Letter

Carbon Nanotubes Fabricated at the Cathode Spot in a Vacuum Arc

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Cathodic vacuum arc plasma with graphite or graphite-metal composite cathode was ignited under medium vacuum filled with helium gas. The craters of cathode spots and their vicinities were observed using a high-resolution scanning electron microscope. Multiwall carbon nanotubes and nanocapsules were observed at the cathode spot crater. The nanotubes were further observed using a high-resolution transmission electron microscope.

Keywords: cathodic vacuum arc, graphite-metal composite cathode, cathode spot, multiwall carbon nanotubes

In the conventional carbon arc discharge method, nanotubes and nanocapsules are synthesized by the thermal arc plasma generated between two graphite electrodes under low pressure (10-100 kPa) [(1)-(3)]. Multiwall nanotubes are found at the cathode deposit, which was formed from the evaporated anode material. However, are the anode evaporation and the material transfer from the anode to the cathode necessary for nanotube growth on a cathode? This question is difficult to answer if the conventional arc discharge is used, since it always involves anode evaporation. However, a cathodic vacuum arc discharge might be available for this purpose, because in the cathodic vacuum arc, generally, an anode is inert and only acts as an acceptor of the plasma stream diffused from the cathode spot.

In this study, we ignited the cathodic vacuum arc for a short period, with graphite and graphite-metal composite cathode, under medium vacuum filled with helium (He) gas. Subsequently, the craters of cathode spot traces and their vicinities were microscopically investigated.

The cathodic vacuum arc apparatus was originally designed for thin solid film deposition of diamond-like carbon, titanium nitride, *etc* [(4),(5)]. The smaller vacuum chamber (SUS304, water-cooled, 200 mm in diameter, 320 mm in length)[(6)] was used as an anode. The cathode was located in one plane of the cylindrical chamber. The apparatus was evacuated once to lower than 0.01 Pa, and then He gas was introduced until the pressure became 0.5 Pa. The vacuum arc was ignited with a molybdenum trigger electrode rod (3 mm in diameter). Diffuse arc plasma appeared between the cathode spot and the entire anode surface. This arc plasma exhibited completely different characteristics from the thermally constricted arc plasma, which is established between the electrodes at higher pressure (generally more than 1kPa) and has been used for nanotube synthesis to date. Various metal-composite electrodes measuring 6 mm in diameter were used; pure C (purity, 99.998%), C-Ni (referring to graphite containing Ni: metal content, 3.2 wt%), C-Y (0.82 wt%), C-Fe (3 wt%), C-Ni/Y (14.6 and 4.9 wt%, respectively). The arc was operated at 100 A for discharge periods of approximately 1 s. The arc voltage was measured to be about 30 V.

After the discharge, the mark of the cathode spot or cathode spot crater was found on the cathode (C-Ni/Y) surface, as shown in fig. 1. The crater was further observed using a high-resolution scanning electron microscope (HR-SEM; Topcon, ABT-150F). Figure 2 shows the rim of the crater (square A in Fig. 1), providing a view of the deep crater (left side), the rim (center), and the original cathode surface (right side). Figure 3 is a magnified image of the rim, showing the fine nanotubes and nanocapsules. More dense nanotubes were frequently found at the bottom of the spot crater, as shown in Fig. 4 (corresponding to square B in Fig. 1). These nanotubes were verified as being multiwall using a high-resolution transmission elec-

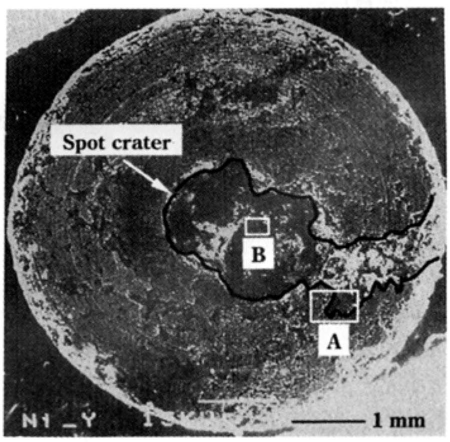

Fig. 1. SEM photograph of C-Ni/Y cathode surface.