MECHANICAL PROPERTIES OF CARBON NANOTUBES AND ITS APPLICATIONS – A REVIEW

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Abstract - *Carbon Nanotubes have a property of low density and high strength due to which they can be used in various fields such as the mechanical industry, aerospace. They are also used in many thermal-related fields due to their vast thermal-related properties. These carbon nanotubes are nothing but just the rolled-up single layer of carbon atoms. CNTs are acicular like, building the elastic parameters of a solid from single crystals of high aspect ratio which contain only a its microscopic few defects*. *The nanotubes have high Young's modulus and tensile strength, which makes them preferable for composite materials with improved mechanical properties. The nanotubes can be metallic or semiconducting depending on their structural parameters. The carbon network of the shells is closely related to the honeycomb arrangement of the carbon atoms in the graphite sheets. Mechanical is a vast emerging field for great innovations and modifications. It is necessary to achieve low weight, high strength of the materials used to manufacture machines in order to get high efficiencies or to increase the performance of the automobiles including the mechanical industry. This paper, it is shown the recapitulation of mechanical properties of carbon nanotubes including thermal, strength, and conducting properties of the Carbon Nanotubes along with their applications in various fields. A detailed note on the mechanical properties of the carbon nanotubes and its applications is given in this paper based on the previous researches made by the research scholars using specific methods for each of the property of carbon nanotubes.*

Key Words: Elastic properties, Corrosion resistance, Density, Thermal and conducting properties, Hardness.

1.INTRODUCTION

Carbon Nanotubes are manufactured from carbon which is at the diameter of nanometers. CNTs are typically classified as SWCNTs (Single-walled carbon nanotubes), DWCNTs (Double-walled carbon nanotubes), and MWCNTs (Multi-walled carbon nanotubes). Since the discovery of CNTs in the year 1991 by Iijima and Ichichashi [1] and Bethune et al. [2]. They have been used in a wide range of applications where strength and stiffness matter the most. CNTs are needle-shaped single crystals of a high aspect ratio that hardly have imperfections. DWCNTs have 2 concentric nanotubes, one over the other in which the inner tube has a smaller diameter and the outer tube has a larger diameter. Keeping the inner tube untouched, the outer tube can be recast which yields engrossing characteristics. MWCNTs comprise many concentrically interconnected nanotubes of the utmost diameter of 100 nanometers [3].

A new allotrope of carbon, Buckminsterfullerene C_{60} was invented by the group of Smalley and Kroto in 1985 for which Nobel Prize has been awarded in chemistry in 1997 [4]. The use of carbon nanotubes has been increased drastically as a reinforcement material in Polymers, Ceramics, and Metals due to their low density and tremendous theoretical strength [5].

2. METHODOLOGY

This paper shows the mechanical properties of Carbon Nanotubes by a descriptive analysis method based on the previous researches done on this material and also by some reference books. The material used is the different types of carbon nanotubes. MWCNTs are prepared by catalytic methods. The property of corrosion resistance is judged by the porosity in the acrylic matrix and epoxy coatings. Raman spectroscopy method is used to find the thermal properties of the Carbon Nanotubes along with the rule-of-mixtures, and Kerner and Schapery models.

3. MECHANICAL PROPERTIES

Mechanical properties play a major role in enhancing the efficiency and performance of mechanical machines and automobiles. In various fields like aerospace, Aluminum is used as a fundamental material because of its low weight which helps the aerial vehicle and UAVs. IN the fields related to the same purpose, CNTs can replace other materials. CNTs have interesting conducting properties, high strength, and low weight.

3.1 Elastic Properties

Modulus of Elasticity or Young's Modulus (E) is the key element to use material as a structural element. Young's Modulus is directly proportional to the cohesion of solid which is straightly connected to the chemical bonding integral atoms. Young's modulus for CNTs is at the minimum as that of graphite and also possibly higher for SWCNTs. The arc-grown MWCNTs represent a modulus almost equal to that of Graphite (Approximately 1 Tpa), but this value reduces for MWCNTs prepared by catalytic methods. The extracted value of Young's modulus increases as the imperfections in between the tube walls gets high [6]. Figure 1 gives the result that Young's modulus is inversely proportional to the disorders [7].

