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A STUDY OF THE MECHANICAL PROPERTIES OF CARBON NANOTUBES AND THEIR TRIBOLOGICAL APPLICATIONS

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ABSTRACT

Carbon nanotubes (CNTs) have attracted a great interest in the field of nanotechnology ever since their discovery in 1991. Researchers have revealed that these nanoscale structures possess many extraordinary qualities. CNTs have a unique molecular structure, good chemical stability, and outstanding mechanical and electrical properties. Because of these excellent characteristics, a multitude of applications are being developed in a large number of fields. In addition to an analysis of the distinctive features of these special nanotubes, this research aims to analyze CNTs in the tribological sense, particularly in current applications and their interaction with other materials. The investigation of the nanotribological applications of CNTs will include scanning probe microscopy (SPM), dry adhesion, and enhancements in lubrication and wear reduction. Future and potential improvements and applications will also be explored.

1) INTRODUCTION

Carbon Nanotubes CNTs were first discovered in 1991 by S. Ijima [1]. CNTs are allotropes of carbon with a cylindrical nanostructure. Nanotubes have been constructed with length-to-diameter ratio of up to 132,000,000:1, significantly larger than any other material. CNTs are members of the fullerene structural family, which also includes the spherical buckyballs, and, in fact, the ends of a nanotube may be capped with a hemisphere of the buckyball structure. Their name is derived from their long, hollow structure with the walls formed by one-atom-thick sheets of carbon, called graphene. These sheets are rolled at specific and discrete ("chiral") angles, and the combination of the rolling angle and radius decides the nanotube properties. Individual nanotubes naturally align themselves into "ropes" held together by van der Waals forces [2].

CNTs exist in three different forms:

- Single-Walled Nanotubes (SWNTs);
- Double-Walled Nanotubes;
- Multi-Walled Nanotubes (MWNTs) (Fig.1).

CNTs have attracted great interest in the field of nanotechnology because of their extraordinary mechanical, electrical, and transport properties. Over the past couple of years there have been many studies on the

mechanical properties and deformation of CNTs such as bending, buckling, twisting, and curvature effects. In addition to analyses of these properties, an understanding of the nanotribological behavior, such as adhesion and friction between CNTs and different materials, plays a key role in the exploration of new applications for CNTs. The objective of this research is to explore the nanotribological properties and look at the present and future applications of CNTs.

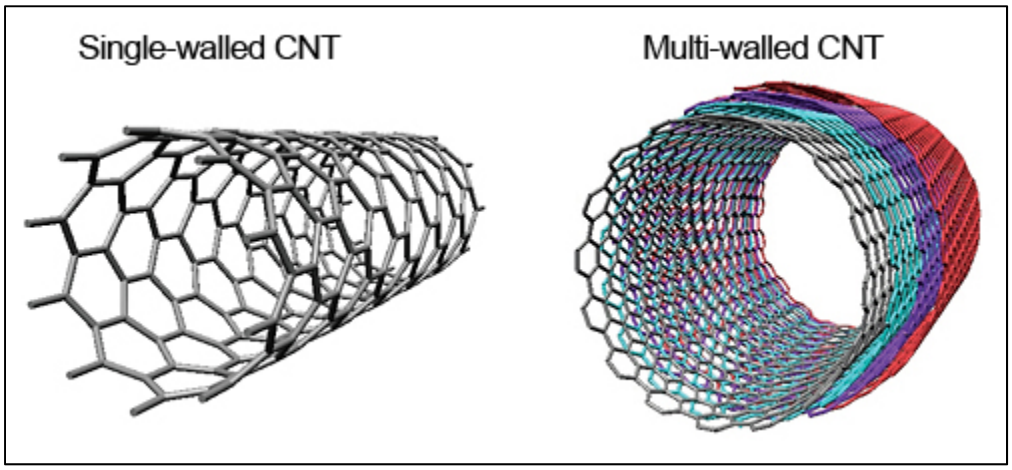

Figure 1. Single-walled CNT and Multi-walled CNT

1.1) Single-Walled Nanotubes (SWNTs)

Single-walled nanotubes have a diameter of about 1 nanometer, and a tube length between a few to 10 million times the diameter (the observation of the longest SWNT was of 18.5cm long). The structure of a SWNT can be visualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder. The way the graphene sheet is wrapped is represented by a pair of indices (*n*,*m*) . The integers *n* and *m* denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene. If *m* = 0, the nanotubes are called zigzag nanotubes, and if *n* = *m*, the nanotubes are called armchair nanotubes. Otherwise, they are called chiral. The diameter of an ideal nanotube can be calculated from its (n,m) indices as follows

$$d = \frac{a}{\pi}\sqrt{(n^2 + nm + m^2)} \qquad \text{(Eq. 1)}$$

where a = 0.246 nm.

