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Design and characterization of the annular cathode high current pulsed electron beam source for circular components

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ABSTRACT

In order to irradiate circular components with high current pulsed electron beam (HCPEB), an annular cathode based on carbon fiber bunches was designed and fabricated. Using an acceleration voltage of 25 kV, the maximum pulsed irradiation current and energy of this annular cathode can reach 7.9 kA and 300 J, respectively. The irradiation current density distribution of the annular cathode HCPEB source measured along the circumferential direction shows that the annular cathode has good emission uniformity. In addition, four 9310 steel substrates fixed uniformly along the circumferential direction of a metal ring substrate were irradiated by this annular cathode HCPEB source. The surface and cross-section morphologies of the irradiated samples were characterized by scanning electron microscopy (SEM). SEM images of the surface reveal that crater and surface undulation have been formed, which hints that the irradiation energy of the HCPEB process is large enough for surface modification of 9310 steel. Meanwhile, SEM cross-section images exhibit that remelted layers with a thickness of about 5.4 μm have been obtained in all samples, which proves that a good practical irradiation uniformity can be achieved by this annular cathode HCPEB source.

1. Introduction

High current pulsed electron beam (HCPEB) has been proved to be an effective method for surface modification of different materials [1–3]. The heating and cooling rates of the HCPEB irradiation in the surface of treated material can reach 10^9 K/s [4,5]. In most cases, HCPEB irradiation is accompanied by a surface morphology change, which will improve surface properties such as hardness, wear resistance and corrosion resistance [6–9].

The cathode plays an important role in the HCPEB facility. The emission properties of different cathode materials, such as metal, graphite, metal ceramic, carbon fiber and velvet fabric, were reported in recent years [10–13].The carbon fiber, which possess low threshold voltage, big emission current density, good emission uniformity and long lifetime, has shown great potential in HCPEB process [14–17].

However, since most of the current HCPEB irradiation facilities use a planar cathode, they can only generate cylindrical electron beam. Up to present, uniform HCPEB irradiation of a circular component is still a great challenge. Some researchers divided a circular component into several uniform regions and used the same HCPEB irradiation parameters for each one, but an excess irradiation of the overlap region cannot be avoided [18]. In order to realize a uniform high current pulsed electron beam irradiation for a circular component, we designed an annular cathode for HCPEB irradiation. The principle and practical irradiation properties of the annular cathode HCPEB source are discussed.

2. Design of the annular cathode HCPEB source

Commercial carbon fiber yarns (T300-3 K, 7 μm) were used for the emission material of the annular cathode. 10–20 pieces of carbon fiber yarns were bundled together, and then tailored into a same length of 20 mm. In order to enhance the stiffness of the carbon fiber bunch, it was immersed in a 15% aluminum metaphosphate binder solution for 5 min and baked for an hour at 550 °C.

The treated carbon fiber bunches were used as the emission points for the annular cathode. As Fig. 1a shows, the annular cathode is composed of a copper ring, one inner insulator nylon cylinder, one outer insulator nylon ring, 24 copper electrodes and 72 carbon fiber bunches. On the wall of the inner insulator cylinder, three rows of holes (ϕ2.5 mm) with a transverse spacing of 15 mm were drilled, and 24 holes for each row were obtained uniformly in the circumferential direction. Carbon fiber bunches were installed into the holes of the insulate cylinder, and brazed on the

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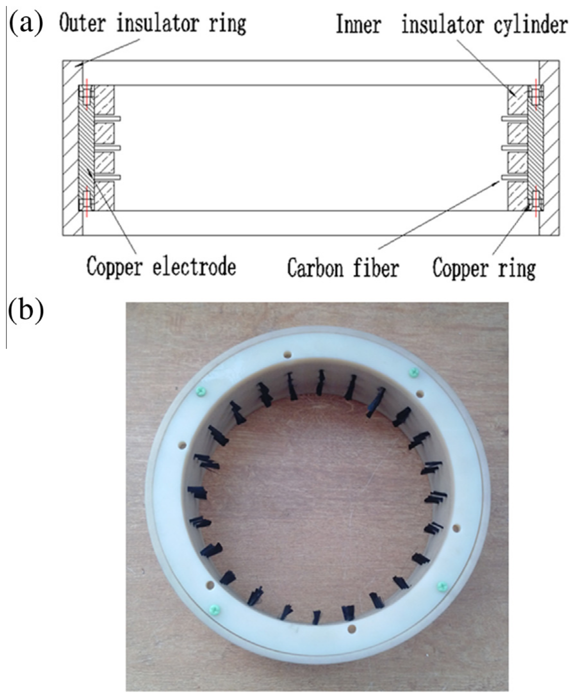

Fig. 1. Cross-section of the annular carbon fiber cathode (a) and image of the annular carbon fiber cathode (b).

copper electrode by SnPb alloy at 200–250 °C. The 24 copper electrodes were fixed on the copper ring through bolts. In order to avoid external emissions, the cooper ring and electrodes were capsulated by the outer insulator ring. The finished annular cathode is shown in Fig. 1b. Its inner diameter is about 200 mm, and a circular component with a diameter less than 150 mm can be irradiated with this annular cathode.