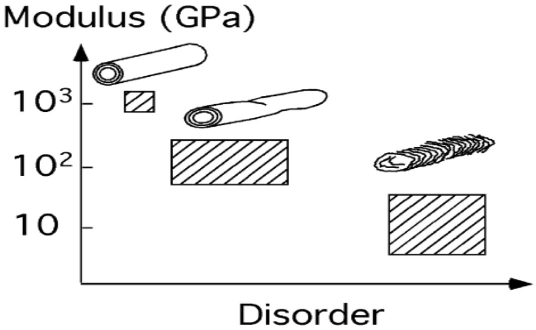

Fig - 1 Modulus vs. Disorder in MWNTs

The elastic properties of SWCNTs and MWCNTs are inconsiderate to the radius, helicity, and the layer of walls present. Shear modulus (~0.5) is relatable to that of the diamond. The Young's modulus of the CNTs decreases sharply with greater radii unless the external radius is below 5 nm and Young's modulus take a large value of 30 ± 10 GPa [8].

3.2 Corrosion Resistance

Avoiding corrosion saves billions of investments and tons of material. An experiment conducted by Dongdong Song et al. shows that the adhesion strength increases remarkably as residual stresses reduce. MWCNTs decrease the porosity in the acyclic matrix resulting in slower Water Diffusion and Absorption rate which is relatively lesser in the original acrylic coating. The Nanocomposite with 3 wt% MWCNTs drastically hyped the electrical conductivity of coating resulting in the lowering the protective capacity against the permeation of corrosion electrolyte [9].

There are several experiments conducted on the effect of carbon nanotubes on the corrosion of CNT composite. The rate of corrosion of Mg-CNT microstructure is directly proportional to wt% CNTs giving the result as an increase from 0.3 to 1.3 [10]. The dispersion of nickel coating remarkably increased the corrosion resistance and gave more positive values which result in homogenous corrosion [11].

Epoxy is also one of the highly used barrier-coating materials for critical corrosion conditions such as in the marine environment. The dispersion of MWCNTs results in the increase of adhesion strength of the epoxy coating. After adding MWCNTs, the epoxy coating became hydrophobic and the hydrophobicity of epoxy coating is directly proportional to the amount of MWCNT dispersion. It is observed that the water Diffusion and Absorption in the epoxy coating dispersed with MWCNTs was relatively less than that of non-MWCNT epoxy coating [12].

3.3 Density and Weight

The density of CNTs is typically low. The weight and density vary based on the number of walls and the diameter of inner and outer tubes. Figure 2 gives information about the relation between the weight and density of carbon nanotubes, and the number of walls and outer diameter of walls [13].

Sub-micron nanotube transistors with high performance were also manufactured based on high-density nanotubes which have been proved as high performance in terms of I_o/w and g_m/w [14].

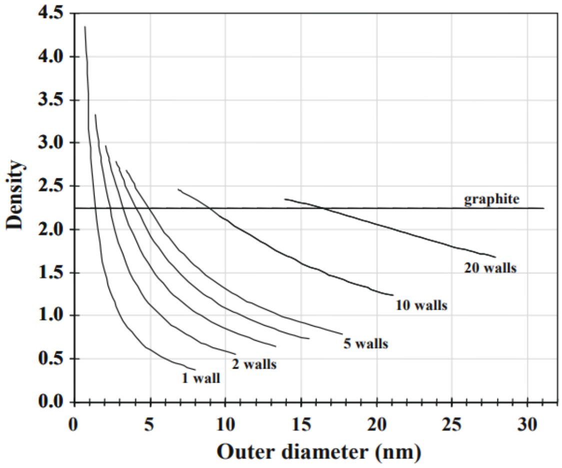

Fig - 2 Density vs. Outer diameter

3.4 Stiffness

The radial stiffness of CNTs declines sharply as the radii increases where the external diameter of CNTs is greater than 5 nm [8]. The investigation held by T. Ozaki et al. says that the SWCNTs buckling shape is highly based on the temperature of the system and is very effective to helicity under that stress below great strain at 0 K [15].

