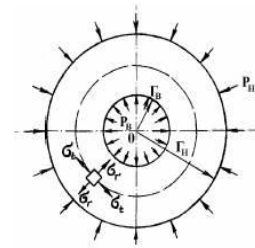
The obtained data shows that it is advisable to use graphite α_{\perp} in the direction perpendicular to the pressing axis. The difference in the thermal linear expansion coefficients of materials in this case is no more than $2 \cdot 10^{-6} \text{ K}^{-1}$.

To estimate the influence of the difference in the linear expansion coefficients of materials by Lamé equations, the internal mechanical stresses occurring at the tungsten-graphite boundary were calculated. The temperature dependence of the thermal linear expansion factor of materials can be determined using the analytical expression $\gamma = \varphi \cdot T^{0.67}$, where φ depends on the material properties.

Arising radial and hoop stresses can be written in the following form:

$$\sigma_r = -\frac{1}{R_H^2 - R_B^2} \left[P_H \cdot R_H^2 \cdot \left(1 - \frac{R_B^2}{R^2} \right) + P_B \cdot R_B^2 \cdot \left(\frac{R_H^2}{R^2} - 1 \right) \right]$$

$$\sigma_t = -\frac{1}{R_H^2 - R_B^2} \left[P_H \cdot R_H^2 \cdot \left(1 + \frac{R_B^2}{R^2} \right) - P_B \cdot R_B^2 \cdot \left(\frac{R_H^2}{R^2} + 1 \right) \right]$$



where σ_r and σ_t - radial and circumferential stresses, R - linear coordinates in the anode body, R_B and R_H - inner and outer radii, and P_B , P_H - pressure acting from the cylinder axis (inside) and to the cylinder axis (from the outside).

The internal stresses arising at the tungsten-graphite boundary with the use of graphite in the direction parallel to the pressing axis is 0.33 GPa and 0.18 GPa in the direction perpendicular to the pressing axis.

For products operating at high temperature, the efficiency of heat dissipation is an important parameter. The heat dissipation in vacuum is possible with radiation from the surface and thermal conductivity. From the analysis of the results of our studies [5] and the literature data, it is shown that the thermal conductivity of polycrystalline tungsten decreases linearly from 104 to 90 W/(m·K) with increasing the temperature from 1200 to 2400°C.

Based on our results obtained, the degree of blackness increases monotonically in the temperature range of 1200-2200 °C and its value is higher by 10-15% than that of the reference data.

In this work, the heat capacity was measured and it was showed that the specific heat of polycrystalline tungsten varied in the range of 130-160 J/(kg·K) at the temperature of 1500 to 2100 °C.

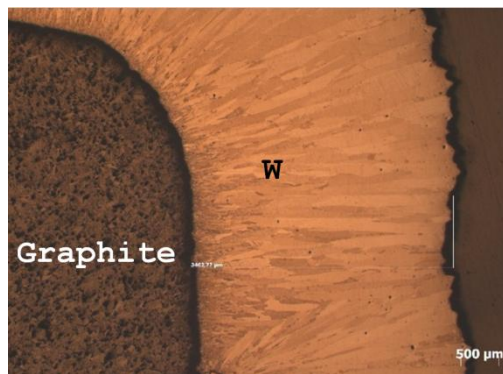
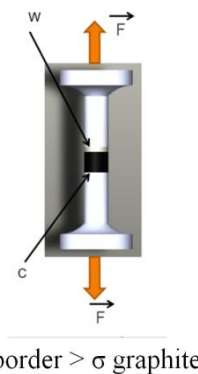


Figure 2. Structure of the deposited W coating.



$\sigma_{\text{border}} > \sigma_{\text{graphite}}$

Figure 3. Qualitative determination of the adhesion of the tungsten coating for a small sample.

To analyse the state of the boundary after the deposition of tungsten, the graphite sample was cut into several parts for metallographic analysis.

Figure 2 shows that the surface relief of the tungsten coating is 40 μm. The quality of adhesion of the applied layer to the substrate is satisfactory. To determine the quality of the adhesion of the tungsten boundary, standard graphite samples were tested using a tensile testing machine (Figure 3). It is shown that failure occurs along the body of graphite. This shows qualitatively that the strength of adhesion of the tungsten-graphite boundary is higher than the graphite tensile strength on stretching. Open pores, cavities and cracks on the tungsten-graphite boundary are not detected. The result is formation of a coating with a columnar structure, a high density, and the presence of a certain growth texture. The initial layers of the deposited tungsten consist of small grains (≤ 1 mm), which indicates the presence of a plurality of nucleation.

Taking into account the results obtained by the methods of mathematical modelling, the anode temperature fields were calculated. The maximum temperature at the tungsten-graphite boundary at 100 kW for 1 s is 1450°C, the maximum temperature on the surface of the target under the same conditions is 1800°C.

To determine the growth rate of the carbide layer (Figure 4) at the tungsten-graphite interface from temperature, a series of annealing was carried out. The carbide layer thickness was 10 µm after annealing at 1400°C for 5 h and 100 µm at 1700°C for 1 h (Figure 5).

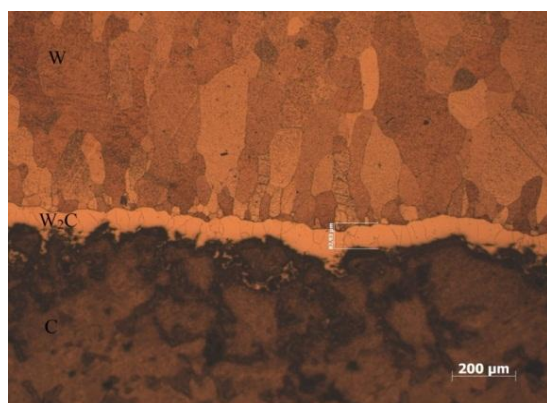


Figure 4. Structure of the tungsten-graphite boundary after annealing at 1700°C for 1 h.

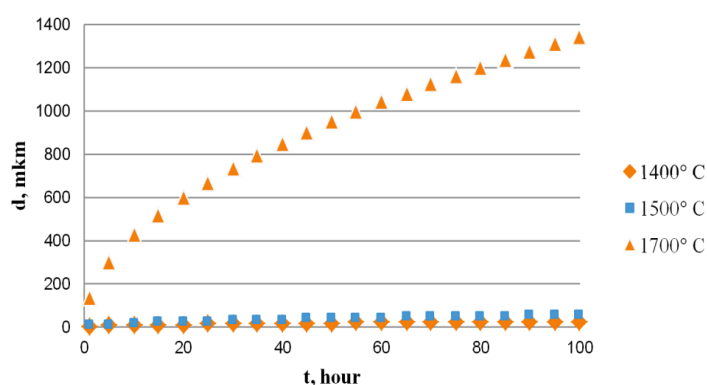


Figure 5. Dependence between the calculated thickness of the carbide layer and the time of annealing.

3. Conclusions

A calculated-experimental research of the effectiveness of the CVD method for forming a target tungsten layer on the graphite anode has been carried out. It has been shown that the given method can be regarded as an advanced one in the manufacture of X-ray tube anodes working in conditions of high-intensive, alternating mechanical and thermal loads.

Acknowledgements

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