SWNTs are an important variety of carbon nanotube because most of their properties change significantly with the (*n*,*m*) values, and this dependence is non-monotonic (Kataura plot). In particular, their band gap can vary

from zero to about 2 eV and their electrical conductivity can show metallic or semiconducting behavior. One useful application of SWNTs is in the development of the first intramolecular field-effect transistors (FET). Production of the first intramolecular logic gate using SWNT FETs has recently become possible as well. To create a logic gate you must have both a p-FET and an n-FET. Because SWNTs are p-FETs when exposed to oxygen and n-FETs otherwise, it is possible to protect half of an SWNT from oxygen exposure, while exposing the other half to oxygen. This set-up results in a single SWNT that acts as a NOT logic gate with both p and n-type FETs within the same molecule.

Single-walled nanotubes are dropping precipitously in price, from around $1500 per gram as of 2000 to retail prices of around $50 per gram of as-produced 40–60% by weight SWNTs as of March 2010.

1.2) Double-Walled Nanotubes (DWNTs)

Double-wall carbon nanotubes (DWNTs) are the simplest archetypical manifestation of MWNTs and as such combine the outstanding properties of SWNTs with the possibility to study concentric intertube interactions with high precision. Two complementary routes for the efficient growth of DWNTs are discussed. Firstly, SWNTs filled with various carbon sources, such as fullerenes or acenes can form inner-shell tubes by a high-temperature treatment under cleanroom conditions. Inner–outer tube pairs can be identified with a well-defined mutual chirality. Isotope labeling and full isotope substitution is possible. Using different carbon sources, DWNTs with intrinsic functionality and special electronic and magnetic properties can be grown. Alternatively, a direct growth using chemical vapor deposition and subsequent purification is described. Large-scale growth of very long continuous DWNTs for application in composites and as advanced field emission sources is straightforward for this technique. The two techniques for growth of DWNTs are evaluated with respect to their scientific novelty and application potential. Stability, electronic structure, transport and mechanical properties are reviewed. Double-walled carbon nanotubes (DWNT) form a special class of nanotubes because their morphology and properties are similar to those of SWNT but their resistance to chemicals is significantly improved.

This is especially important when functionalization is required (this means grafting of chemical functions at the surface of the nanotubes) to add new properties to the CNT. In the case of SWNT, covalent functionalization will break some C=C double bonds, leaving "holes" in the structure on the nanotube and, thus, modifying both its mechanical and electrical properties. In the case of DWNT, only the outer wall is modified. DWNT synthesis on the gram-scale was first proposed in 2003 by the CCVD technique, from the selective reduction of oxide solutions in methane and hydrogen.
The telescopic motion ability of inner shells and their unique mechanical properties permit to use multi-walled nanotubes as main movable arms in coming nanomechanical devices. Retraction force that occurs to telescopic motion caused by the Lennard-Johnes interaction between shells and its value is about 1.5 nN.

1.3) Multi-Walled Nanotubes (MWNTs)

Multi-walled nanotubes (MWNT) consist of multiple rolled layers (concentric tubes) of graphite. There are two models that can be used to describe the structures of multi-walled nanotubes. In the *Russian Doll* model, sheets of graphite are arranged in concentric cylinders, e.g., a (0,8) single-walled nanotube (SWNT) within a larger (0,17) single-walled nanotube. In the *Parchment* model, a single sheet of graphite is rolled in around itself, resembling a scroll of parchment or a rolled newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å. The Russian Doll structure is observed more commonly. Its individual shells can be described as SWNTs, which can be metallic or semiconducting. Because of statistical probability and restrictions on the relative diameters of the individual tubes, one of the shells, and thus the whole MWNT, is usually a zero-gap metal.

2) CURRENT APPLICATIONS

2.1) Fine tips of AFM (Atomic Force Microscopes)

CNTs currently have several viable tribological applications. One such application is the use of a CNT as the probe tip in atomic force microscopy (AFM), a type of scanning probe microscopy (SPM) (Figure 2). The extremely slender and strong nanotubes have the favorable ability to probe the deepest and sheerest asperities while also resisting wear and breakage better than typical silicon tips. To utilize a CNT in AFM, it must first be attached to the tip of a conventional silicon pyramid. The earliest attempts involved simply attaching ready-made CNTs to the pyramidal tip using adhesives. An alternative, and popular, method for creating a CNT tip is by directly growing the CNT on the AFM silicon pyramid which, despite being convenient, can be time consuming and may result in suboptimal orientation of the nanotube [3]. Whatever the current manufacturing limitations, it is clear that CNT AFM technology is quite viable and continuing to improve.