3.5 Hardness

SWCNTs do not enter the plastic region until the hardness crosses 25 GPa. The invention of Polypropylene in CNTs (PPCNT) gave a significant increase in hardness. Figure 3 represents the increase in hardness [3].

The 1% SWCNT epoxy gave a normal increase in Young's modulus by 4% and hardness by 5%. The hardness and modulus of elasticity are inversely related to the depth of the indentation [16].

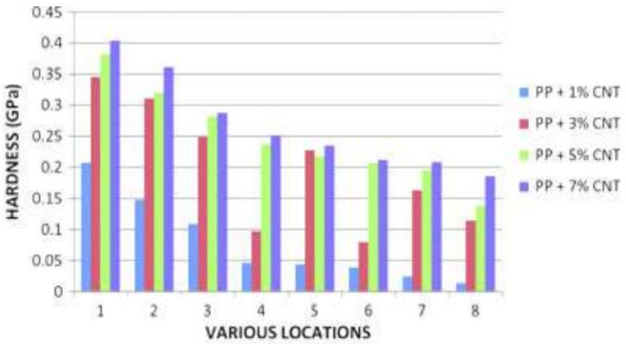

Fig - 3 Effect of CNT hardness of PP

The hardness reached utmost value at HV_{20}=151 for 6 wt% MWCNTs and this is the highest known wt% of MWCNTs. A few linking carbon Nanotubes to crack surfaces which represent a load transfer mechanism [17].

Alumina ceramic composites are manufactured by adding 0.1 wt% of various kinds of CNTs by the process of pressureless sintering (PLS), hot isostatic pressing (HIP), and sintering + hot isostatic pressing (Sinter+HIP) routes. The investigation conducted by M H Bocanegra-Bernal et al. showed that the fracture toughness increased to 63% for 0.1 wt% MWCNT-CIMAV/AL_2O_3 composites. Further improvements in toughness resulted in crack deflection, crack bridging, and CNT pull-out [18].

3.6 Electrical Conductivity

The semiconducting carbon nanotubes and graphene have a very high electron mobility of $1*10^5$ cm^2/V and $1.25*10^5$ – $2.75*10^5$ cm^2/V which are related to the manufacture of transistor developments, micro or Nanoelectronics, or electrical cables. The low dimensionality of the electronic structure is the cause of the magnificent electrical performance. An investigation has been conducted by Aljoscha Roch et al. to find the influence of surroundings on the electrical conductivity of SWCNT. The conductivity straightly depends on the oxidative agents, which results in increasing p-type conductivity. The conductivity of SWCNT networks has an influence on oxygen and moisture [19].

The improvement of K_e/K_m remains unchanged when P has a value above 100 which results in effective thermal conductivity for particles with needle shape ($P \rightarrow \infty$) which is relatively larger than that with disc shape ($P \rightarrow 0$). Hence it is proved that a large conductivity improvement has been found in the disc-shaped Nanoparticles [20].

The bulk conductivity is directly rooted in packing density. The conductive behavior is ruled by the mechanisms, which are, the rearrangement and fragmentation of agglomerates control the density in the first pressing stage and the elastic and plastic deformation decides the density in the second stage [21].

3.7 Thermal Expansion

The CTE values predicted by rule-of-mixtures (ROM), Kerner and Schapery models are higher than the obtained CTE values of 0 to 15 vol% SWNTs. The experimental values obtained by a study conducted are less than that of theoretical values. The below results shown in Figure 4 represents the reduction of CTE by 65% due to adding of SWNTs of 15 vol% to Nano-Al, which results in a great electronic packaging material [22].

