PRELIMINARY TESTING OF CARBON-NANOTUBE FIELD EMISSION CATHODES FOR ELECTRODYNAMIC TETHERS

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Abstract

Preliminary testing of field emission cathodes using carbon nanotubes was conducted aiming at applying for electrodynamic tether propulsion. The Japan Aerospace Exploration Agency (JAXA) has performed the research and development of debris removal systems equipped with electrodynamic tethers and this study is a part of this effort. Our goal is to develop a propellant-free debris de-orbiting system by the combination of the field emission cathode and a bare tether. In the preliminary experiments, electron extraction tests of carbon nanotube cathodes made by thermal chemical vapor deposition and arc discharge process were conducted. The results showed that the carbon nanotube cathodes had sufficient emission capability for the electrodynamic tether application, although its endurance performance was not sufficient in our test. Further investigations on the durability improvement and the optimization of electrode configuration have been started.

1. Introduction

In recent decades, increase in space-debris population around the earth has become a serious problem. In order to keep safety in near-earth orbits, not only suppressing new debris production but also the mitigation of existing ones is necessary. A highly effective propulsion system is needed for the debris removal missions and electrodynamic tether (EDT) propulsion is the most promising candidate because it needs almost neither propellant nor electric power. In the Institute of Space Technology and Aeronautics, Japan Aerospace Exploration Agency (JAXA), the effort to develop an EDT propulsion system for space debris mitigation has been performed [1, 2].

This paper describes the status of a preliminary study [3, 4] on carbon nanotube (CNT) field emission cathodes (FECs) as a part of the EDT system study. The FECs have some attractive features as an electron emission device of EDTs; no working gas needed and robust mechanism. In several types of FECs, the CNT-FEC is one of the most promising devices because of its electron emission capability and high tolerance to electric breakdown.

2. Electrodynamic Tethers and Field Emission Cathodes

An EDT propulsion system essentially consists of a long electric conductive tether and plasma contactors for electron emission and collection at both the ends. The EDT generates Lorentz (JxB) force when it crosses geomagnetic field by its own orbital motion. Figure 1 depicts a typical image of the EDT system for space debris removal. In this configuration, the tether with an electron emitter at its end is deployed downward to the earth from a debris object and drag force against flight direction is generated by the interaction between the geomagnetic field and upward electric current through the tether. This electric current is driven by electromotive force caused by the orbital motion of the EDT in the geomagnetic field when a closed current loop is formed through a space plasma via plasma contactors. Since a bare tether is assumed to be used as the electron-collecting device in our plan, a totally propellant-free debris de-orbiting system is realized when the FEC is used as the electron-emitting device. The EDT can also generate thrust force to raise its altitude when the electric power enough to overcome the electromotive force is supplied and the electric current flows downward.

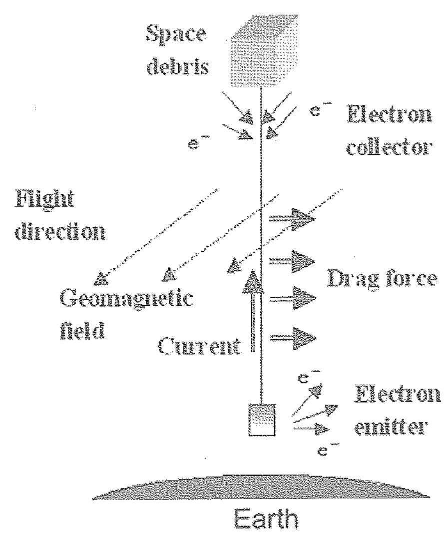

Fig. 1 Concept of EDT propulsion system for debris removal.

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An expected electric potential profile of the EDT is shown in Fig. 2. Due to the electromotive force, the tether has potential gradient along itself. When electrons are emitted from the one end, the bare tether collects equivalent electrons from an ambient plasma and the tether potential with reference to plasma space potential is determined automatically depending on the electron emission current, properties of the ambient plasma, tether geometry, geomagnetic field, and plasma contacting impedance of the electron-emitter. Redundant potential difference is consumed in a electric power generator and the power is distributed to electric devices on-board.