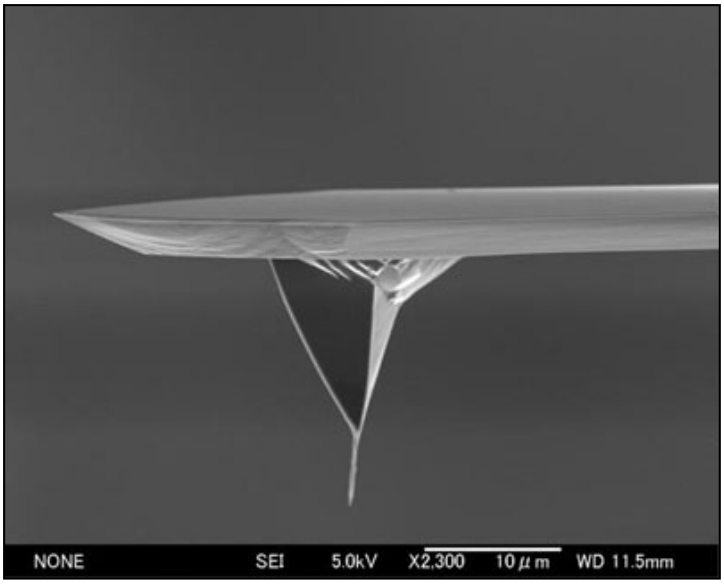

Figure 2. A MWNT attached to a standard probe tip on an AFM cantilever. [4]

A CNT tip is superior to the brittle silicon-based tips because it can reach into fine and narrow surface features while avoiding loss of resolution as depicted in Figure 3 (notice the greater detail and more accurate incline/decline measurements with the CNT tip). Typical pyramid/cone shaped tips

(with a ~10nm radius) may lose topological detail and lateral resolution due to the tip broadening effect and wear; a conventional pyramid-shaped Si scanning probe exhibits angled sides and a low aspect ratio which prevent it from being able to trace the surface morphology [5].

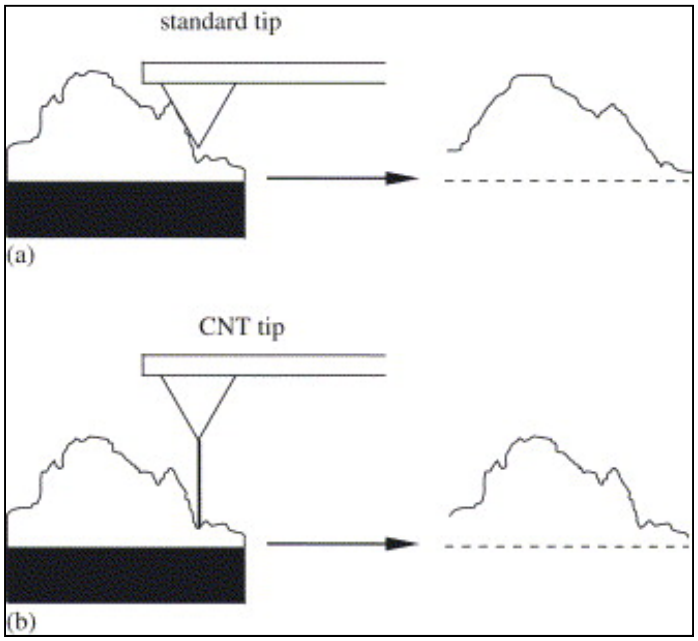

Figure 3. Interaction of standard (a) and CNT (b) tip and the biological sample. [6]

Although the physical dimensions of CNTs makes them superb candidates for AFM tips, it is their unique mechanical properties that propel them to the forefront of nanomaterials with similar structures. Even though there have been advances to increase the aspect ratio of SI probes, CNTs remain a more favorable choice due to their superior physical qualities which make them less susceptible to wear and breakage. The elastic modulus of a SWNT is about 1 TPa (terapascal) which makes CNTs one of the strongest known materials [5].

The strength and elastic response of CNT tips can be described by bending and compression force constants which are given, respectively, by the following relationships:

$$k_B = \frac{3Y\pi(r_o^4 - r_i^4)}{4L^3} \qquad \text{(Eq. 2)}$$

$$k_C = \frac{Y\pi(r_o^2 - r_i^2)}{L} \qquad \text{(Eq. 3)}$$

where Y is the elastic modulus, r_o and r_i are the outer and inner diameters of the nanotubes, and L is the length of the nanotube [5]. From these two equations it can be seen that the bending response is the more significant component of the CNT's elastic deformation. It can also be seen that the force constants will increase with increasing outer radius and thickness and decreasing length. Of course, such increases in diameter will lower the aspect ratio and, therefore, the resolution of the scan. An appropriate balance of strength and resolution must be found based on the parameters of the specific application.

