Synthesis of carbon nanotubes by arc-discharge and chemical vapor deposition method with analysis of its morphology, dispersion and functionalization characteristics

Ritu Sharma1, Anup Kumar Sharma1* and Varshali Sharma2

Abstract: In this paper, multi-walled carbon nanotubes are synthesized by arc-discharge and chemical vapor decomposition methods. Multi-walled carbon nanotubes are synthesized on thin film of nickel sputtered on silicon substrate by thermal chemical vapor deposition of acetylene at a temperature of 750°C. The flow of current in arc-discharge method varies in the range 50–200 A. Further arc-synthesized carbon nanotubes are characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and the results are compared with nanotubes grown by chemical vapor deposition method. XRD result shows a characteristic peak (0 0 2) at 26.54° corresponding to the presence of carbon nanotubes. SEM and TEM results give morphology of as-synthesized multi-walled nanotubes. TEM results indicate synthesis of well-graphitized carbon nanotubes by arc-discharge method. Dispersion of arc-synthesized nanotubes in SDS solution under the effect of different sonication times is studied. DISPERSION OF NANO-TUBES IN SDS SOLUTION UNDER THE EFFECT OF DIFFERENT SONICATION TIMES IS STUDIED. Dispersion of nanotubes in SDS solution is analyzed using UV–vis–NIR spectroscopy and it shows an absorption peak at 260 nm. It was found that with the increase in sonication time, the absorption peak in UV–vis–NIR spectra will increase and optimum sonication time 002.

© 2015 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.
time was 2 hours. Functionalization of synthesized carbon nanotubes by $\text{H}_2\text{SO}_4$ and $\text{HNO}_3$ acids has been studied and analysis of functionalized groups has been done using FT-IR spectroscopy and compared and the results are reported in this paper. FT-IR spectroscopy verifies the presence of carboxylic groups attached to carbon nanotubes. These functional groups may change properties of carbon nanotubes and may be used in vast applications of carbon nanotubes.

Subjects: Engineering & Technology; Materials Science; Nanoscience & Nanotechnology

Keywords: electron microscopy; FT-IR spectroscopy; multi-walled carbon nanotube; X-ray diffraction

1. Introduction

Due to unique properties, carbon nanotubes attracted a lot of interest with their nanoscale cylindrical structure after being discovered by Iijima in 1991 (Iijima, 1991; Planeix et al., 1994; Saito, Fujita, Dresselhaus, & Dresselhaus, 1992). Carbon nanotubes possess unique mechanical and electrical properties depending on the varied chiralities, which is of great importance in every field of engineering (Calvert, 1999). Carbon nanotubes are classified as single-walled and multi-walled depending on the number of concentric cylindrical layers in nanostructure (Pan et al., 2007). On the basis of experimental conditions, carbon nanotubes are synthesized by three methods: (a) laser-ablation method, (b) arc-discharge method, and (c) thermal chemical vapor deposition method (Rafique & Iqbal, 2011). In laser-ablation method, a high intensity laser beam is used for the sublimation of graphite and gives high-quality and high-purity nanotubes, but the drawback is high cost of synthesis (Guo, Diener, & Chai, 1992; Scott, Arepalli, Nikolaev, & Smalley, 2001; Thess & Lee, 1996). Classically, carbon nanotubes are synthesized by arc-discharge method, in which an arc is generated in between two graphitic rods kept at a certain distance of few mm (Bethune et al., 1993; Jahanshahi & Seresht, 2009; Journet et al., 1997; Lange et al., 2003; Xing & Jia, 2007). This method is cost-efficient. Normally, carbon nanotubes are synthesized by thermal chemical vapor deposition method, in which a carbon containing gas is decomposed at high temperature in the presence of a metal catalyst (Cassell, Raymakers, Kong, & Dai, 1999; Harutyunyan, 2009; Kumar & Ando, 2010; Magrez, Seo, Smajda, Mionić, & Forró, 2010; Tian, Li, Zhao, & He, 2009). This method is best suited as it allows the control over experimental conditions.