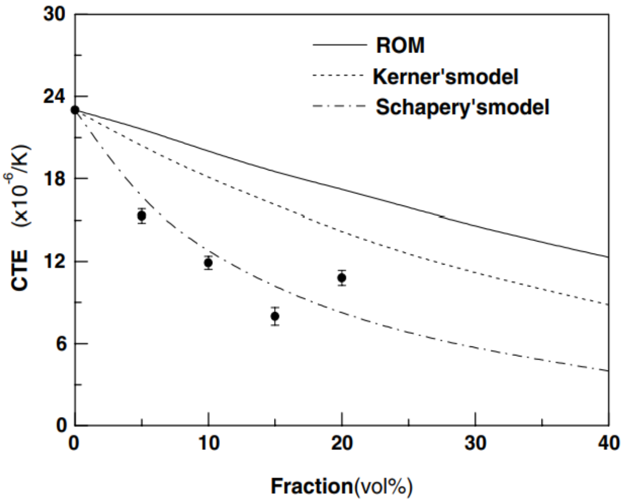

Fig - 4 Comparison between experimental CTEs and theoretical predictions for SWNT/Nano-Al composites.

The thermal expansion coefficient has been approximated to be (2.9 ± 0.4) * 10^{-5} K^{-1} at 220K for MWNTs from Figure 5. Microscopic local structural features for MWNTs and graphite are almost the same since thermal expansion is the same for both [23].

Libo Deng et al. extracted the CTEs of SWCNTs and DWCNTs by considering strain and temperature effects on the band frequency of the nanotubes. It is predicted that the value of the coefficient of thermal expansion of SWCNTs and DWCNTs are 1.9 * 10^{-5} K^{-5} and 2.1*10^{-5} K^{-1} respectively at room temperature [24].

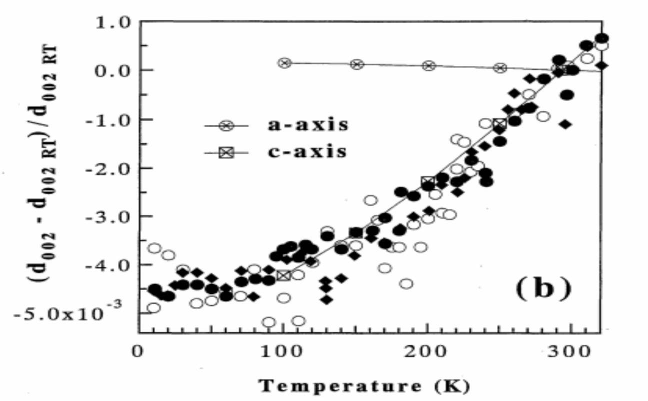

Fig - 5 Temperature dependences.

3.8 Strength

Qingzhong Zhao et al. studied the mechanism of strain-induced disorder formation of CNTs by calculations of extensive quantum mechanical and molecular mechanics to extract the ultimate strength of CNT. The characteristics of additional electric energy in a strained Nanotube are allowed to let go by spontaneous topological defects, depends on the geometry and diameter of the Nanotube. The activation energy required for the formation of defects is predicted higher than the estimated values resulting in the increase of theoretical predictions of the elastic response [25].

Graphite has the strongest sp^2 C-C bonds in its base. Its weak inter-planar bond makes the graphite less used as a structural interior. The elastic buckling shown by CNT makes them great resilient materials. The property of CNT to sustain more deflection angled elastic loads makes them accommodate some amount of energy [26].

The yield strains of SWCNT and MWCNT are 5 to 6% and 12% respectively, gave the same tensile strength of 40-50 GPa for SWCNT rope and MWCNT. CNTS having a small diameter and larger diameter yields around 9±1% and 2-3% tensile strain when the strain rate is 1%/h at 300K to expect a defect-free micrometer long single wall Nanotube [27].