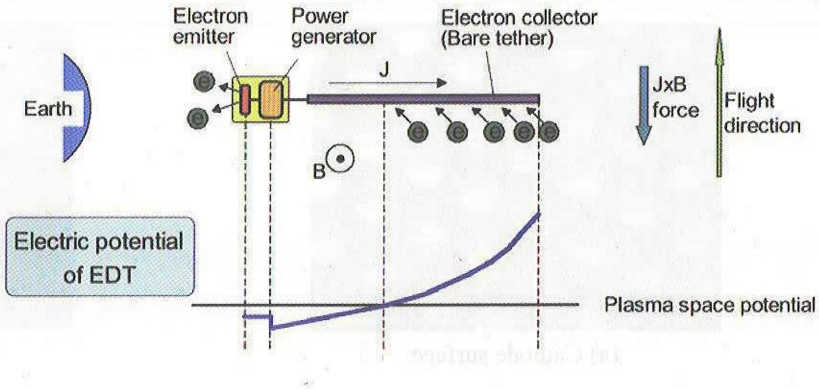

Fig. 2 Expected electric potential profile of EDT system.

There are various electron emitters for space use; filaments, electron guns, hollow cathodes, FECs, and others. In these options, FECs are suitable for the EDT de-orbiting system because they need no consumables, no warming-up time, low electric power, low contact impedance to the ambient plasma, and have robust mechanism. Figure 3 shows the expected configuration of the FEC in the EDT system. A negative potential difference of no less than 50 V should be required between the cathode and the plasma to keep sufficient electron emission and this potential drop is given as a part of the electromotive force as shown in Fig. 2. In addition to this essential potential difference, the FECs need electron extraction voltage on a gate electrode to make strong electric field adjacent to the cathode surface. Lower gate voltage, which depends on the separation distance between the cathode and the gate, is desirable for the EDT system and the FEC itself.

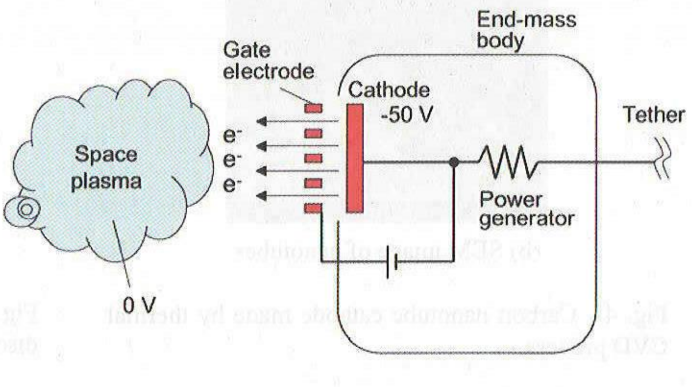

Fig. 3 Typical image of FEC in EDT system.

3. Carbon Nanotube Cathodes

In various types of FECs, CNT cathodes were selected as the first candidate of the electron emission device of our EDT propulsion system. The most important reason of the choice is that the CNT-FECs have high tolerance to electric breakdown and thus can be operated in lower vacuum condition compared with other conventional FECs such as a Spindt type field emitter. The CNT-FECs are also expected to have high tolerance to exposure to atomic oxygen in low earth orbits [5].

In our preliminary experiments, two types of CNT-FECs were tested; the CNTs made by a thermal chemical vapor deposition (CVD) process and the ones by an arc discharge process. The specifications of both the CNT samples are summarized in Table 1. Both the CVD-CNTs and arc-CNTs have multi-wall structure and the tube diameters are approximately 40 to 100 nm. In the CVD-CNTs shown in Fig. 4, nanotubes were grown directly on a metal alloy substrate, while the arc-CNTs shown in Fig. 5 were adhered on a substrate. This bonding process limited the size of the arc-CNT samples in our study. In both the samples, the substrates have many small apertures like ion-engine grids to prevent nanotubes from removing.