Mostly used methods for synthesis of carbon nanotubes require vacuum systems and sophisticated inert gas handling system, pump system, etc. which increases the cost of production. Bulk synthesis of carbon nanotubes with high purity and low cost is very demanding for their applications in various fields of science. A lot of research is still going on to develop a method for low cost synthesis of high-quality and high-purity carbon nanotubes. Arc-discharge method is the cost-efficient technique for the synthesis of carbon nanotubes and the time required for CNT synthesis is also less as compared to other methods. Ishigami, Cumings, Zettl, and Chen (2000) reported a low-cost simplified-arc method for the continuous production of multi-walled carbon nanotubes in liquid nitrogen. Liquid nitrogen provides an oxygen-free environment for the reaction. This method has advantage of not using seals, pumps, inert gas handling system or water-cooled vacuum chambers, but produced multi-walled carbon nanotubes of distorted morphology. Hsin, Hwang, Chen, and Kai (2001) produced metal-filled multi-walled carbon nanotubes in deionized water. Zhu et al. (2002) produced metal-encapsulated MWCNTs in aqueous solution of $\text{NiSO}_4$, $\text{CoSO}_4$, and $\text{FeSO}_4$. Hosseini, Allahyari, and Besheli (2012) produced MWCNTs encapsulating metal particles along with nanofibers and nano-onions in which NaCl solution provides reaction environment, and iron and nickel are used as catalysts. Purification of encapsulated metal particles is quite a difficult process and may damage CNT sidewalls (Hou, Liu, & Cheng, 2008). Saravanan, Babu, Sivaprasad, and Jagannatham (2010) fabricated MWCNTs in open air using metal arc welding machine. In open air, carbon vapor may oxidize to form carbon dioxide and monoxide.

Keeping these thoughts in mind an effort is made for the synthesis of nanotubes without using metal catalyst using arc method and varying current and voltage values. The growth conditions for
carbon nanotubes are optimized. Multi-walled carbon nanotubes synthesized by arc-discharge method have been analyzed and compared with those synthesized by chemical vapor deposition method. During the synthesis of carbon nanotubes, no catalyst was used hence purification of grown CNT was easy. Further the characterization of as-produced carbon nanotubes has been done by X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) and the results are reported in this paper. Due to strong van der-Waals forces carbon nanotubes get arranged in the form of ropes, bundles, and agglomerates, in order to disperse carbon nanotubes surfactant solutions are used. Sodium dodecyl sulfate (SDS) is used as surfactant in deionized water to disperse carbon nanotubes. In this paper, the effect of sonication time on the dispersion is also studied using UV–vis spectrometry. Oxidation of as-synthesized multi-walled carbon nanotubes and analysis of functional groups attached to the sidewalls of CNT are done using FT-IR spectrometry. FT-IR shows attachment of groups that may tune the properties of CNT and this is good for the variety of applications that these CNT may be applied for.

2. Synthesis of carbon nanotubes (experimental procedure)

In the arc-discharge set-up, two graphite rods of 7 and 20 mm in diameters are used as anode and cathode electrodes, respectively. An arc is produced in between the electrodes by a DC power supply capable to provide 100–200 A current voltage range 20–30 V. The reaction environment is provided by an open vessel containing deionized water. Deionized water has good cooling capabilities and less strongly evaporating than liquid nitrogen and it is able to insulate the reaction from the atmospheric oxygen. Arc is produced manually between electrodes for time less than 1 minute after that the two electrodes are brought to a certain distance to terminate the operation. Under the effect of arc, anode electrode sublimates and carbon deposits on the cathode electrode in the form of carbon nanotubes and other form of carbon. The carbon soot deposited over cathode is collected and observed. Graphite particles with very few thick MWCNTs having diameter around 500 nm with current and voltage values 50 A and 20 V, respectively, were observed at the start of the experiment. On varying the current and voltage values for arc production between graphite rods, we get carbon nanotubes having lesser number of layers and diameter in the range 15–150 nm.

Multi-walled carbon nanotubes are also synthesized by chemical vapor deposition method in which nickel is used as catalyst and acetylene as carbon containing gas. A layer of nickel was sputtered onto a 1 cm × 1 cm dimension glass substrate. The glass substrate was placed inside the quartz tube in a ceramic boat and the furnace was heated to 750°C under the flow of hydrogen and argon. As soon as the furnace temperature reached 750°C, acetylene is allowed to flow and the flow of argon is stopped. After 30 minutes of reaction time, acetylene flow is stopped and furnace is allowed to cool to room temperature under the flow of argon.

