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LIGHT AND STRONG CNT FIBER SPUN WITH CNT WEB

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We invented a simple one-step chemical vapor deposition growth system to produce ultra-long vertically aligned multi-walled carbon nanotube arrays. Densely grown carbon nanotubes are vertically aligned on a quartz substrate. The height of the carbon nanotube array reached 2.4 mm in 20 min with a high growth rate of over 0.1mm/min. The array can easily be drawn into a web. During drawing, nanotubes are drawn with taking neighbors one after another with the aid of van der Waals force. The endless drawn web is easily fabricated into the nanotube fiber. The achieved fiber strength is 475 MPa and the probabilities of applying carbon nanotube fibers to the cables of space elevators are discussed.

I. INTRODUCTION

Carbon nanotubes (CNTs) offer remarkable characteristics of strength, heat conductance, and high electron emission [1, 2]. There are two types of carbon nanotubes. Single-walled nanotubes (SWNTs) consist of a single graphite sheet seamlessly wrapped into a cylindrical tube and its diameter ranges from 1 nm to 5 nm [3]. Multi-walled nanotubes (MWNTs) are comprised of nanotubes that are concentrically nested like rings of a tree trunk and the diameter is 5 to 100 nm [4]. We recently invented a simple one-step growth method of millimeter-long vertically aligned MWNT arrays. Our method requires no pre-process (pre-deposition) for catalyst thin film, and only requires iron chloride powder and acetylene gas [5].

To realise the strength of CNT at the macro scale, it is necessary to arrange them in highly ordered constructs such as aligned webs or yarns. The MWNT arrays gained by our method can easily be drawn into webs, and the webs are fabricated into CNT fibers of tens of meters. We present here the growth method, web-drawing and results on the mechanical properties of CNT fibers produced by our process.

II. GROWTH OF CNT ARRAY

A MWNT array was synthesized using a conventional thermal chemical vapor deposition (CVD) system (Fig. 1). A smooth quartz substrate was placed in a horizontal quartz tube furnace with $FeCl_2$ powder. When the acetylene gas is flown, MWNTs densely grow on the substrate by the mediate of chloride (Fig. 2). As shown in Fig. 3, the diameter of our MWNT is around 30 nm. MWNTs are vertically aligned on a quartz substrate. The height of the MWNT array reached 2.5 mm in 20

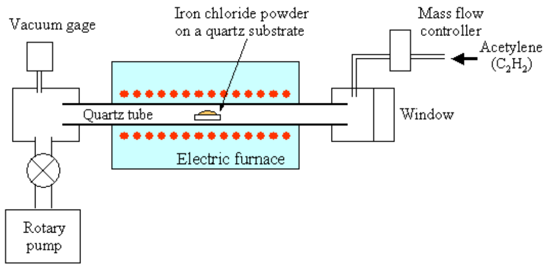

Fig. 1: Schematic of the CVD system for CNT growth.

Fig. 2: Densely aligned Multi-walled carbon nanotubes on a quartz substrate (10 x 10 x 1 mm)

min with a growth rate over 100 μm/min. This growth rate is remarkably high. The established one-step growth method offers a potentially viable MWNT mass production method. In the present system, 1g of MWNT array is produced with a growth time of 20 min, and material cost performance is as low as US$0.5/g.

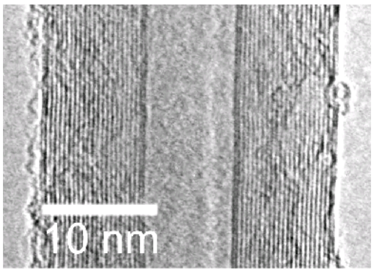

Fig. 3: Transmission electron micrograph of a multi-walled carbon nanotube grown by our method. Its diameter is 25nm.

III. DRAWING

Our MWNT array sample has a high drawable feature. The CNT web is easily drawn by pulling out the edge of the array as shown in Fig. 4.

Array samples are consistently drawable for each trial. The CNT bundle web can be drawn over 60 m with no twisting. This drawn length is limited just by the amount of CNTs on the substrate. This means that drawing a web from an array is an endless phenomenon. During drawing, CNTs are drawn with taking neighbors one after another with the aid of van der Waals force (Fig.5). Tiny CNTs are connected at surfaces with each other, and are highly aligned in the drawing direction. Therefore CNTs are also aligned in the longitudinal direction in macroscopic fibers.

Fig. 4: CNT web is drawn by tweezers from CNT array.