Table 1 Specifications of carbon nanotube cathodes fabricated.

Process	CNT structure	Diameter	Substrate
Thermal CVD	Multi-wall	50 mm *	Metal alloy
Arc discharge	Multi-wall	4 mm	Metal alloy

* The effective emission area was 45 mm in diameter.

4. Experimental setup

The electron extraction tests of the CNT samples were performed in a diode mode, which means no gate electrodes

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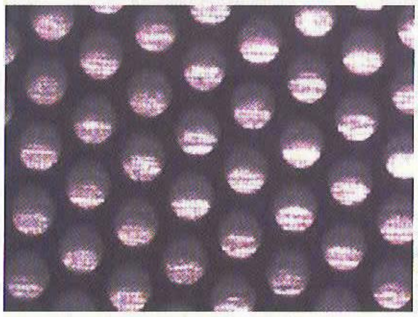
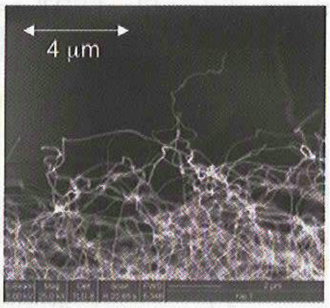
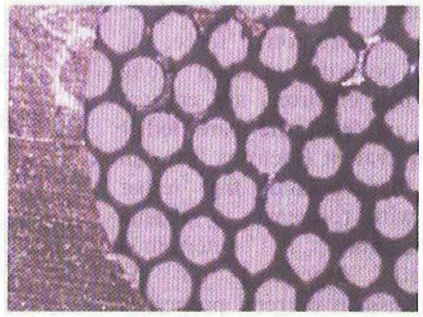


(a) Cathode surface

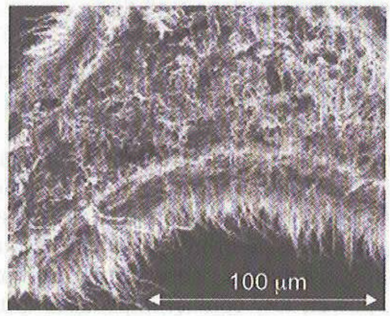


(b) SEM image of nanotubes

Fig. 4 Carbon nanotube cathode made by thermal CVD process.



(a) Cathode surface



(b) SEM image of nanotubes

Fig. 5 Carbon nanotube cathode made by arc discharge process.

were used for electron extraction. Figure 6 shows the configuration of the experiment and the electric circuit. A thin anode plate was placed parallel to the CNT emitters with the separation distance of approximately 1 mm. Negative high voltage of several kilovolts was applied on the cathode, while the anode and a vacuum chamber were earthed. Electron emission current was measured by a shunt resistance and a digital multimeter. Pressure in the vacuum chamber was less than 1 x 10^{-4} Pa throughout the experiment by turbo molecular pumping.

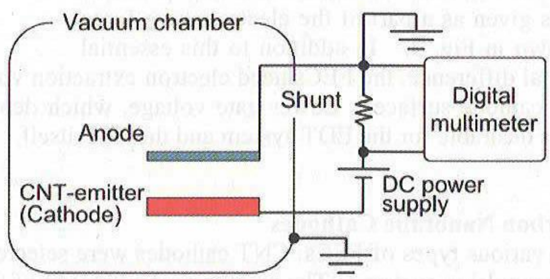


Fig. 6 Experimental setup of electron extraction test. (Diode mode operation.)