A high electrical field in front of the carbon fiber is essential for its explosive emission. In order to construct the electrical field, as Fig. 2 shows, a grounded metal ring was placed in the center of the annular cathode, and a pulsed bias generated by a Marx high voltage generator was applied on the copper ring of the annular cathode. During the experiment, the acceleration voltage of the pulsed electron beam was measured by a capacitive voltage divider (1:3500) and the beam current was detected by a Rogowski coil (1:500) and recorded by an oscilloscope (Tektronix, TPS2024B).

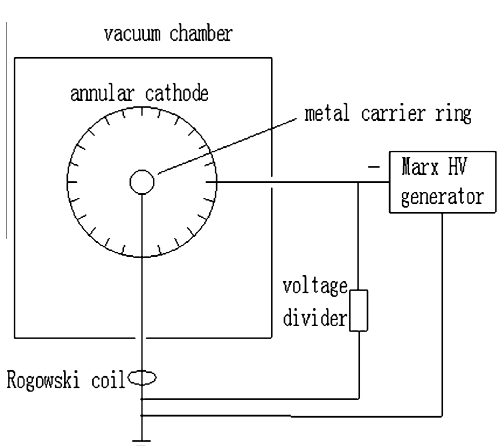

Fig. 2. Experimental configuration of annular cathode.

3. Experimental results

In 2.0×10^{-2} Pa, when a pulsed bias of about 25 kV was applied on the annular cathode, an obvious pulsed electron irradiation process has been observed. The waveforms of the acceleration voltage and the beam current of the annular cathode are shown in Fig. 3. It can be found that the peak acceleration voltage has reached about 25 kV, the peak beam current is about 7.9 kA, and the pulse duration time is about 5 μs. According to the time integral of the irradiation voltage and current, the calculated irradiation energy is approximately 300 J. However, since the electron current is so large, the acceleration voltage decreases rapidly and obvious oscillations of the voltage and the current can be found. In addition, after the first oscillation period, the magnitudes of the voltage and the current decrease rapidly and their effect on surface modification can be omitted. Therefore, we just studied the magnitudes of the voltage and the current in the first oscillation period.

In order to study the relationship between the pressure and the irradiation current, an accelerating voltage of 25 kV, an irradiation distance of 70 mm and varied pressures were employed in the experiments. The relationship between the pressure and the irradiation current is shown in Fig. 4. The obtained curve shows that an increase of the pressure will lead to a decrease of the irradiation current. When the pressure is 2.0×10^{-2} Pa, the average irradiation current has the value of 7.7 kA. When the pressure is increased to 8.0×10^{-2} Pa, the average irradiation current is about 6.5 kA. When the pressure is further increased to 5.0×10^{-1} Pa, the average irradiation current is reduced to 3.7 kA. As we know, the collision probability between electrons and neutral particles in the vacuum chamber will raise by the increase of the pressure. Since the electron density is very large in the irradiation process, the loss of electrons by collisions will increase dramatically if the pressure is high enough. When the pressure is lower than 2.0×10^{-2} Pa, because the collision probability between the electron and the neutral particle is very small, the irradiation current is close to the measured emission current of the carbon fiber bunch. Therefore, we can deduce that the increase of the irradiation current will not be obvious when the pressure is below 2.0×10^{-2} Pa. Meanwhile, the emission of the carbon fiber becomes more difficult under such conditions. As a result, the range of the working pressure for this annular cathode is selected as $2.0–8.0 \times 10^{-2}$ Pa.

Besides the working pressure, the irradiation distance, which is defined as the spacing between the annular cathode and the surface of the metal ring, may have an influence on the irradiation current. In order to study the influence of the irradiation distance, metal rings with different diameters were installed in the annular cathode. Through this method, the irradiation distance was varied

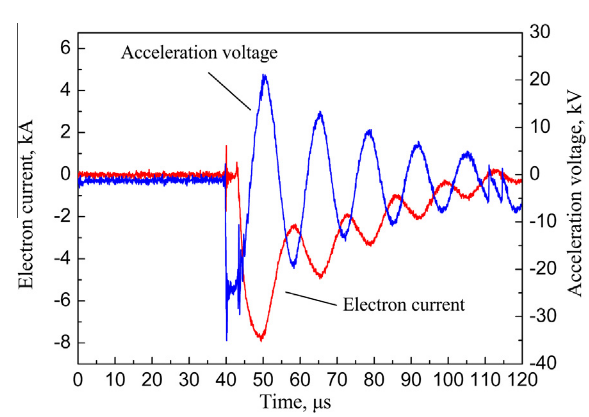

Fig. 3. Typical waveforms of the acceleration voltage and the beam current for the annular carbon fiber cathode.