The samples (as-synthesized CNT using arc-discharge and CVD methods) are characterized by various analysis techniques such as Nova Nano 450 field emission scanning electron microscope (SEM) operated at 15 kV, PANalytical Xpert Pro X-ray diffractometer, Tecnai G2 20 (FEI) S-Twin transmission electron microscope (TEM) operated at 200 kV. Functionalization of carbon nanotubes synthesized by arc-discharge method by various acids was analyzed by FT-IR spectroscopy. Dispersion of as-grown multi-walled nanotubes with SDS in deionized water and effect of sonication time on dispersion are analyzed by UV–vis–NIR spectrometry in the range 200–800 nm.

3. Results

3.1. X-ray diffraction

XRD is a common technique for the analysis of crystal structures and atomic spacing. Figure 1 shows the XRD pattern of carbon nanotubes synthesized by arc-discharge and chemical vapor deposition methods. Arc-discharge output was directly picked up on the glass substrate from the water surface and a thin film XRD is carried out without further purification. XRD pattern gives a peak (0 0 2) at 26.54° corresponding to carbon nanotubes oriented along the c-axis in accordance with previous reports available in the literature (Hosseini et al., 2012; Hsin et al., 2001; Saravanan et al., 2010; Zhu et al., 2002) and
The obtained XRD spectrum is in good agreement with standard JCPDF data reference (PDF#58-1638). All other peaks correspond to other forms of carbon i.e. for amorphous carbon, fullerenes, catalyst particles in case of CVD method as shown in Figure 1(b) (Mo, Kibria, & Nahm, 2001). There is no significant peak other than at 26.5° in XRD pattern for arc-synthesized nanotubes, which indicates that impurity contents are less and synthesized nanotubes are of high purity.

Figure 1. XRD pattern for as-produced CNTs (a) by arc method (thin film on glass substrate), (b) by CVD method (powder).

Figure 2. SEM micrograph of MWCNTs synthesized by (a) arc-discharge method, (b) CVD method.
It was observed from Figure 1(a) that XRD peak for arc-synthesized nanotubes has a broader peak around 26.5° indicating amorphous nature of carbon. Average crystallite size for CNTs fabricated by CVD method and arc method is 20.7 and 9.9 nm, respectively, which is obtained using Debye Scherer formula (Cullity & Rstock, 2001).

\[ D = \frac{0.94 \lambda}{\beta \cos \theta} \]  

(1) 

where \( \lambda \) is the X-ray wavelength, \( \beta \) is the full-width-half-maximum (FWHM) of the diffraction peak, and \( \theta \) is the diffraction angle.

### 3.2. Scanning electron microscopy

Scanning electron microscope is a powerful tool to get high resolution three-dimensional image of the product which provides morphological and compositional information about the material under investigation. Figure 2(a and b) shows the SEM images of carbon nanotubes synthesized by arc-discharge method and chemical vapor deposition method, respectively. It can be observed from SEM image Figure 2(a) that multi-walled carbon nanotubes grown by arc method are short, thick, and curved. While, as seen from Figure 2(b), MWCNTs synthesized by CVD method are thin, long, and curved.
straight. MWCNTs synthesized by arc method produce CNT with diameter ranging from 15 to 115 nm and very few nanotubes of diameter as low as 8 nm are also produced. CVD produced CNTs have diameter in the range 10–50 nm. Mostly MWCNTs of varying diameter are found in arc output, indicating good yield.

3.3. Transmission electron microscopy (TEM)

In order to identify the degree of crystallinity of as-produced carbon nanotubes and the presence of amorphous carbon, TEM analysis is done. As-synthesized multi-walled carbon nanotubes are dispersed in isopropanol using ultrasonication for five minutes. The isopropanol is used because it (a) is chemically inert, (b) should not result in agglomeration of the carbon nanotubes, and (c) should evaporate in a short time frame. A few drops of solution are dropped on 2-mm diameter copper grid. The grid is dried on a filter paper under an infrared lamp. TEM images reveal that CVD-synthesized nanotubes (Figure 3(b)) have less number of layers as compared to arc-synthesized nanotubes (Figure 1(a)). By viewing TEM image of Figure 3(a), it was observed that arc-synthesized MWCNTs have high crystalline outer sidewalls with nearly no sign of presence of amorphous carbon. As arc-synthesized MWCNTs have good crystallinity, the method can be used for mass production of highly crystalline carbon nanotubes by further optimization of current and voltage values.