Dai et al. first demonstrated a CNT as an AFM tip using a MWNT [5]. In their work, they generated a relationship to determine the Euler buckling force, F_{Euler}:

$$F_{Euler} = \frac{\pi^3 Y r^4}{4L^2} \qquad \text{(Eq. 4)}$$

where Y is the elastic modulus (~1 TPa), and r and L are the radius and length of the CNT, respectively. They also found that the MWNTs glued to the silicon tip would translate minimal damage to the samples being measured because they acted as compliant springs when the probe tapped and interacted with the surface. The ability of CNT tips to bend and elastically deform limits the maximum force transmitted to the surface so damage to a biological sample can be prevented [6].

It has been demonstrated that SWNTs, with the smaller inherent diameter (which can be sharpened to 0.5 - 2 nm) could also be used for even higher lateral resolution [5]. This extremely high AFM resolution can be very important to the IT industry where future silicon devices will require analysis of ultrathin films, with thicknesses of a few atomic layers. The nondestructive nature and high resolution of SPM with a SWNT tip can provide very precise and consistent data for optimization of such nanoscale applications [5].

While their smaller diameter makes them attractive for use in AFM, there are some drawbacks of SWNTs as AFM tips. SWNTs can be difficult to grow on the probe, generally have nonvertical orientation, a low bending force constant, and a weak connection to the silicon tip which is purely a

result of van der Waals force. These downsides may result in changes in the tip orientation and actual loss of the tip. Nguyen notes that, as a solution to this problem, sharpening the probing end of a much more stable MWNT can be effective and cites several methods [5]. These methods involve removing layers from the MWNT near the tip which would result in resolutions close to that of a SWNT (<5nm radius of curvature). Additionally, these sharpened MWNTs also have the necessary mechanical strength to withstand the demands of a high number of operation cycles

2.2) CNTs as a dry adhesive

Another very interesting characteristics of CNTs is their adhesion to a target surface. The source of the adhesion is due to van der Waals forces in the contact area, which are inversely proportional to the feature size of the structure. When a vertical aligned CNTs array comes into contact with a "rough" target surface, the fine structures of CNTs fill in the cavities at the interface which results in friction and adhesive forces. As an array of CNTs is applied to a surface, many of the tubes bend and become parallel to the surface resulting in an increased area of contact. As the contact area increases, so do the adhesive van der Waals forces. Recent research suggests that it is possible to generate adhesive strengths of more than 100 N/cm^2 (~1 kg/cm^2 or 14 lb/in^2) in shear, assuming that most tubes in the array make effective contact with the target surface.

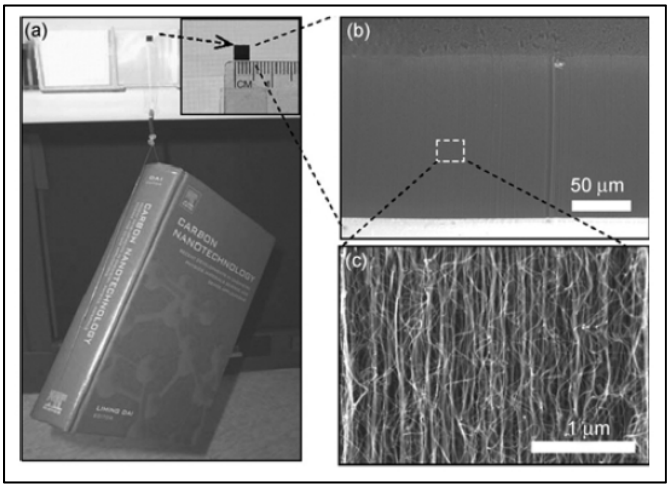

Figure 4. Carbon nanotube adhesive arrays [7]

In Table 1 is possible to compare mechanical properties of different kind of materials used to reproduce the artificial foot hair array of a gecko. The CNT-based artificial array shows excellent tribological properties.

Table 1. Adhesive performance and the related parameters of the different gecko-inspired micro/nano-adhesion arrays [7].

Materials	Gecko [1,2]	PP [10]	PI [23,24,31]	PU [9,29,40]	PDMS [33–36]	CNT [21,41,42]
Modulus (GPa)	1–3	~1	~3	<0.01	~0.003	>500
Length/ diameter	7–43	~30	0.5–7	1–4	0.5–7.5	>100
Adhesion force (N/cm^2)	10		0.1–3	0.2–18	~6	~20
Shear force (N/cm^2)	55	2	—	—	—	91
Pre-load force (N/cm^2)	<0.05	<0.1	50	12	0.8	125

Different types and orientations of CNTs have varying properties. For instance, SWNT arrays have a lower packing density and higher flexibility which causes them to exhibit lower adhesion and friction due to reduced intermolecular interaction. The higher value of adhesive force in MWNT arrays is due to the higher packing density of carbon atoms and therefore larger van der Waals forces in the contact area (Fig.5) [8].

