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Research Article

Effect of Carbon on the Emission Performance of Tungsten Electrode Electron in Gas Discharge Lamps

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Tungsten electrodes are widely used as electric light sources because of their excellent performance. Impurity elements, such as carbon, can be easily introduced during the preparation of lamp tubes; therefore, it is necessary to analyze the influence of carbon impurities on the performance of gas discharge lamps and propose reasonable solutions. In this study, we investigated the manner in which carbon enters a gas discharge lamp and compared the electron emission properties of carbon and noncarbon electrodes through extensive experiments. The results showed that the current density was reduced by more than 50% at 1450°C, and the most obvious change was 75.00%. Furthermore, we propose a detailed solution for the introduction of carbon, which provides technical support for the quality control of gas discharge lamps.

1. Introduction

Tungsten, which has a melting point of 3680 K, is a refractory element, second only to the melting point of carbon (4100 K). Owing to its low steam pressure, tungsten is used as a thermal electron emission material and has attracted considerable attention in the field of light sources [1]. As early as 1908, after many material selection experiments, Edison invented the first tungsten filament incandescent lamp using the tungsten filament. In 1913, Miler invented a powerful, long-lived, efficient, inflatable tungsten filament bubble. Since then, mercury lamps, xenon lamps, krypton lamps, and other gas discharge lamps have been developed and widely used in microscopes, endoscope cold light sources, and other fields. Gas discharge light is an important optical component, and its failure may cause equipment to work abnormally or even lead to serious consequences. Therefore, it is important to study the operating characteristics and failure principles of gas discharge light. The electrode is a key component of the gas discharge lamp. The structural design, material selection, and welding method of the electrode affect the photoelectric parameters and service life of the lamp [2].

Since impurities have a negative impact on the start and discharge of the gas discharge light, it is impossible to ignore the harm caused by impurities. It has been shown that impurities not only reduce the luminous maintenance rate but they can also cause an increase in the starting voltage and contraction of the discharge arc, which can result in a variety of problems such as an unstable discharge arc, easy arc extinguishment, serious electrode evaporation, shortened lamp life, and poor light color consistency [3, 4]. The effect of carbon adsorption on the surface of tungsten on the electron emission characteristics of tungsten was investigated by Márquez-Mijares et al. [5] using density functional theory calculations. A flat carbon layer was deposited on top of a clean tungsten surface, and it was demonstrated that this resulted in an increase in the surface work function and a decrease in electron density, thereby lowering the level of electron field emission.

Traxler et al. [6] believed that the carbon in a tungsten electrode can be replaced by radioactive pollution produced

by the thorium tungsten electrode. However, some researchers acknowledge that adding carbon to the WL20C600 electrode significantly increases the lamp tube's blackening. This is due to the cathode emitter evaporating and condensing in the quartz ball, which creates some unfavorable conditions for lamp operation.

We analyzed various possible carbon sources in gas discharge lamps and conducted carburization simulation experiments in this study. The experimental data were analyzed to determine the effect of carbon on the electron emission performance of tungsten electrodes and to propose feasible methods for controlling the electrode's impurity content and improving its performance. The analysis and conclusions of this paper can be applied to a variety of high-pressure lamps, such as high-pressure sodium lamps, high-pressure mercury lamps, xenon lamps, metal halide lamps, and so on [7].

2. Experimental Materials and Methods

First, a gas discharge lamp was selected for the dissection experiment. The morphology of the electrode and lamp wall was observed, and the carbon conditions were analyzed using the energy spectrum. Subsequently, a carburizing experiment was designed for the tungsten electrode, and changes in the electron emission properties of the same electrode before and after carburizing were compared. The specific method adopts the powder metallurgy method to prepare the tungsten electrode material. The tungsten electrode samples were cut into 1 mm thick sheets, embedded in carbon black, placed in a crucible, and sintered in a vacuum furnace at a sintering temperature of 1200°C.

3. Experimental Results and Discussion

3.1. Analysis of Discharge Lamp Materials. It was found that gas discharge lamps have different service lives, with some lamps having shorter service lives. To explore the performance difference of the discharge lamp, a gas discharge lamp scrapped in a short time was dissected, and microstructural observations and energy spectrum analyses were performed.