4. APPLICATIONS

Basically, Nanotubes are used in the field of aerospace, energy, automobile, medicine, or chemical industries as templates, actuators, composite reinforcements, catalyst supports, probes, chemical sensors, Nano pipes, Nano-reactors, and so on [28]. Due to the chemical stability, high electrical conductivity, structural integrity, CNTs are used as electro-emitters. They are used in the manufacturing of high-resolution displays, due to their low-emission density, which is represented in Figure 6.

CNTs are used in the manufacturing of Nano-probes because of their flexibility, high mechanical strength, and high conductivity which are also used as chemical sensors. Nanotubes have strong capillary forces with which they can accommodate fluids and gases. So, they can also be used as templates. As mentioned earlier CNTS have wide tensile properties using which tuning a range of resonating frequencies is possible [29]. CNTs play a major role in the fabrication of Nanodevices which is represented in figure 7.

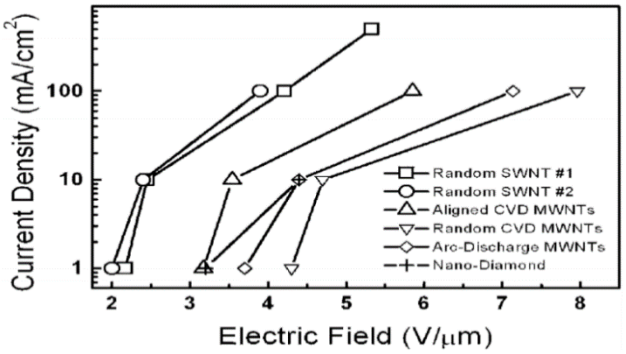

Fig - 6 for different forms of carbon nanotubes, electric field vs. current density is measured.

There are wide commercial applications of CNT since its discovery in 1991. As a result of electrochemical testing, MWCNTs electrodes are able to transfer a reversible capacity of 340mAh/g in Li-ion cells which is almost the same as a few graphite electrodes. Minimizing the structural defects of CNTs enhances the reversible lithium storage capacity [30].

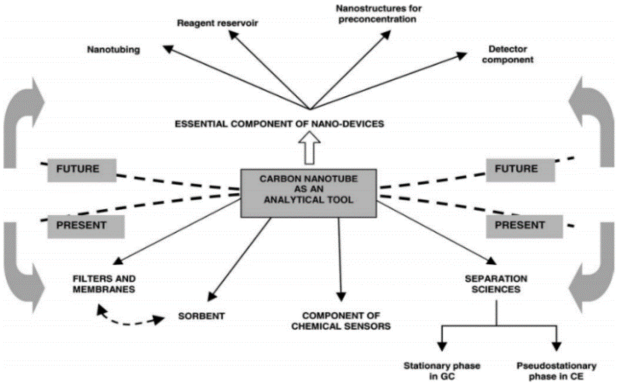

Fig - 7 Present and potential future applications of carbon Nanotubes as an analytical tool.

These nanotubes are used in fields where the properties matter such as high strength, durability, electrical and thermal conductivity along with lightweight. They are used to manufacture energy storage devices, boat hulls, sporting goods such as frames of racing bicycles, water filters, thin-film electronics, and electromagnetic shields. They are also used in the Medical and Pharmacy fields.

They are mainly used for gene delivery to cells, tissue regeneration, and biosensor diagnostics and analysis.

5. CONCLUSIONS

In summary, we can conclude that the CNTs are materials that have high strength, and low density. Since they also have thermal and electrical conducting properties, they can be used in other fields. From the previous researches, it is shown that the Elasticity of CNTs is approximately 30±10 GPa, has a great corrosion resistive property, low density, and a hardness of about 25 GPa. The electron mobility of semiconducting Nanotubes is $1*10^5$ cm^2/V and can withstand a strength of 40-50 GPa.

REFERENCES

[1] Iijima, S. (1991). Helical microtubules of graphitic carbon. nature, 354(6348), 56-58.