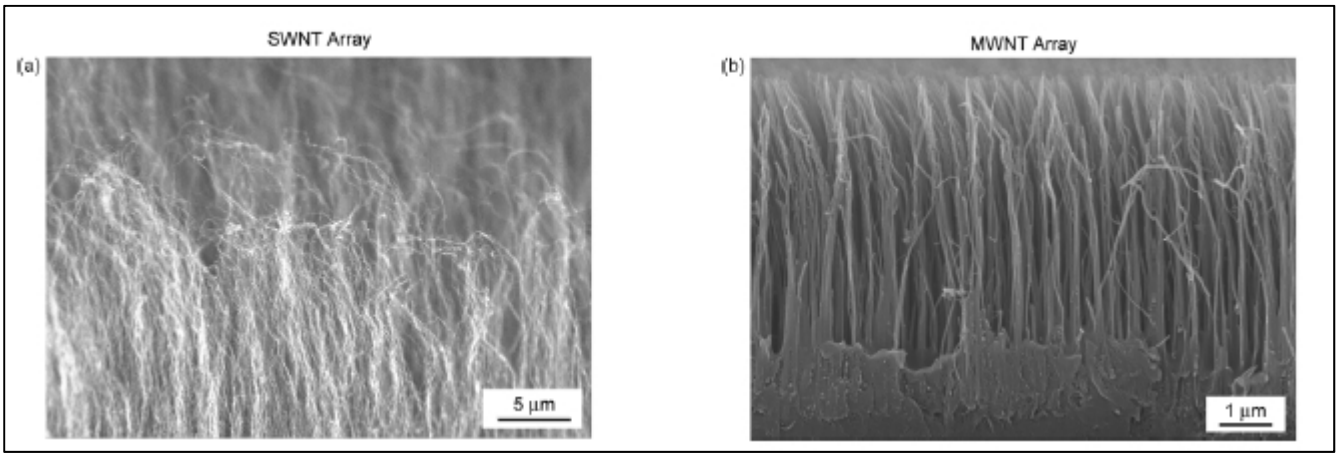

Figure 5. (a) SWNT Array – (b) MWNT Array. When such arrays encounter a surface, the CNTs flex to increase the contact area and, thusly, the van der Waals adhesion forces.

One of the first applications of the adhesive properties of CNTs, supported by several researchers, is a dry adhesive imitating the setae found on gecko footpads. It is possible to reproduce the high adhesion forces of the gecko using the knowledge of van der Waals forces at the atomic scale relating to an increased area of contact.

"The contact surface area matters a lot. When we have a line contact, we have van der Waals' forces acting the entire length of nanotubes, but when we have a point contact, the van der Waals forces act only at the tip of the nanotubes. That allows us to truly mimic what the gecko does naturally," according to Zhong Lin Wang, a Regents Professor in the Georgia Tech School of Materials Science and Engineering [9]. In tests done on a variety of surfaces, it is evident that the adhesive force in the shear direction is ten times higher than the adhesive force in the normal direction (Fig.6). It is also interesting to note that the resistance to shear increased with the length of the nanotubes, while the resistance to normal forces is independent from the tube length.

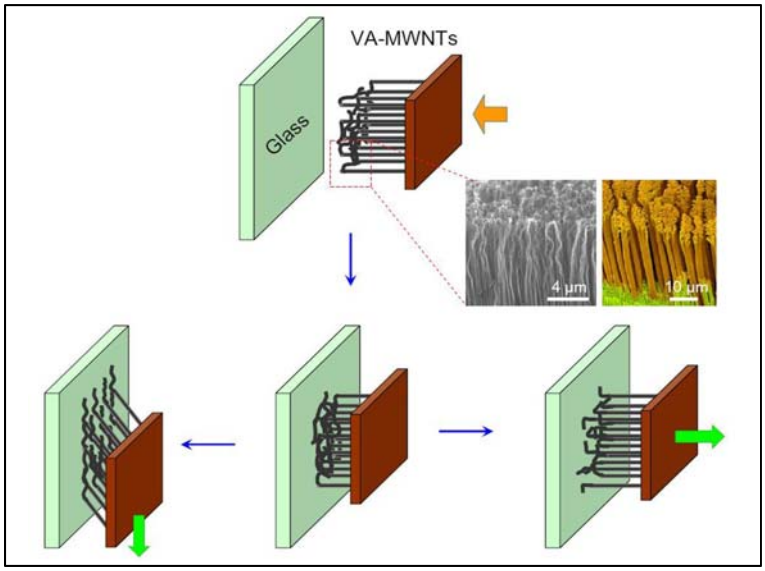

Figure 6. Researchers have created a gecko-inspired adhesive with ten times the stickiness of a gecko's foot, by combining vertically aligned nanotubes with curly spaghetti-like nanotubes [10].