The energy spectrum analysis of the electrode surface in the gas lamp is shown in Figure 1, which shows that 8.66% of the carbon exists on the electrode. The tube surface energy spectrum showed a high carbon content (13.78%) (Figure 2). Therefore, a certain amount of carbon is present in the gas discharge lamp. The analysis of the introduction path of carbon elements and the influence mechanism on the key components of the discharge lights can help avoid introducing a carbon source and improve the service life and application stability of gas lamps. The energy spectrum analysis of the gas discharge lamp tube is shown in Figure 2. The surface energy spectrum data of the gas discharge photoelectrode are shown in Tables 1 and 2.

After the analysis, the possible sources of carbon introduced into the electrode of the gas discharge lamp are as follows:

(1) Impurity of gas inside the electrode and surface contamination: tungsten electrodes are usually prepared by powder metallurgy, which requires multiple steps, such as pressing, sintering, and machining. In powder metallurgy, a sintering neck is formed between powder particles during high-temperature sintering. Under the action of temperature, the sintered neck grew gradually. This requires the migration of the materials into the sintered compact, and the sintering neck continues to grow. Independent pores are created, the gas between the pores diffuses outward, the pores shrink, and the density increases [8]. Therefore, improper sintering can easily result in gas impurities remaining inside the tungsten electrode. During machining, organic impurities are easily introduced into the spinning hammer and grinding processes, resulting in carbon pollution.

(2) Introduction of auxiliary processes, such as welding and bonding: one way for the electrodes in the gas discharge lamp to be used is to insert a tungsten spring into a tungsten core rod and weld the equipment. The welding of the electrodes in the lamp always adopts the traditional resistance-welding method. The technology adopts upper and lower electrode discharge welding, which is pressed between the two welding electrodes by the welding parts, and a current is applied to heat it by the electric resistance heat effect generated through the contact surface and the adjacent area, thus forming metal binding. Yan ad Luo [9] found that nonmetallic impurities such as C and O and metal elements such as Cu and Na are seriously polluted after resistance welding, which affects the quality of the subsequent lamps. Organic glue is also used in the lamp assembly process, and there is the possibility of melting and volatilization in a high-temperature environment.

(3) A small amount of impurity gas is present in the gas discharge lamp. Yang et al. [10] studied the potential chemical reaction between a rare earth tungsten (RE-W) cathode and carbon dioxide (CO_2) gas at 1273 K. The experimental results showed that a thermally activated rare-earth tungsten cathode can emit electrons owing to its very low work function (2.67 eV). The emitted electrons promote the separation of CO_2 from CO, oxygen, and carbon at high temperatures. Atomic oxygen can easily combine with tungsten to form tungsten oxide. Part of the generated carbon reacts with CO_2 to generate CO, and most of the carbon is deposited on the surface of the sample and the quartz tube.

3.2. Effect of Carbon on the Electron Emission Properties of the Electrodes. To study the effect of carbon on the electron emission performance of the electrode, a carburizing experiment was designed for tungsten electrodes, and the changes in the electron emission performance of the same electrode before and after carburization were compared. The effect of carbon on the electron emission performance of the electrodes was also investigated.

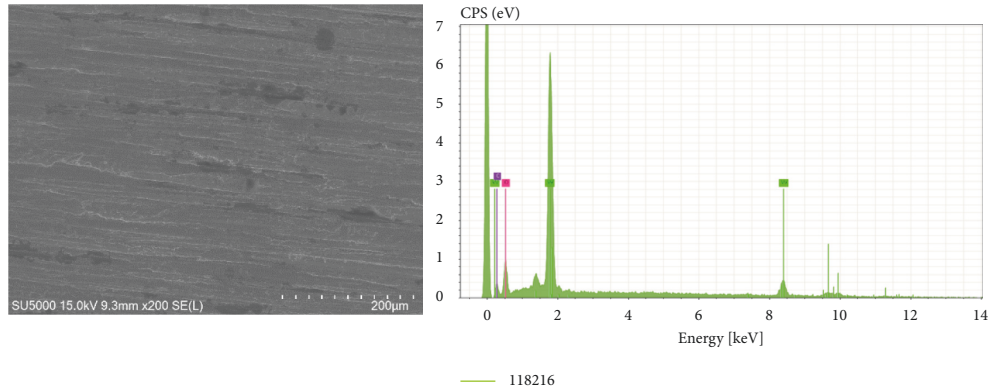


Figure 1: Energy spectrum analysis of the electrode surface in the gas lamp.

