Study on High Thermal Conductivity of X-ray Anode with Composite Diamond Substrate

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Abstract. The thermal loading capacity of the anode of a micro-focus X-ray source is an important factor to limit the output power. In this paper, a composite reflective anode model with a thick film diamond layer as the target substrate of X-ray source was proposed. With the advantage of high thermal conductivity of the diamond film, the heat accumulated in a micro-focus area can be quickly output, to improve the thermal loading capacity of the anode. A composite anode with diamond substrate was modeled and simulated with the finite element analysis method. By studying the principle of high thermal conductivity of composite anode in the numerical simulation and comparing the composite anode with copper substrate anode, the essential causes of the high thermal conductivity of the anode with diamond substrate were identified. The relevant technical parameters were obtained in the simulation and comparison, which can be used for the design of anode of micro-focus X-ray sources.

1. Introduction
There is a problem of thermal dissipation in the target during X-ray excitation process. Because a small effective excitation area (micro-focus) is desired, the electron beam density acting in the micro-focus area will be increased greatly. X-ray can be produced when the target atoms are excited by only a small fraction of the electrons. The efficiency of conversion from the electron energy into X-ray is very low (about 1%), and the remaining energy (99%) is converted into the thermal energy in the anode material[1]. The temperature in micro-focus area may be increased by the excessive thermal energy to above the melting point of the target, resulting in damage to the target material. Therefore, the thermal dissipation of X-ray source in anode micro-focus has become a research focus.

The diamond is selected as the thermal conductive substrate of the composite anode because it has a very high thermal conductivity, which can be illustrated with the calculation with the thermal conductivity formula, as shown in Fig.1. Based on Formula 1-1, under the same geometric conditions, the thermal conductivity rate Q can be determined with the thermal conductivity λ[2]. Compared with the silver with a high thermal conductivity (411W/m*K), the thermal conductivity of the diamond is in the range of 1500~2000W/m*K[3-6], which is one of the widely used thermal dissipation materials. With the diamond as the anode substrate, the thermal energy in the micro-focus area can be rapidly diffused to avoid thermal accumulation caused with a high power.
\[ Q = \lambda A \frac{dt}{b} \]  

(1)

Figure 1. The heat transfer diagram

The existing all-metal anode can be replaced with this new composite anode. As a thermal conductive substrate, a thick layer of diamond substrate was used and brazed with a conventional anode substrate material together. With the high thermal conductivity of the diamond, the thermal energy generated by high-density electrons in the micro-focus area can be dissipated quickly, to solve the problem of excess thermal energy in the micro-focus area. In this paper, the thermal conduction method in a composite X-ray anode on diamond substrate was studied, the influences of the geometric parameters of the diamond substrate on the thermal conductivity of the composite anode was analyzed, and the composite anode was compared with the traditional copper-based anode with the finite element analysis method[7-8], and the achieved results can be used as the data and theoretical supports for the future composite anode production.

2. Virtual Experiment

Most of X-ray anodes are composite all-metal ones, and are bonded mainly in the forms of laminating welding and plating. If there are no impurities, bubbles or cracks in the contact surface, in the thermal transfer theory, the anode bombarded by electron beam can be regarded as the second type of boundary condition; the surface thermal dissipation in the copper substrate can be regarded as the fourth type of boundary condition, and the thermal conduction form between various layers can be regarded as the multilayer flat plate thermal conduction model, as shown in Fig.2.

Thus, in the thermal conductivity rate \( Q \) of the anode, only three factors should be considered as below: the contact surface \( A \) between the film layers, the film thickness \( b \), and the thermal conductivity of the film material \( \lambda \). Under ideal conditions, the contact surface \( A \) between the film layers of the anode is the same and it is assumed that the thermal conductivity of the film material \( \lambda \) is a constant at different temperatures, therefore, the geometric variable is only the film thickness \( b \) and Formula 2 can be transformed as below:

\[
q = \frac{\Delta t}{\sum_{i=1}^{n} R_{\lambda,i}}
\]