The CNT-based artificial array, as we reported, has high adhesion performance and strong mechanical properties, but this kind of gecko's foot has also some weaknesses:

- A high pre-load is always required to obtain an high adhesion force;
- The foot hair detachment is rather difficult.

The existing studies suggest four main physical characteristics to obtain a great adhesion performance and to solve the CNT related problems [7]:

1. High density is required to guarantee an highly adhesion performance, since a strong adhesion (van der Waals force) is derived from a full contact;
2. An end-large structure of the CNTs foot hair permit a extended contact area, thus optimize the adhesion forces;
3. A leaning foot hair array can tune its mechanical properties and make detaching motion more convenient;
4. Branched and multi-level structures can tailor the effective contacted area on diverse interfaces, thus improve the foot-hair adaptability.

2.3) CNTs as Lubricant Additives and Wear Reducers

Another potential triboligical application of CNTs is as an additive to various lubricants. There have been numerous papers published demonstrating that even small weight percentages of CNTs dispersed in the lubricant can lead to drastic decreases of both friction and wear at the interacting surfaces. Dassenoy et al. [11] added CNTs to polyalphaolefin (PAO) oil and demonstrated that just 1 to 2 wt% of nanotubes dispersed in the oil was very effective at improving the lubrication between steel surfaces. They found that with a contact pressure of at least 0.83 GPa, the coefficient of friction was reduced by 70%. They also observed that wear of the surfaces was reduced threefold. The improved sliding is a result of crushed nanotubes sliding under the shearing motion. The reduction in wear may be a result of the formation of a protective carbon layer on the surfaces.

Lim et al. [12] also experimented with the tribological effects of CNTs. In their work, CNTs (in phenolic resin) were infiltrated into the pores of carbon/carbon composites which were then subjected to ball-and-disc type wear tests. As more and more nanotubes were applied to the C/C composite, the wear significant reduced (Figure 7). At a concentration of about 20% CNT, the wear was reduced by 100%. It was found that the enhanced wear properties are a result of the MWNTs acting as a reinforcing agent in both the CNT/carbon composite layer and in the C/C composite itself. One problem this study found was that friction begins to increase as more CNTs are added to the surface. This increase in friction is likely due to the aggregate strength of a large number of undamaged nanotubes in the wear debris on the surfaces. It is possible that with a high number of nanotubes and an insufficient amount of force, not all CNTs undergo the necessary crushing and shearing as described by Dassenoy et al. [11] and, thus, increase, rather than decrease the friction of the interacting surfaces. It may be possible to decrease the friction by applying a force great enough to cause the CNTs to deform and shear but more work needs to be done in this regard. At the very least, this CNT property may be utilized in applications where wear reduction is more important than slight frictional losses.

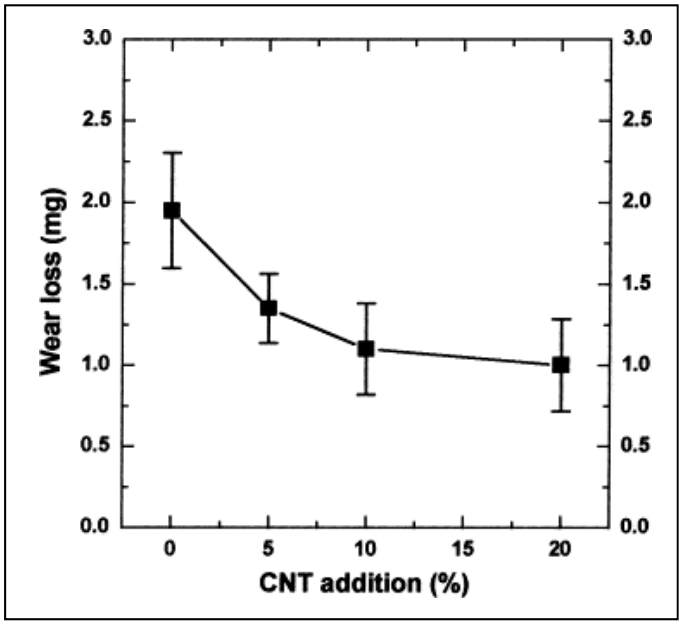

Figure 7. Variations of material loss as a function of CNT addition after wear test. [12]

2.4) Future Application of CNTs

Due to the significant development of techniques to create and utilize the CNTs, many future applications in a wide variety of fields are possible. Some of those are related to the contacts mechanics. See Appendix A.

