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Investigation of the surface morphologies and the microstructures of graphite cathodes for explosive emission

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ABSTRACT

Graphite cathodes are ideal for explosive electron emission due to advantages of stable operation and long lifetime of over 10^6 pulses under repetitive pulsed high voltage. In this study, emission properties of two graphite cathodes, fabricated from petroleum coke (PC) and carbon black (CB) respectively, were examined at operating voltages in the range ~350–550 kV and pulse duration of 35 ns. The PC graphite cathode has superior emission properties in relation to higher currents and lower current–voltage delay times, which is probably due to greater field enhancement factor of microscopic flakes than that for round carbon black particles. The resonance tunneling of electrons through a potential barrier for the PC flakes with higher graphitization degree is also suggested. Smoothing of the cathode surfaces was found and the graphitization degree of the PC graphite cathode was decreased after 10^3 pulses as a result of continued actions of strong electric field and ion bombardment from anode plasma during explosive emission process. By contrast, the change of the graphitization degree of the CB graphite cathode was insignificant as the amorphous carbon microstructure of the carbon black was rather difficult to alter.

1. Introduction

High-current electron beams with current densities of hundreds to thousands of A/cm^{-2} at electric fields of ~10–100 kV/cm have broad applications such as high-power microwave (HPM) generation [1], surface modification of materials [2], X-ray production [3] and high-energy laser pumping [4]. Explosive electron emission (EEE) cathodes are currently the most promising choice for providing high current densities of several kA/cm^2. Application of an external high electric field leads to initiation of localized EEE and subsequently localized plasma formation, initially at inhomogeneities such as impurities, microprotrusions and sharp edges where the electric field is hundreds of times larger than the externally applied electric field. Then, the emission rapidly expands over the cathode surface as result of the spread of the plasma. The cathode plasma is the source of electrons and it has a zero or very low work function [5].

Explosive emission cathode materials vary from polymer velvet, metal-ceramic to carbon fiber and graphite. Velvet cathodes have short turn-on time for current emission, low emission threshold and uniform emittance. However, they discharge a great deal of excess gases during EEE process and the fiber tips get ablated easily after ~10^3 pulses [6,7]. Carbon fiber cathodes have long lifetime of over 10^6 pulses under repetitive pulsed high voltage, slow plasma expansion rate and low out-gassing rate. Coated with cesium iodide (CsI), the overall emission performance of carbon fiber cathodes is further improved [8–11]. Nevertheless, these carbon fiber cathodes have difficulties in uniform alignment of the fibers and secure bonding of the fibers with the substrate. Graphite cathodes are ideal for EEE due to advantages of stable operation and long lifetime of over 10^6 pulses [12,13]. However, as compared with carbon fiber cathodes, the emission current is relatively lower and the emission is less uniform for graphite cathodes. The most probable mechanism for explosive emission for graphite cathodes is field enhanced EEE from surface microprotrusions [12]. However, Fursey et al. found that the threshold fields of electron emission are extremely low from carbon nanoclusters and flake graphite structures, which cannot be explained merely by field enhancement at microprotrusions on the cathode surface. Lately, they proposed a new model explaining this effect by resonance tunneling due to size quantization [14,15]. They also found that graphite gets liquefied during EEE under the action of a very high pressure in cathode plasma and they proposed that the liquefied carbon tips secure a high stability and reproducibility of explosive emission from graphite surface [16].

Generally, graphite is a form of crystalline hexagonal carbon rings containing a significant fraction of sp^2 bonds [17]. However, depending upon the kind of raw material and the manufacturing process, graphite has microstructural diversity ranging from disordered carbon to different degrees of hexagonal carbon ring structure. Microstructural characteristics of graphite products vary

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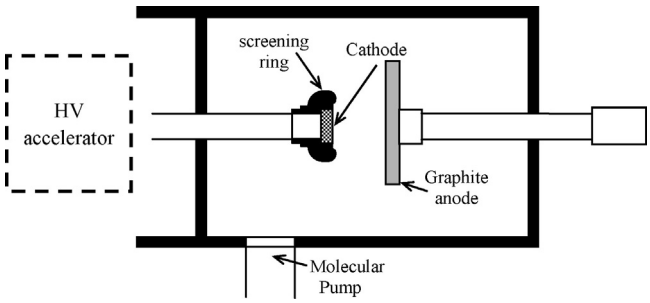

Fig. 1. Schematic diagram of the cathode testing system.

in shape and size of particle, porosity population, microcrystalline size, graphitization degree etc. Differences in microstructure of graphite cathodes could possibly influence their emission properties in relation to emission current density and cathode emission uniformity. However, the relationship between the microstructure of graphite cathode and its emission properties are not well studied. In this paper, the emission properties of two graphite cathodes, mainly fabricated from powders of petroleum coke and carbon black respectively, were examined at operating voltages in the range ~350–550 kV and pulse duration of 35 ns. The relationships between the surface morphologies and the microstructures of the graphite cathodes and their emission properties are investigated. Possible interpretations are given for changes of the surface morphology and the microstructure of the cathodes.

2. Experiment

Two types of graphite were used as cold cathodes for intense electron emission testing. Main constituents of the graphite cathodes were powders of petroleum coke and carbon black, respectively. 20 wt% medium temperature pitch was added as the binder for preparing graphite cylinder block. The graphite blocks were prepared through normal manufacturing process of graphite products. Apparent densities for the petroleum coke (PC) graphite and the carbon black (CB) graphite were 1.68 g/cm^3 and 1.55 g/cm^3, respectively. Both graphite cathodes were machined to final dimensions of Ø 30 mm × 10 mm.