(2)

\[
R = \frac{b_1}{\lambda_1} + \frac{b_2}{\lambda_2} + \ldots + \frac{b_n}{\lambda_n}
\]

In the formula, \( \Delta t \) is the temperature change value; \( R \) is the sum of film thermal resistances. When \( \Delta t \) value is constant (thermal equilibrium), the change of \( q \) is only related to the thermal resistance \( R \); that means, the thermal conductivity rate \( q \) is determined by the relationship between the thickness of
each film layer and the thermal conductivity of the materials. In the calculation, it was found that a large difference in temperature gradient distribution was caused by different thickness of each film layer. During the composite anode production process, the thicknesses of the tungsten film and the solder are constant, and only the thickness of the diamond film is a variable and there are several thickness values (0.001~1mm) of diamond films (c1~c2) as shown in Fig.2(a), therefore, the relationship between the thermal conductivity of the diamond films with different thickness and the overall anode was calculated. In order to theoretically verify the advantages of composite anodes, the overall thermal conductivity of composite anodes and copper-based anodes were compared and analyzed. The thermal conductivity comparison between the composite anode with different diamond film thicknesses and the copper-based anodes was shown in Fig.3.

![Diagram](image)

**Figure 2.** The multilayer flat plate thermal conduction model(a)The composite anode;(b)The copper-based anode.

In the multi-layer thermal transfer theory, the thickness value of the diamond film with high thermal conductivity has the highest in calculation of the total thermal resistance value; that means, the higher the volume fraction of the high thermal conductivity portion is, the smaller the overall thermal resistance value is. During the diamond film production process, there are many process parameters affecting [9]. Based on the estimated power and success rate of X-ray source, the diamond film with thickness of 0.5mm was selected as the substrate.

![Graph](image)

**Figure 3.** The thermal conductivity comparison between the composite anode with different diamond film thicknesses and the copper-based anodes
Based on the above test conditions and analysis results, the composite anode and copper substrate anode were modeled with the finite element method in this paper. During the anode production process, the tungsten film was plated on a copper based diamond surface and it was considered that the contact between tungsten and the substrate is tight, without interference parameters such as gaps and bubbles. With the thermally conductive differential equation theory, the thermal conductivity values of the tungsten film micro-area in all directions were expressed as Formula 3.

\[
\frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho c} \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) + \frac{q_v}{\rho c} 
\]

(3)

The sum of the net thermal energy and the thermal generated by the internal thermal source expressed with the formulas was the increase in thermal energy. As shown in Fig.4, when the anode surface was bombarded by the electron beam, there were the radial thermal conduction in x and z planes and the longitudinal thermal conduction in y plane on the tungsten film. Therefore, there was an increase in thermal energy in each differential unit. In the finite element analysis model, an axisymmetric cylindrical model was used for the test model, so the relationship between thermal energy and the time after the anode was bombarded by the electron beam was calculated with the thermal differential formula of solid (Formula 4).

\[
\frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho c} \left( \frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} + \frac{1}{r^2} \frac{\partial^2 t}{\partial Q^2} + \frac{\partial^2 t}{\partial z^2} \right) 
\]

(4)

**Figure 4.** The heat import and export model

For the thermal conduction surface of the composite anode with the copper substrate, if the other parameters are unchanged, the temperature increment per unit time is 0 under steady-status conditions, only the maximum temperature at the contact between the copper substrate of the tungsten film and the bottom surface of the composite anode should be calculated; that means, based on the distribution of the temperature field, the thermal transfer rate of the anode (the thermal flux density distribution) should be derived with Fourier's Law. Therefore, the temperature at the film layer junction can be determined directly by the thermal flux density. Because there is a functional relationship between the thermal conductivity and the temperature, the temperature can be found in the material thermal conductivity table1 (empirical measurements)[10-12]; the changes of thermal conductivity of tungsten, copper and diamond with temperature can provide the parameter correction for the simulation. As show in Tables 1.
Table 1. The relationship between the thermal conductivity and the temperature

| Temperature(℃) | Thermal Conductivity(W/m·K) | Copper   | Diamond  | Tungsten |
|----------------|-----------------------------|----------|----------|----------|
| 26.8           | 398                         | 1500     | 178      |
| 226.8          | 388                         | 1200     | 149      |
| 426.8          | 377                         | 800      | 131      |
| 626.8          | 364                         | 680      | 123      |
| 826.8          | 350                         | -        | 115      |
| 1726.8         | -                           | -        | 100      |
| 2326.8         | -                           | -        | 93.8     |