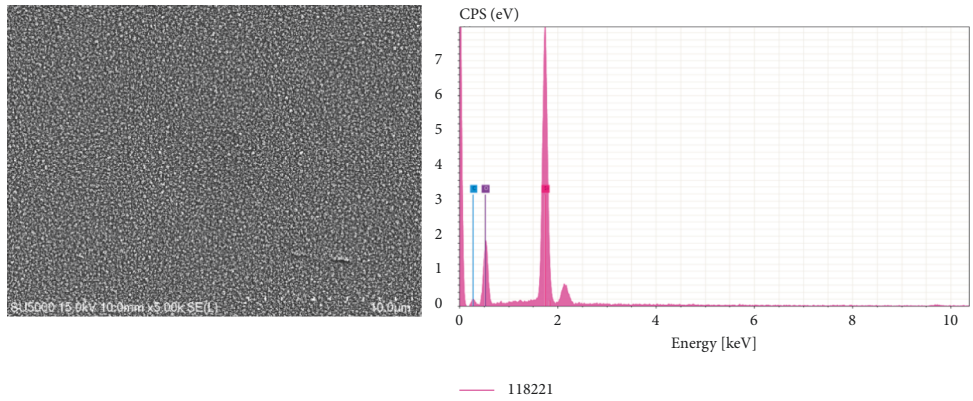


Figure 2: Energy spectrum analysis of the gas discharge lamp tube.

Table 1: Surface energy spectrum data of gas discharge photoelectrode.

Element	Mass (%)	Mass norm (%)	Atom (%)
C	7.37	8.66	36.17
O	11.56	13.59	42.61
W	66.16	77.76	21.22
SUM	85.09	100.00	100.00

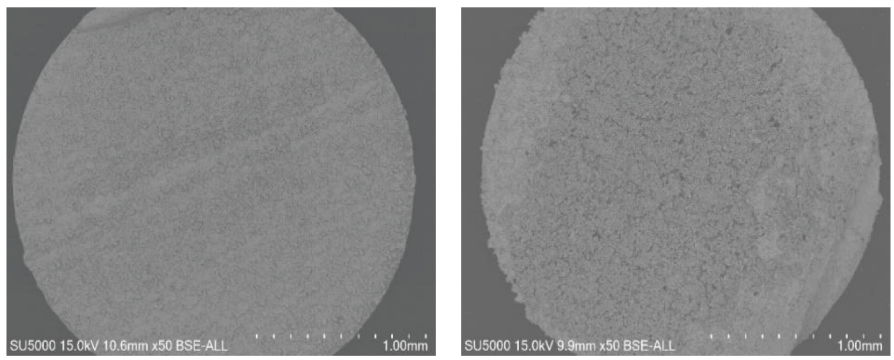
Table 2: Electrode surface energy spectroscopy data.

Element	Mass (%)	Mass norm (%)	Atom (%)
O	28.31	39.22	46.50
Si	33.92	46.99	31.74
C	9.95	13.78	21.76
SUM	72.19	100.00	100.00

3.2.1. Carburization Experiments. The surface morphologies of the samples before and after carbonation are shown in Figure 3. It can be seen that the surface morphology of the tungsten electrode changes greatly before and after carburizing, and the particles are more loosely bonded, with obvious pores. This is possible because of the reaction between the carbon and tungsten bases to produce carbides and other compounds [11], thereby changing the morphology of the sample surface.

To verify the success of the carburizing experiment, we obtained a carburized sample and analyzed the energy spectrum at five points on its surface. Figure 4 shows the distribution of carbon in the cross section of the tungsten electrode. The line graph shows that the surface of the electrode contains higher amounts of carbon. The tungsten electrode line was cut to the profile, panelled, polished, and analyzed by SEM. Figures 5 and 6 show that the distribution of carbon on the electrode fluctuated greatly. However, the carbon element was the lowest at the center, reaching 15.04%, proving that the carbon element successfully penetrated the tungsten electrode interior.