4. Dispersion of MWCNTs in SDS solution

Due to strong van der Waals force between individual CNTs, carbon nanotubes arranged themselves in bundles. These bundle formations make nanotubes insoluble in common organic solvents, which limit the applications of carbon nanotubes. Since past decades, significant work has been done to improve the dispersion of CNTs. The best possible way to disperse nanotubes in a solution is either to add surfactants such as sodium dodecyl sulfate (Nair, Kim, Braatz, & Strano, 2008), sodium dodecyl benzene sulfate (Tan, Fang, Chen, Yu, & Wang, 2008), sodium deoxycholate (Liu, Feng, Tanaka, Urabe, & Kataura, 2010), etc. or to functionalize carbon nanotubes by various hydroxyl groups. UV–vis–NIR spectrometry is an effective method for analyzing the dispersion of individual nanotubes in a solution. UV–vis–NIR spectrometry was recorded with LAMBDA 750 (Perkin Elmer) spectrometer operating in range 200–800 nm. Figure 4 shows the UV–vis–NIR spectra for as-synthesized arc MWCNTs-SDS solution for different sonication periods.

Figure 4 depicts the effect of sonication time on dispersion of nanotubes in 1 M SDS solution. Dispersed MWCNTs have strong absorbance peak at 260 nm which can be seen from Figure 4. It was
observed that the peak in the absorbance spectra increases at the beginning of sonication process. It is due to the fact that, increasing sonication time weakens the interaction force between individual nanotubes and results in more dispersion of nanotubes (Shi, Ren, Li, Gao, & Yang, 2013). The SDS molecules adsorbed on the outer layer of MWCNTs prevent re-aggregation. At higher sonication time, the absorbance peak decreases. But sonication for a longer time will damage the carbon nanotubes, which results in lower absorbance values as shown in Figure 4, for higher sonication time. Optimum time is 2 h in this experimental work. It is observed that absorbance peak will increase on increasing sonication time up to 2 h.

5. Functionalization of CNTs by acid treatment

Use of CNTs effectively in various applications requires the improvement in dispersion of nanotubes. Wet acid oxidation is an efficient method to improve the dispersion of CNTs due to the attachment of functional groups (Martínez et al., 2003; Van Thu Le, Le, Ngo, Nguyen, & Vu, 2013; Zhang et al., 2003; Ziegler et al., 2005). These functional groups promote many electrical and chemical properties of carbon nanotubes such as reactivity, resistance, and conductivity (Balasubramanian & Burghard, 2005; Mohammed, Li, Cui, & Chen, 2014; Yang, Wang, Zhou, & Xie, 2012). Cui et al. reported that nitric and sulfuric acid-treated multi-walled carbon nanotubes show a downshift in Fermi level and significant reduction in MWNT film internal resistance (Mohammed et al., 2014). In addition, these functionalities may render dispersion of carbon nanotubes in aqueous solution and organic solvents, a highly desired property for fabrication of thin conducting films of carbon nanotubes (Peng-C, Siddiqui, Gad, & Kim, 2010). Arc-synthesized MWCTs were treated with 8 M nitric acid and 8 M sulfuric acid solution. For the acid-oxidative treatment, 0.1 g of the MWCNTs synthesized by arc method was mixed with 50 ml of one of the acid solution and heated for 3 h on a hot plate at 50°C. After heating, the solution is diluted by 10 times. In the next step, the slurry is filtered out and washed 8–9 times with distilled water to remove trace amounts of acid. Functional groups attached to carbon nanotubes are analyzed using FT-IR spectroscopy on KBr discs containing a very small amount of acid-treated nanotubes. The FT-IR spectrum was conducted on as-functionalized MWCNTs with Perkin Elmer FT-IR in a spectral range 4,000–6,000 cm⁻¹.

As shown in Figure 5 some absorption peaks are same for arc-synthesized and oxidized MWCNTs such as absorption bands at 3,436 cm⁻¹ (attributed to OH stretching), 2,926 and 2,856 cm⁻¹ (for the asymmetric and symmetric CH2 stretching), 1,632 and 1,634 cm⁻¹ (assigned to conjugated C=C bonds).
stretching), and 1,096 cm^{-1} (corresponding to C-O stretching). These common functional groups were introduced during growth and/or during purification process. As a result of acid treatment new peaks arose at 1,721–1,745 cm^{-1} corresponding to the presence of carboxylic group in accordance with previous reports available in the literature (Avilés, Cauich-Rodríguez, Moo-Tah, May-Pat, & Vargas-Coronado, 2009; Peng-C et al., 2010). These functional groups attached to nanotubes surface may tune the electrical and chemical property of carbon nanotubes and these functionalized nanotubes can be used for many applications.