In the test, the thermal dissipation capacity under steady status conditions and the maximum temperature $T_{max}$ in the micro-focus areas of each film in the two anodes at different powers was simulated. However, the cause that the diamond can greatly improve the thermal transfer rate in the micro-focus area is the expansion of the thermal flux density. It was believed that the nature of the expansion is that the energy generated by the high density electron beam was rapidly transferred radially and longitudinally on the diamond film between the tungsten film and the copper substrate, to interfere with the formation of the thermal flux value with high density in geometric parameters and transfer the thermal energy into the copper substrate in a short time. In order to verify the large change in the thermal flux density inside the diamond film, the thermal flux density values on the copper substrate surface of the two anodes were sampled at the same power, to fit the relationship between the sampling positions and the thermal flux density. When the micro-focus area was applied with 50W power, the changes in thermal flux density in each film was calculated, so as to verify the thermal conductivity advantage in the micro-focus area of the composite anode.

3. Conclusion
The simulation tests showed that the temperature gradient distributions on the two anodes under electron beams with different powers were quite different, as shown in Fig.5. Under the steady-status conditions with different powers, the temperature at each film layer of the composite anode was lower than that of the copper-based anode. Therefore, the ultimate power of the composite anode was higher than the copper-based anode at the temperature below the melting point of the material. In Fig.5(a), due to the high thermal conductivity of the diamond, the temperature at solder joint interface was basically same as that at the copper substrate, and the maximum temperature was increased slowly. Due to thin solder layer and basically same thermal conductivity, the temperature increases in the solder layer and the copper substrate were very similar. Compared Fig.5(a) with Fig.5(b), the maximum temperature difference at the copper substrate interface was quite large at the same power. At the power of 50W and the copper surface temperature of 46.5℃, the temperature at the composite anode was 3.4% of the copper-based anode temperature, the critical melting point of the copper substrate and the limit power value of the copper-based anode were only within 38.6W. The thermal conductivity of the overall composite anode can be calculated with Formula 2. It was calculated that the thermal resistance $R_{copper}$ was 5.156e-5K/W and $R_{composite}$ was 5.0598e-5K/W. Calculated with the thermal resistance calculation formula, the thermal conductivity $\lambda_{composite}$ was 405.48W/m·K and $\lambda_{copper}$ was 397.95W/m·K. Through comparison, it was found that the composite anode with diamond film had a higher thermal conductivity.

Figs.6(a) and (b) showed the comparison of the thermal flux density on the copper surfaces of the composite film and the tungsten film at 50W power; in order to compare them with the thermal flux density on the copper substrate at the same thickness, the copper film with the same thickness as the composite film (Referred to as "Cu") was added, as shown in Fig.6(c). The effective thermal transfer area of the composite film was 1.54e-4m², which was 12.32 times of that of the tungsten film and 2.4 times of that of the copper film; the maximum thermal flux density at the comparative film was 2.3e7W/m², which was 2% of that of the tungsten film and 65.7% of that of the copper film. It was
proved that the contact between the diamond film and the tungsten film had a high thermal conductivity to transfer quickly the high thermal flux density in the micro-area and the role of diamond was not only to improve the overall thermal conductivity of the anode.

Figure 5. Maximum temperature of each film layer at different powers (a) The composite anode; (b) The copper-based anode.
Figure 6. (a) The thermal flux density on the copper surfaces of the composite film; (b) The thermal flux density on the copper surfaces of tungsten film; (c) The thermal flux density on the copper surfaces of “Cu” film

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