3.2.2. Cathodic Emission Current-Density Test. It has been shown that [12] the electronic emission performance of the electrode directly affects the burn resistance of the electrode, thereby affecting the service life of the electrode. The carbonized samples were cut and ground according to the test requirements, and the electron emission performance of the tungsten electrodes before and after carbonization was tested using a water-cooled anode ultrahigh vacuum dynamic system. The device includes a high-voltage power supply test system, vacuum extraction system, and high-temperature thermometer. The distance between the cathode and anode was approximately 0.5 mm, which ensured that the electric field between the cathode and anode was close to the parallel plate electric field and reduced the influence of the cathode edge emission on cathode emission. When the cathode temperature reached the working temperature, the high



(a) (b)

Figure 3: The surface topography of the electrodes (a) before carbation and (b) after carbonation.

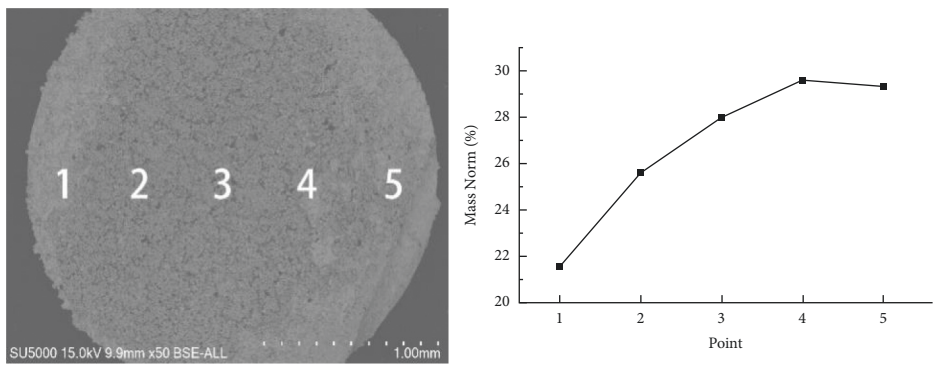


Figure 4: Distribution of carbon elements in the cross section of the tungsten electrodes.

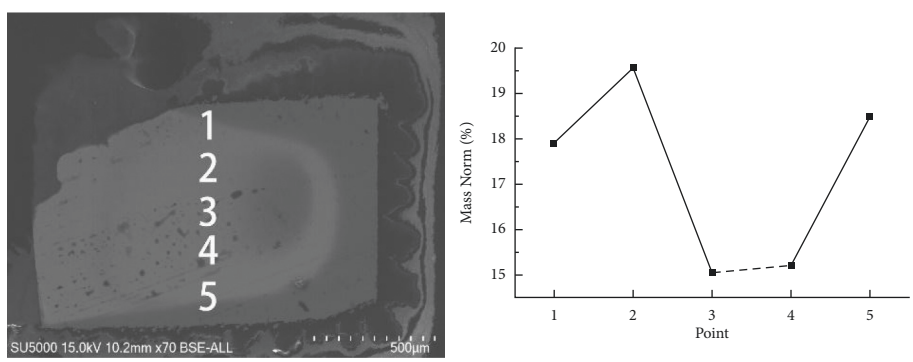


Figure 5: Distribution of carbon elements of tungsten electrode profile (Y direction).

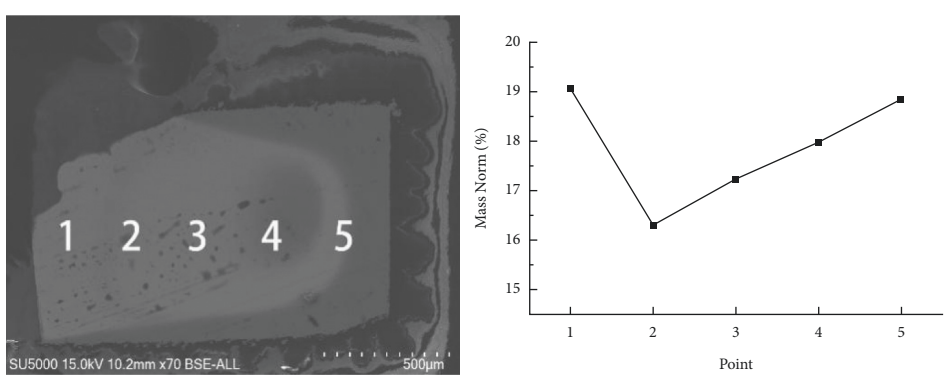


Figure 6: Carbon element distribution of tungsten electrode profile (X direction).