5. Experimental results

The electron emission characteristics of the CVD-CNTs and arc-CNTs were obtained in the diode mode operation. Figure 7 shows the typical emission plotted against the electric field between the electrodes. In both the CVD-CNTs and arc-CNTs cases, a threshold for emission was 1.0 to 1.5 kV/mm and the emission currents rose sharply with increase in the electric field. In these measurements, the maximum emission currents were limited by high voltage breakdown occurred between the electrodes. In the CVD-CNT cases, a 2nd current-voltage curve, which was obtained after the 1st breakdown, is also drawn and the similar behavior is observed. The rapid increases in the emission current indicate that setting and keeping the electrode separation distance in appropriate value is very important for stable FEC operations.

From Fig. 7, we can estimate the electron emission capability of the CNT cathodes. In the case of the CVD-CNT, the maximum current of approximately 120 mA was extracted from the 45 mm diameter cathode, and the arc-CNT performed 2 mA electron emission from the 4 mm cathode. The electron emission current densities of the CVD-CNTs and the arc-CNTs were approximately 8 mA/cm^2 and 16 mA/cm^2, respectively. Depending on these current densities, the required area for 1 A electron emission is estimated as 11 x 11 cm in the CVD-CNT case and 8 x 8 cm in the arc-CNT case. These sizes seem to be reasonable for the electron emission device in the EDT propulsion system.

Figure 7 demonstrated the good electron emission capability of the FECs, however, there was another problem on the FEC operation; the durability. Time-dependent characteristics of the electron emission current of the CNT

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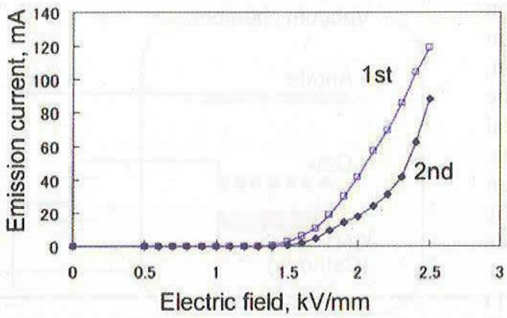
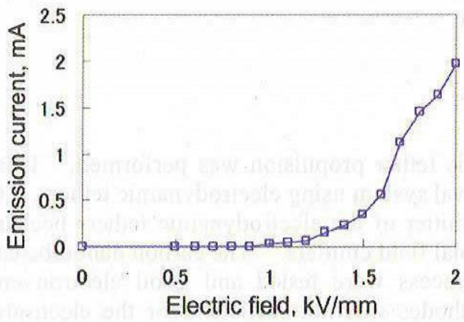
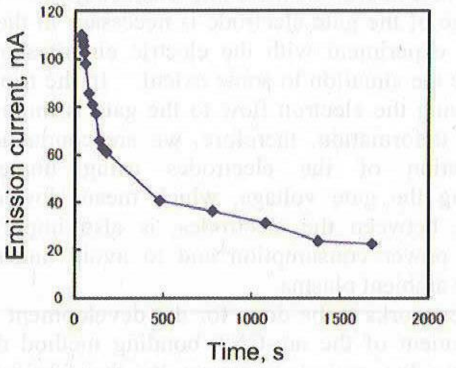


(a) CNT made by thermal CVD

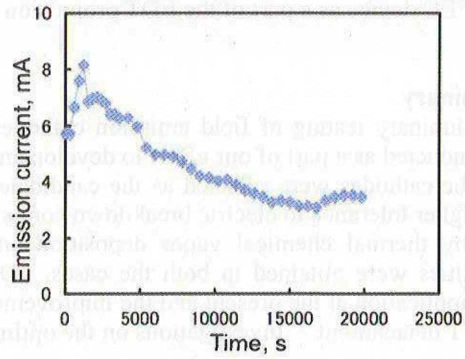


(b) CNT made by arc discharge

Fig. 7 Electron emission current plotted against electric field.



(a) CNT made by thermal CVD



(b) CNT made by arc discharge

Fig. 8 Time dependent degradation of electron emission capability.

cathodes are shown in Fig. 8. The currents were obtained under the constant cathode voltage condition in this measurement.