The cathode testing chamber is shown in the schematic diagram of Fig. 1. The diode was housed in a stainless steel chamber. The system operated at a base pressure of 9.0×10^{-3} Pa with a molecular pump providing the vacuum. A SINUS-881 accelerator with a main air switch at 0.9 MPa provided high voltage pulses in a range of 200–600 kV to the cathode. The accelerator operated at a pulse length of 35 ns and frequencies of 1–10 Hz. The diode voltage was measured using a capacitive voltage divider, and the diode current measured using a Rogowski coil. Waveforms of the diode voltage and the diode current were monitored by a DS07104A digital oscilloscope from Agilent Technologies Inc. The average waveforms from each set of repetitive emissions for 10 pulses at 10 Hz were selected for comparison. In order to avoid the undesirable field enhancement at the cathode edge, the graphite cathode was press fit into place by a screening ring of stainless steel, which was screwed onto a stainless steel cathode rod. A graphite plate of Ø 100 mm × 10 mm was used as the anode. All cathode tests were performed at an anode–cathode (A–K) gap of 12 mm.

Surface morphologies of the cathodes were observed by scanning electron microscopy (SEM), using a Hitachi S-4800 I instrument operated at 5 kV. The microstructures of the graphite cathodes were examined by X-ray diffractometry (XRD) using a Rigaku D/Max 2550VB+ instrument, operating at 40 kV and 200 mA, with a Cu K_α radiation ($\lambda = 0.15406$ nm) scanning at a speed of 2°/min in the 2θ range of 20–30°. In order to eliminate the measurement error, grinded powders of graphite cathodes were mixed with 10 wt% silicon powder (99.9% pure) before XRD examination. Characterization of the structures of the surface layer before and after electron emission was also carried out by Raman Spectroscopy, using a Senterra instrument with a laser of 532 nm wavelength at a power of approximately 20 mW.

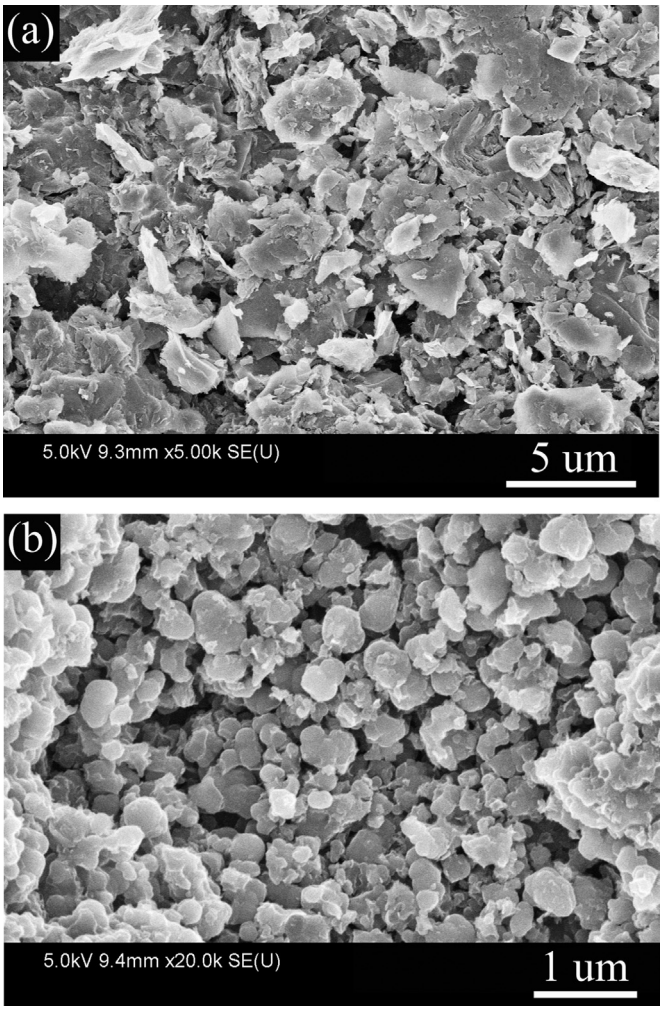

Fig. 2. Surface morphologies of graphite cathodes mainly consist of (a) petroleum coke and (b) carbon black before electron emission testing.

3. Results and discussion

Fig. 2 shows the surface morphologies of the prepared graphite cathodes before electron emission tests. The PC graphite consists of irregular-shaped flakes of petroleum coke with sizes of ~1–3 μm. By contrast, the CB graphite is composed of carbon black particles in approximately round shape and in diameters of ~200–400 nm. It is shown that pores exist between the particles on the surfaces of both graphite cathodes, with relatively more uniform distribution of pores in the CB graphite. The CB graphite has a higher porosity population and lower apparent density of 1.55 g/cm^3. Approximately 50 wt% of the medium temperature pitch transferred to graphite after the graphitization process at 2600 °C, with the rest decomposed and vaporized. Pitch-derived graphite binds the majority of petroleum coke/carbon black particles together, as shown in Fig. 2.

Fig. 3 shows the measured XRD patterns of the graphite cathodes before emission tests. Pure silicon powder was added to powders of the graphite cathodes to obtain better determination of the diffraction angle of the graphite. For the PC graphite, an