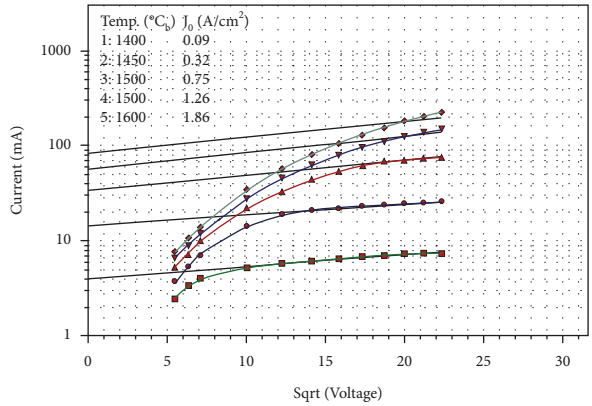


Figure 7: Zero-field emission current and current density at different temperatures of tungsten electrodes.

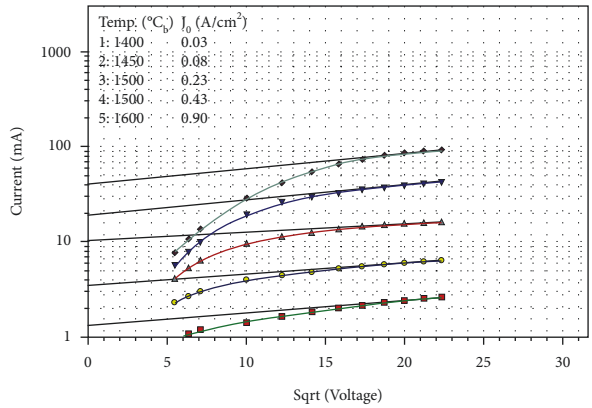


Figure 8: The zero-field emission current and current density at different temperatures of tungsten electrodes.

Table 3: Changes of emission current density at different temperatures before and after carbonation.

Test temperature (°C)	Posmotic electrode current density (A/cm^2)	After carbon seepage electrode current density (A/cm^2)	Amplitude of variation (%)
1400	0.09	0.03	↓66.67
1450	0.32	0.08	↓75.00
1500	0.75	0.23	↓69.33
1550	1.26	0.43	↓65.87
1600	1.86	0.90	↓51.61

pressure between the cathode and anode gradually increased to avoid excessive pressure and ventilation of the anode and cathode poisoning. The test temperatures were 1400, 1450, 1500, 1550, and 1600°C.

According to the measured pulse voltage and current data, the I-V curve was drawn with $lg\mathrm{I}_a$ as the ordinate and $\sqrt{U_a}$ as the abscissa. The I-V curve was drawn as the ordinate and abscissa and extended the straight line part of the I-V curve to intersect the ordinate. The intersection point represents the emission current when the accelerating electric field is zero at a given temperature I_0.

The zero-field emission current density can be obtained using the following equation:

$$J_0 = \frac{I_0}{S}. \quad (1)$$

J_0 is the zero-field emission current density, measured in A/cm^2. S is the cathodic emission area, as measured in cm^2.

Figure 7 shows the emission current and density changes in the tungsten electrodes before carburization at different temperatures. It can be observed from the diagram that the zero-field emission current and current density of the tungsten electrode increased with the test temperature.

With respect to temperature, Figure 8 depicts the changes in emission current and emission density of the carburated tungsten electrodes at several temperature levels. When comparing the two plots, the emission current of the electrode exhibits a statistically significant overall reduction trend following carbonation. Based on the data in Table 3, the effect is most noticeable when the temperature is raised to 1450°C, where the seeping electrode emission current density is reduced by 75%. After all is said and done, the

carbon element has a significant negative impact on the electron emission performance of the electrodes, and their content should be kept within a certain range before they are used in practical applications.

4. Conclusions

(1) Tungsten electrodes are widely used as electric light sources, and their application is an important cause of material failure. Through electron microscope observations, it was found that the carbon contents of the electrode surface and gas discharge lamp wall were high. To avoid the carbon effect, the material should be controlled by electrode preparation, lamp installation assistance, heat treatment exhaust, and other links.

(2) Through the simulation experiment conducted in this study, we studied the influence of carbon on the electronic emission performance of a gas discharge light electrode. The results showed that the current density was reduced by more than 50% at 1450°C, and the most obvious change was 75.00%.

In the future, we will focus on studying the effect of other elements on the electron emission properties of gas discharge lamp electrodes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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