6. Conclusion

Synthesis of MWCNTs using simplified arc-discharge method and chemical vapor deposition method is done and compared in this paper. As-synthesized MWCNTs are analyzed using SEM, TEM, and XRD analysis. SEM and TEM results revealed that carbon nanotubes synthesized by arc-discharge method at current and voltage values 200 A and 30 V, respectively, have good crystallinity with less impurity contents. It was observed during synthesis of carbon nanotubes that growth rate will increase at higher values of voltage and current. The synthesized nanotubes are cheap and after oxidation are ready to use in different electronic applications which definitely reduce the cost of electronic devices and can be further optimized for industrial production which has been reported in this paper. Produced crystalline MWNTs are expected to be used as field emitters. Owing to the metallic nature of MWCNTs, the nanotubes produced may be used in solar cells as conductive electrodes which reduce cost of solar cells. It is observed from UV–vis spectrometry that there is a strong dependence of nanotube dispersion on sonication time. The sonication-based dispersion study can be used to prepare homogeneous MWCNTs' dispersion for various applications. FT-IR spectra verify the presence of carboxylic group on sonication time. The sonication-based dispersion study can be used to prepare homogeneous MWCNTs’ dispersion for various applications. FT-IR spectra verify the presence of carboxylic group attachment on nanotubes. The successful attachments of these functional groups onto the surface of MWCNTs may tune properties of nanotubes and open diversified application of CNTs in biology, nanocomposite, solar cell, etc.

Acknowledgment

The MNIT, Jaipur, is acknowledged for the MRC support for the synthesis of CNTs using CVD method. The characterization using SEM, TEM, and XRD is performed at MRC-Lab, MNIT, Jaipur. The spectroscopic study using FT-IR and UV–vis–NIR spectroscopy is carried at MRC-Lab, MNIT, Jaipur.

Funding

The authors acknowledge Aquafil Polymers Co. Pvt. Ltd., Ahmedabad, Gujarat, India-380015 for funding this project.

Author details

Ritu Sharma
E-mail: ritusharma.mnit@gmail.com
Anup Kumar Sharma
E-mails: 2012rec9531@mnit.ac.in; urs.anup16@gmail.com
Varshali Sharma
E-mail: hxsadb@gmail.com

1 Electronics and Communication Department, Malviya National Institute of Technology, Jaipur, India.
2 Electronics and Communication Department, Manipal University, Jaipur, India.

Citation information

Cite this article as: Synthesis of carbon nanotubes by arc-discharge and chemical vapor deposition method with analysis of its morphology, dispersion and functionalization characteristics, Ritu Sharma, Anup Kumar Sharma & Varshali Sharma, Cogent Engineering (2015), 2: 1094017.

References

Avilés, F., Cauich-Rodríguez, J. V., Moo-Tah, L., May-Pat, A., & Vargas-Coronado, R. (2009). Evaluation of mild acid oxidation treatments for MWCNT functionalization.

Carbon, 47, 2970–2975.

Hosseini, A. A., Allahyari, M., & Besheli, S. D. (2012). Synthesis of carbon nanotubes, nano fibbers and nano union by arc discharge method using NaCl accuse as catalyst. Nanotechnology, 9, 210–211.

Balasubramanian, K., & Burghard, M. (2005). Chemically functionalized carbon nanotubes. Small, 1, 180–192.

Cassell, A. M., Raymakers, J. A., Kong, J., & DAI, H. (1999). Large scale CVD synthesis of single-walled carbon nanotubes. The Journal of Physical Chemistry B, 103, 6484–6492.

Cullity, B. D., & Stock, S. (2001). Elements of X-ray diffraction. New Jersey, NJ: Prentice Hall.

Hosseinia, A. A., Allahyari, M., & Besheli, S. D. (2012). Synthesis of carbon nanotubes, nano fibbers and nano union by electric arc discharge method using NaCl accuse as solution and Fe and Ni particles and catalysts. IJEST, 1, 217–225.

Hou, P. X., Liu, C., & Cheng, H. M. (2008). Purification of carbon nanotubes. Carbon, 46, 2003–2025.