In the CVD-CNT operation, the emission current decreased rapidly at first and it became approximately 25 mA after 30 minutes. This saturated value is about a quarter of the initial emission current. We conducted microscopic observation after this endurance test, however, no remarkable difference between the before and after the test was observed. In addition, anticipated deposition of sputtered aluminum on the CNTs from the substrate material was so thin that its affect on the electron emission performance could be negligible. At the present, the reason of severe degradation of the emission is not clear and we are pursuing further investigations.

In the arc-CNT operation, on the other hand, the emission current declined gradually with time proceeding and it became constant at over a half value of the initial current after the 5 hours operation. The reason of the initial current rise shown in Fig. 8 (b) is not clear but it may be attributable to the change in the electrode separation distance due to thermal expansion. Figure 9 is a SEM image of the arc-CNT sample after the long time operation. This figure indicates that nanotubes were removed on a part of the substrate. Since the similar CNT detachments were observed in many sections, the popular reason of the emission degradation shown in Fig. 8 (b) should be this CNT removing problem. We think that this problem can be solved by improving the CNT bonding method on the substrate and the effort has been started.

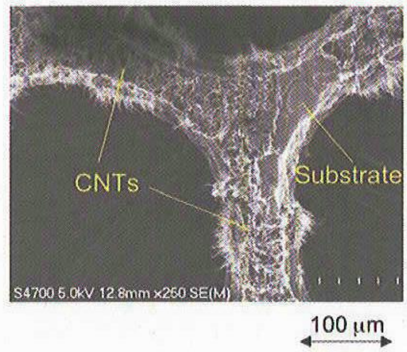


Fig. 9 SEM image of arc-CNT emitter after long time operation.

6. Future work

In order to develop an FEC device as the electron source of the EDT propulsion system, there remain some subjects to be tested. The electron extraction test in a triode mode, which is essential for on-orbit

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operation, is one of the most important subjects. As shown in Fig. 3, the usage of the gate electrode is necessary in the on-orbit operation and the experiment with the electric circuit shown in Fig. 10 can simulate the situation to some extent. In the triode mode operation, suppressing the electron flow to the gate is important to prevent the thermal deformation, therefore, we are conducting the geometrical optimization of the electrodes using numerical calculations. Lowering the gate voltage, which means lowering the separation distance between the electrodes, is also important to reduce the electric power consumption and to avoid undesirable interference with the ambient plasma.

Other works to be done for the development of the FECs are 1) improvement of the arc-CNT bonding method described above, 2) increasing the emission current by the fabrication of large-sized emitters or arrayed emitters, 3) evaluation of environmental influences on FEC operation, such as the influences of atomic oxygen, an ionospheric plasma, and ultraviolet radiation, and 4) system design of the FEC device as a part of the EDT propulsion system.

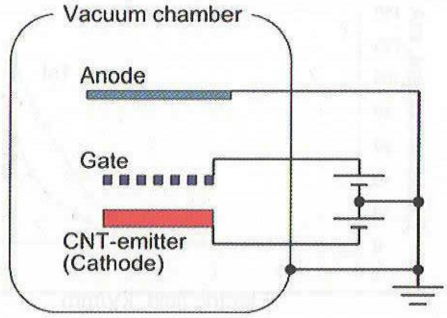

Fig. 10 Triode mode circuit for FEC operation.

7. Summary

Preliminary testing of field emission cathodes for electrodynamic tether propulsion was performed. This study was conducted as a part of our effort to develop an active debris removal system using electrodynamic tethers. Carbon nanotube cathodes were selected as the candidates of the electron emitter of the electrodynamic tethers because they have higher tolerance to electric breakdown compared with conventional field emitters. The carbon nanotube cathodes made by thermal chemical vapor deposition and arc discharge process were tested and good electron emission capabilities were obtained in both the cases. Durability of the cathodes was not sufficient for the electrodynamic tether application at the present and the improvement study on the CNT bonding method has been started for preventing the CNT detachment. Investigations on the optimization of the electrode configuration have also been started.

References

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