[2] Bethune, D., Kiang, C., de Vries, M. et al. Cobalt-catalysed growth of carbon nanotubes with single-atomic-layer walls. Nature **363,** 605–607 (1993). https://doi.org/10.1038/363605a0.

[3] Krishnan, Akshay & Shandilya, Sarthak & Gupta, Pushparaj & Hs, Balu. (2020). A Review on Applications of Carbon Nanotubes in Automobiles. 11. 204-210.

[4] Dai, H. (2002). Carbon nanotubes: opportunities and challenges. Surface Science, 500(1-3), 218-241.

[5] Bradbury, Christopher & Gomon, Jaana-Kateriina & Kollo, Lauri & Kwon, Hansang & Leparoux, Marc. (2014). Hardness of Multi Wall Carbon Nanotubes reinforced aluminium matrix composites. Journal of Alloys and Compounds. 585. 362-367. 10.1016/j.jallcom.2013.09. 142..

[6] Salvetat, JP., Bonard, JM., Thomson, N. et al. Mechanical properties of carbon nanotubes. Appl Phys A **69,** 255–260 (1999). https://doi.org/10.1007/s003390050999.

[7] Lu, J. P. (1997). Elastic Properties of Carbon Nanotubes and Nanoropes. Physical Review Letters, 79(7),1297-1300. https://doi.org/10.1103/physrevlett.79.1297

[8] Palaci, I., Fedrigo, S., Brune, H., Klinke, C., Chen, M., & Riedo, E. (2005). Radial elasticity of multiwalled carbon nanotubes. Physical review letters, 94(17), 175502. https://doi.org/10.1103/PhysRevLett.94.175502.

[9] Song, Dongdong & Yin, Zhongwei & Liu, Fengjuan & Wan, Hongxia & Gao, Jin & Zhang, Dawei & li, Xiaogang. (2017). Effect of carbon nanotubes on the corrosion resistance of water-borne acrylic coatings. Progress in Organic Coatings. 110. 182-186. 10.1016/j.porgcoat.2017.04. 043.

[10] Naing, Naing & Aung, Naingnaing & Zhou, Wei & Goh, Chwee & Mui, Sharon & Nai, Mui Ling Sharon & Wei, Jun. (2012). Effect of carbon nanotubes on corrosion of Mg–CNT composites. Corrosion Science. 52. 1551-1553. 10.1016/j.corsci.2010.02.025.

[11] Chen, X. H., Chen, C. S., Xiao, H. N., Cheng, F. Q., Zhang, G., & Yi, G. J. (2005). Corrosion behavior of carbon nanotubes–Ni composite coating. Surface and Coatings Technology, 191(2-3), 351-356.

[12] Jeon, HaeRi & Park, JinHwan & Shon, Minyoung. (2013). Corrosion protection by epoxy coating containing multi-walled carbon nanotubes. Journal of Industrial and Engineering Chemistry. 19. 849–853. 10.1016/j.jiec.2012.10.030.

[13] Laurent, Christophe and Flahaut, Emmanuel and Peigney, Alain the weight and density of carbon nanotubes versus the number of walls and diameter. (2010) Carbon, vol. 48 (n° 10). pp. 2994-2996. ISS N 0008-6223.

[14] Wang, C., Ryu, K., De Arco, L.G. et al. Synthesis and device applications of high-density aligned carbon nanotubes using low-pressure chemical vapor deposition and stacked multiple transfer. Nano Res. **3,** 831–842 (2010). https://doi.org/10.1007/s12274-010-0054-0.

[15] Ozaki, T., Iwasa, Y., & Mitani, T. (2000). Stiffness of Single-Walled Carbon Nanotubes under Large Strain. Physical Review Letters, 84(8), 1712–1715. https://doi.org/10.1103/physrevlett.84.1712

[16] Dutta, A., Penumadu, D., & Files, B. (2004). Nanoindentation testing for evaluating modulus and hardness of single-walled carbon nanotube–reinforced epoxy composites. Journal of Materials Research, 19(1), 158-164. doi:10.1557/jmr.2004.19.1.158.