Hsin, Y. L., Hwang, K. C., Chen, F. R., & Kai, J. J. (2001). Uranium stabilization of C28: A tetravalent fullerene. Science, 257, 1661–1664.
in water. Advanced Materials, 13, 830–833. http://dx.doi.org/10.1002/1521-4095(200106)13:11<830:AID-ADMA830>3.0.CO;2-4
Ilijima, S. (1991). Helical microtubules of graphitic carbon. Nature, 354, 56–58. http://dx.doi.org/10.1038/354056a0
Ishigami, M., Cunnings, J., Zettl, A., & Chen, S. (2000). A simple method for the continuous production of carbon nanotubes. Chemical Physics Letters, 319, 457–459. http://dx.doi.org/10.1016/S0009-2614(00)00151-2
Jahanshahi, M., & Seresht, R. J. (2009). Catalysts effects on the production of carbon nanotubes by an automatic arc discharge set up in solution. Physica Status Solidi (c), 6, 2174–2178. http://dx.doi.org/10.1002/pssc.v6.10
Journet, C., Maser, W. K., Bernier, P., Loiseau, A., Chapelle, M., Lefrant, S., ... Fischer, J. E. (1997). Large scale production of single wall carbon nano-tubes by the electric arc technique. Nature, 388, 756–758.
Kumar, M., & Ando, Y. (2010). Chemical vapor deposition of carbon nanotubes: A review on growth mechanism and mass production. Journal of Nanoscience and Nanotechnology, 10, 3739–3758. http://dx.doi.org/10.1166/jn.2010.299
Lang, H., Sioda, M., Huczko, A., Zhu, Y. Q., Kroto, H. W., & Walton, D. R. M. (2003). Nanocarbon production by arc discharge in water. Carbon, 41, 1617–1623. http://dx.doi.org/10.1016/S0008-6223(03)00111-8
Liu, H., Feng, Y., Tanaka, T., Urabe, Y., & Kataura, H. (2010). Diameter-selective metal/semiconductor separation of single-wall carbon nanotubes by agarose gel. Journal of Physical Chemistry B, 114, 9270–9276.
Magrez, A., Seo, J. W., Smajdor, R., Monic, M., & Forró, L. (2010). Catalytic CVD synthesis of carbon nanotubes: Towards high yield and low temperature growth. Materials, 3, 4871–4891. http://dx.doi.org/10.3906/mna-0910-181
Martínez, M. T., Callejas, M. A., Benito, A. M., Cochet, M., Seeger, T., Anson, A., ... Maser, W. K. (2003). Sensitivity of single wall carbon nanotubes to oxidative processing: Structural modification, intercalation and functionalisation. Carbon, 41, 2247–2256. http://dx.doi.org/10.1016/S0008-6223(03)00250-1
Mo, Y. H., Kibria, A. K. M. F., & Nahm, K. S. (2001). The growth mechanism of carbon nanotubes from thermal cracking of acetylene over nickel catalyst supported on alumina. Synthetic Metals, 122, 443–447. http://dx.doi.org/10.1016/S0379-6779(00)00565-8
Mohammed, M., Li, Z., Chen, T.-p., & Chen, T.-p. (2014). Acid-doped multi-wall carbon nanotube-MoS2 heterojunctions for enhanced light harvesting. Solar Energy, 106, 171–176. http://dx.doi.org/10.1016/j.solener.2014.03.014
Nair, N., Kim, W. J., Brotz, R. D., & Strano, M. S. (2008). Dynamics of surfactant-suspended single-walled carbon nanotubes in a centrifugal field. Langmuir, 24, 1790–1795. doi:10.1021/la70516u
Pan, X. L., Fan, Z. L., Chen, W., Ding, J. J., Luo, H. Y., & Bao, X. H. (2007). Enhanced ethanol production inside carbon nanotubes. Journal of Electrochemical Science, 2, 3712–3718. http://dx.doi.org/10.1016/j.jes.2007.08.008
Zhu, H. W., Li, X. S., Jiang, B., Xu, C. L., Zhu, Y. F., Wu, D. H., & Chen, X. H. (2002). Formation of carbon nanotubes in water by the electric arc technique. Chemical Physics Letters, 366, 664–669. http://dx.doi.org/10.1016/S0009-2614(02)01648-2
Ziegler, K. J., Gu, Z., Peng, H., Flor, E. L., Hauge, R. H., & Smalley, R. E. (2005). Controlled oxidative cutting of single-walled carbon nanotubes. Journal of the American Chemical Society, 127, 1541–1547. http://dx.doi.org/10.1021/ja044537e

Page 9 of 10