3) MECHANICS CNTs MODELS

3.1) FEM Model of CNTs

As with most mechanical systems, it is desirable to create a simulation or model for facilitated analysis. CNTs are no exception and, in fact, are quite important to model due to their extraordinary mechanical characteristics. As described previously in this paper, CNTs have many tribological applications which depend on these properties and it is important to model them effectively. CNTs can be modeled by an atomistic approach using molecular dynamics or by continuum mechanics. An atomistic approach is useful to study the dynamics of individual molecules or atoms within the structure but there is a huge computational cost to analyze such models when a large number of atoms is desired. With continuum mechanics, however, it is possible to model and analyze larger and more complicated structures with significantly less computing power. Nahas and Abd-Rabou [13] used finite element modeling (FEM) to model a SWNT under various loads to determine the elastic modulus.

Nahas and Abd-Rabou's used the finite element package ABAQUS 6.6 to first model a 2-dimensional sheet of carbon atoms, also known graphene sheet. This sheet was then bent around a vertical edge to form a three-dimensional cylinder representing a CNT. Applying known constants and boundary conditions it is possible to compute the stiffness of the structure, K, by the following equation:

$$\sum_{i}^{n} F_i = K\delta \qquad (Eq. 5)$$

Where ΣF is the sum of the reaction force in the y direction at the fixed end and δ is the displacement imposed on the free end of the tube. The modulus of elasticity would then be calculated by utilizing the relations for stiffness and area:

$$K = \frac{AE}{L} \quad \text{(Eq. 6)}$$

$$A = \pi D t \quad \text{(Eq. 7)}$$

where A is the cross-sectional area of the CNT, E is the modulus of elasticity, L is the length of the tube, D is the diameter of the tube, and t is the wall thickness.

These equations can now be rearranged to solve for the modulus of elasticity:

$$E = \frac{KL}{\pi D t} \quad \text{(Eq. 8)}$$

which Nahas and Abd-Rabou found to be 1.03 TPa [13].

This result is in agreement with results obtained by other means of analysis and is also approximately the same value as reported by Nguyen [5].

It has been shown that FEM is an effective way to model CNTs and yield reasonable results. It is a valuable tool for analyzing the mechanical behavior of CNTs and interaction with various boundary conditions which is vital for application development and optimization.

3.2) Molecular Dynamics (MD) Simulation and continuum model for CNT

One of the most common models used to study the mechanical properties of CNTs, such as bending, buckling, twisting, and curvature effects, is the molecular dynamics simulation (MD). With the development of this modeling technique, many behaviors of CNTs have been observed. Molecular simulations offer advantages over physical testing due to their lower cost, versatility, and precision. Carbon nanotubes can be considered as rolled up graphite sheets. One of this sheet can be rolled up at different discrete angles to create the SWNT which can be described by the hexagonal base vector (a,b)

[14]. Thus the SWNT is a closed molecule with few or no imperfections and is a hexagonal ring bonding structure similar to graphite. The ring bonding structure, specifically the hybridized sigma bonds (sp^2), imparts the impressive mechanical properties. There is also the MWNT to model, consisting of a series of SWNTs separated from each other by about 3.4Å, which widens the range of tube properties and application possibilities. From experimental data this model considers two assumptions:

- CNTs are a linear elastic material;
- CNTs have a thickness corresponding to the density of graphite (t=0.34 nm).

Using the above assumption, the Young's modulus had been found to be between 0.75 and 1.25 TPa.

Molecular dynamics simulation is a method of modeling the intermolecular force, including bonding and non-bonding force, with simple polynomial and trigonometric expansions. The advantage of molecular dynamics is the precision with which test can be done and that several tests not yet feasible experimentally, such as torsion, can be performed.

Two popular models exist for nanotubes, both using molecular physical phenomena to define characteristic geometries.

a) Thick walled tube: same density as the graphite. This model works for global responses, such as predicting the deflection of a MWNT cantilevered in bending. It does not work to simulate high bending curvatures.
b) Thin walled model: valid for local instability modeling such as shell wall buckling.

Aaron Sears [14] built a model able to predict local global mechanical responses for various loads for both SWNTs and MWNTs. This model is basically made up of three parts. First, a material model for a SWNT has been developed using MD simulation. MD is useful to mimic traditional material property tests. Simple tests, such as tension and torsion, have been used to build the continuum

model. More complex tests have been run to verify the quality of the model. Next, the model has been extended to MWNTs. Here the major test was to model the interwall interactions due to the van der Waal forces. Lastly, a nanomechanics composite model has been developed that can consist of composite materials for various nanotubes.