[17] Bradbury, C.R., Gomon, J., Kollo, L., Kwon, H., & Leparoux, M. (2014). Hardness of Multi Wall Carbon Nanotubes reinforced aluminium matrix composites. *Journal of Alloys and Compounds, 585*, 362-367.

[18] Bocanegra-Bernal, M & Domínguez-Ríos, Carlos & Etxeberria, Jon & Reyes-Rojas, A & Garcia-Reyes, A & Aguilar-Elguezabal, Alfredo. (2017). Effect of low-content of carbon nanotubes on the fracture toughness and hardness of carbon nanotube reinforced alumina prepared by sinter, HIP and sinter + HIP routes. Materials Research Express. 4. 085004. 10.1088/2053-1591/aa7f22.

[19] Roch, A., Greifzu, M., Talens, E. R., Stepien, L., et al., (2015), Ambient effects on the electrical conductivity of carbon nanotubes Carbon, 95, 347–353. https://doi.org/10.1016/j.carbon.2015.08.045

[20] Gao, Lei & Zhou, Xiaofeng & Ding, Yulong. (2007). Effective thermal and electrical conductivity of carbon nanotube composites. Chemical Physics Letters. 434. 297-300. 10.1016/j.cplett.2006.12.036.

[21] Marinho, B., Gomes Ghislandi, M., Tkalya, E., Koning, C. E., & With, de, G. (2012). Electrical conductivity of compacts of graphene, multi-wall carbon nanotubes,

carbon black, and graphite powder. *Powder Technology*, *221*, 351-358. https://doi.org/10.1016/j.powtec.2012.01.024.

[22] Yongbing Tang et al., Thermal expansion of a composite of a single-walled nanotubes and nano crystalline aluminium, Letters to the Editor / Carbon 42 (2004) 3251–3272.

[23] Bandow, S. (1997). Radial Thermal Expansion of Purified Multiwall Carbon Nanotubes Measured by X-ray Diffraction. Japanese Journal of Applied Physics, 36(Part 2, No. 10B), L1403–L1405. https://doi.org/10.1143/jjap.36.l1403.

[24] Libo Deng, Robert J. Young, Ian A. Kinloch, Rong Sun Guoping Zhang, Laure Noe, and Marc Monthioux, "Coefficient of thermal expansion of carbon nanotubes measured by Raman spectroscopy", Applied Physics Letters 104, 051907 (2014). https://doi.org/10.1063/1.4864056

[25] Zhao, Q., Nardelli, M. B., & Bernholc, J. (2002). Ultimate strength of carbon nanotubes: A theoretical study. Physical Review B, 65(14). https://doi.org/10.1103/physrevb.65.144105

[26] Demczyk, B. & Wang, Y. M. & Cumings, J & Hetman, M & Han, W & Zettl, A & Ritchie, Robert. (2002). Direct Mechanical Measurement of the Tensile Strength and Elastic Modulus of Multiwalled Carbon Nanotubes. Materials Science and Engineering A334. 334. 173-178. 10.1016/S0921-5093(01)01807-X.

[27] Wei, C., Cho, K., & Srivastava, D. (2003). Tensile Strength of Carbon Nanotubes Under Realistic Temperature and Strain Rate. *Physical Review B, 67*, 115407.

[28] Popov, V. N. (2004). Carbon nanotubes: properties and application. Materials Science and Engineering: R: Reports, 43(3), 61-102.

[29] Naidu, Pavan & Vinod, Narasimha & Pulagara, & DONDAPATI, RAJA SEKHAR. (2014). Carbon Nanotubes in Engineering Applications: A Review. Progress in Nanotechnology and Nanomaterials. 3. 10.5963/PNN0304003.

[30] Wang, G. X., Ahn, J. H., Yao, J., Lindsay, M., Liu, H. K., & Dou, S. X. (2003). Preparation and characterization of carbon nanotubes for energy storage. Journal of power sources, 119, 16-23.

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