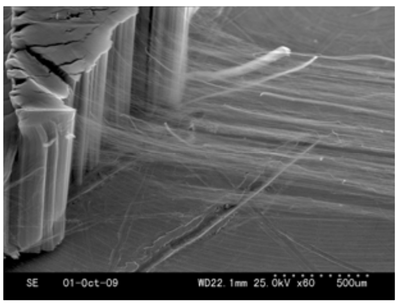

Fig. 5: Scanning electron micrograph of web drawing from CNT array.

IV. PROPERTIES OF A CNT FIBER

Our CNT fiber is made of only CNTs, and no binder material is used. Although CNTs are connected with weak van der Waals force, the tensile strength of the resulting CNT spun fiber is high. The stress-strain characteristic of a CNT spun fiber, as shown in Fig. 6(a) and (b), was measured. The gauge length is 10 mm. The achieved strength is 475 MPa as shown in Fig. 7.

Figure 8 shows the fracture portion of a CNT spun fiber that underwent the stress-strain test. Breaking each CNT is not a cause of breaking the fiber. CNT's slipping mutually and being pulled out are the causes of breaking the fiber.

Fig. 6: (a) A 27cm-long CNT spun fiber. (b) Magnified view of the fiber.

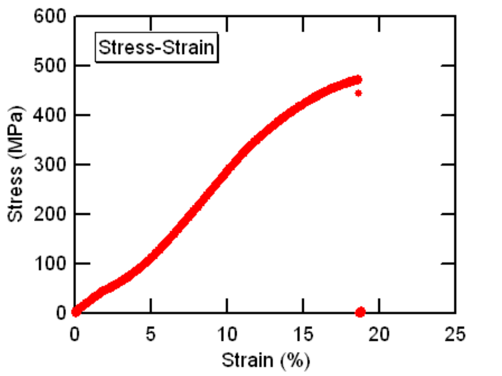

Fig. 7: Stress-strain curve of the CNT spun fiber. The gauge length is 10 mm.

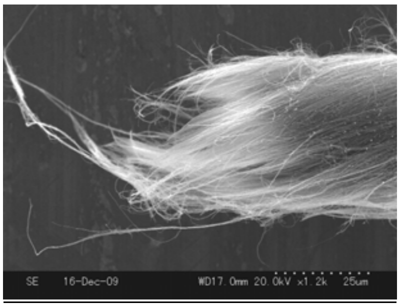

Fig. 8: Scanning electron micrograph of fracture portion of the CNT spun fiber after the stress-strain test shown in Fig. 7.

V. DISCUSSIONS FOR SPACE ELEVATOR

The breaking length is defined as the length of a thread or fiber whose weight is equal to the breaking load. For a space elevator, a cable with a breaking length of 4,960 km is necessary, if the cable has the same diameter throughout its whole length. The specific gravity of the CNT spun fiber shown in Fig. 6 is about 0.8 and the breaking length of this fiber is 61km.

If the strength of CNT fiber reaches 30 GPa, its breaking length is 3,060 km and we can drop this cable from the geosynchronous orbit and can anchor to the Earth's surface when the cable has a taper of 2.2 (Taper; Ratio of cable-diameter at geosynchronous orbit against the diameter at earth’s surface) [6]. When assuming the diameter of this cable on the ground is 1 mm, the necessary diameter at geosynchronous orbit becomes 2.2 mm and the whole weight of this CNT cable from the ground to the geosynchronous orbit becomes about 100 t. In this estimate, the specific gravity of the CNT cable is assumed to 1.0. The Delta IV Rocket would provide a geostationary transfer orbit payload of 13 t, so it is not far apart from the present technology to orbit this weight.

The highest strength for a CNT fiber is currently 9 GPa to the best of our knowledge [2]. This fiber was densified by acetone vapour and the measurement gauge length was 1 mm for the stress-strain test. Improvement of spinning technologies of CNT fibers is required for the cable of space elevators.

Table 1. Properties of various fibers.

Material	Tensile strength	Specific gravity	Breaking length
Aluminium 99.8%	0.06 GPa	2.7	2 km
Steel [7]	5	7.8	65
Glass fiber [7]	3.4	2.6	133
Kevlar 29 [8]	3.6	1.4	255
ZYLON [9]	5.8	1.5	384
TORAYCA [10]	6.4	1.8	361
Our CNT fiber	0.475	0.8	61
CNT fiber [2]	9.0	1	918
CNT molecule [11]	150	1.4	10900

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