The procedure to run this model is as follows:

1. Find the minimum energy configuration of an unloaded nanotube;
2. Estimate the deformed configuration and apply displacement boundary conditions to selected atoms.
3. With some atoms kept fixed, the remaining atoms are allowed to move freely till the minimum energy configuration is attained.

This model gives a quick response to a preliminary investigation of the local and global mechanical properties of SWNTs and MWNTs. A more complete continuous FEM model can be used to verify the first results and obtain more detailed responses.

4) CONCLUSIONS

The unique properties of carbon nanotubes make them viable in several tribological applications. Because of their diminutive size, exceptional strength, and resistance to wear, they are excellent candidates for AFM probe tips which must map the finest of surfaces. Furthermore, since they have the ability to grow very densely, these "forests" of CNTs can have an extremely large contact area with another surface resulting in a strong adhesion due to the aggregation of van der Waals forces. CNTs, when utilized appropriately, also show promise as potential lubricants and wear reducers by creating a strong layer of carbon between interacting surfaces. Additionally, because of their relatively simple structures, CNTs are not difficult to model which can be use to simulated experiments rather effectively. All in all, CNTs show great promise, not only in tribology, but in all fields of engineering.

APPENDIX A – Potential Applications of Carbon Nanotubes

Structural future applications [15]

Carbon nanotubes have valuable qualities as structural materials. Potential uses include:

- Textiles—CNT can make waterproof and/or tear-resistant fabrics
- Body armor—MIT is working on combat jackets that use CNT fibers to stop bullets and to monitor the condition of the wearer. Cambridge University developed the fibres and licensed a company to make them.
- Concrete—CNT in concrete increase its tensile strength, and halt crack propagation.
- Polyethylene—Adding CNT to polyethylene can increase the polymer's elastic modulus by 30%.
- Sports equipment—Stronger and lighter tennis rackets, bicycle parts, golf balls, golf clubs, and baseball bats.
- Space elevator—CNT are under investigation as possible components of the tether up which a space elevator can climb. This requires tensile strengths of more than about 70 GPa.
- Synthetic muscles: Due to their high contraction/extension ratio given an electric current, CNTs are ideal for synthetic muscle.
- High tensile strength fibers—Fibers produced with polyvinyl alcohol required 600 J/g to break. In comparison, the bullet-resistant fiber Kevlar fails at 27–33 J/g.
- Bridges—CNT may be able to replace steel in suspension and other bridges.
- Flywheels—The high strength/weight ratio enables very high rotational speeds.
- Carbon nanotube springs—Single-walled carbon nanotubes aligned in parallel can be elastically stretched for an energy density 10 times greater than that of current lithium-ion batteries, with the additional advantages of long cycling durability, temperature insensitivity, no spontaneous dischange, and arbitrary discharge rate.
- Fire protection—Thin layers of buckypaper can significantly improve fire resistance due to the efficient reflection of heat by the dense, compact layer of CNT or carbon fibers.

Electromagnetic future applications [15]

CNT can be fabricated as electrical conductors, insulators, and semiconductors. Applications include:

- Buckypaper—Thin nanotube sheets are 250 times stronger than steel and 10 times lighter and could be used as a heat sink for chipboards, a backlight for LCD screens or as a faraday cage to protect electrical devices/aeroplanes.
- Conductive films— Canatu of Helsinki, Finland, Eikos Inc of Franklin, Massachusetts and Unidym Inc. of Silicon Valley are developing transparent, electrically conductive CNT films and NanoBuds to replace indium tin oxide (ITO) in LCDs, touch screens, and photovoltaic devices. Nanotube films show promise for use in displays for computers, cell phones, Personal digital assistants, and automated teller machines.
- Electric motor brushes—Conductive CNTs are used in brushes for commercial electric motors. They replace traditional carbon black. The nanotubes improve electrical and thermal conductivity because they stretch through the plastic matrix of the brush. This permits the carbon filler to be reduced from 30% down to 3.6%, so that more matrix is present in the brush. Nanotube composite motor brushes are better-lubricated (from the matrix), cooler-running (both from better lubrication and superior thermal conductivity), less brittle (more matrix, and fiber reinforcement), stronger and more accurately moldable (more matrix). Since brushes are a critical failure point in electric motors, and also don't need much material, they became economical before almost any other application.
- Light bulb filament: alternative to tungsten filaments in incandescent lamps.
- Solar cells—GE's CNT diode exploits a photovoltaic effect. Nanotubes can replace ITO in some solar cells to act as a transparent conductive film in solar cells to allow light to pass to the active layers and generate photocurrent.
- Superconductor—Nanotubes have been shown to be superconducting at low temperatures.
- Ultracapacitors—MIT is researching the use of nanotubes bound to the charge plates of capacitors in order to dramatically increase the surface area and therefore energy storage ability.

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