Applications and Mass Fabrication of Carbon Nanotubes

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Abstract

Carbon nanotubes promise to be a powerful material for many applications. Especially structural is interesting, but also electrical properties of carbon nanotubes (CNTs) are unique. This paper will look critically at the synthesis of CNTs and some of their possible applications commercially. CNTs can be used for their exceptional structural, thermal and electrical properties. They are already in use on a small scale for high-end applications where cost is less of a concern. Carbon nanotubes are another form of carbon together with better known forms like carbon fibers and graphite. The structure of the nanotubes gives it very different material properties than other carbon forms. To get these benefits in everyday applications the cost of high quality CNTs has to go down a lot. To this end the only real contender is production based on chemical vapour deposition (CVD). As opposed to laser ablation and the arc discharge method, chemical vapour deposition scales easily. Moreover CVD can not only produce agglomerated multiwalled nanotubes but, depending on the exact geometry and catalyst used, can even make single walled aligned CNTs in a scaleable fashion.

I. Introduction

First an overview of the properties of CNTs is given, that is what's important after all. Before discussing some of the production methods we will look at the most prominent applications of CNTs currently.

Carbon is easily the most versatile element in chemistry. In recent years more allotropes of carbon have been found apart from diamond and graphite. Due to its valency, carbon can form many allotropes, including so called carbon nanotubes.[2] CNTs are hollow cylinders made out of solely carbon atoms.[2] These carbon atoms bind exclusively by sp^2 bonds to create a honeycomb-like structure.[1] The sp^2 bonds in graphene are the strongest bonds in chemistry, but individual sheets have little interaction between them making the material weak as a whole.[7] Carbon nanotubes do not suffer from this and individual CNTs can have very strong van der waals interactions between them.[7] CNTs embody some of the greatest promises in nanotechnology; stronger than any material, best thermal conductor, best electrical conductor and more.

The carbon nanotube structure can have extreme aspect ratio's, meaning it can be much longer than it is wide. CNTs on the order of tens of centimeters have been confirmed, with aspect ratios of 10^8.[4] This is akin to a 1000 km long fiber optic cable.[3] CNTs are therefor strongly anisotropic, properties along the tube (axial) can be vastly different than in the radial direction.[6]

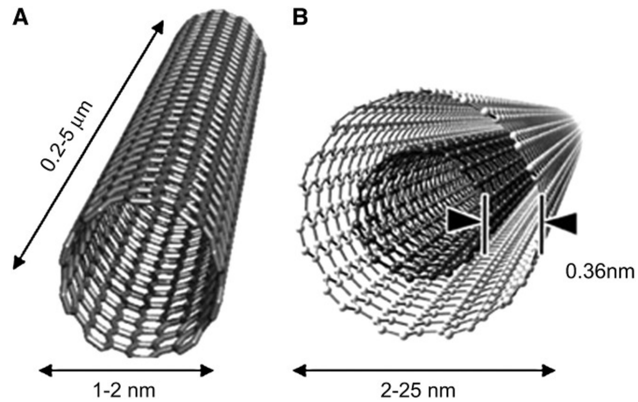

Figure 1: *The different dimensions for the different kinds of carbon nanotubes. The distance between layers in a WMCNT are always very close to 0.36 nm. [13]*

I.1. Single versus multiwalled

There can be differences between individual CNTs such as diameter and length. Carbon nanotubes are often further subdivided into single walled carbon nanotubes (SWCNT) and multi walled carbon nanotubes (MWCNT). SWCNTs are usually about one nanometer in diameter and can be either conducting or semi-conducting, depending on their chirality and size.[1] For this reason SWCNTs are interesting in electrical applications. SWCNTs are often more difficult to fabricate than MWCNTs as the conditions have to be better controlled. Multi walled carbon nanotubes are obtained from wrapping multiple layers of carbon atoms on top of one another. This can be done either with concentric larger carbon tubes, or in rarer cases like a rolled up paper sheet as one continuous layer.[12] MWCNTs are often stronger and metallic compared to single SWCNTs. The amount of layers a MWCNT can have is essentially limited by fabrication only and very large diameters compared to SWCNT can be made. For most applications the SWCNTs are considered better since their properties are well defined (and dependant on chirality[1]). Per nanotube MWCNTs are usually stronger but not per weight, however given the low weight in general this is not such a problem.

I.2. Structural Properties

The main interest into CNTs are their unusual properties compared to other materials. To build anything of consequence will mean large volumes of CNT material, this is then the most important when looking at industrial scale production of CNTs.

To quantify strength there are several constants to denote the properties of materials, most often in Young's modulus and ultimate tensile strength. These relate how a material reacts when being pulled on at both ends, called tensile strain. For compressive strain there are similar numbers, however there have been very few studies to verify the compressive strength of CNTs. Since material strength goes with the size this is denoted in Pascal (Newton per area). Young's modulus or elastic modulus is the slope of force versus deformation curve for elastic deformations. This means high modulus materials don't deform much with force, while they keep their integrity. Tensile strength is how much force must be applied before the cable will break. For the values given below you could hang a 15000 kg weight on a 1 mm^2 carbon nanotube cable while it only elongates by 16% (in theory). Clearly the structural properties of carbon nanotubes are vastly superior to either steel or Kevlar:[6]

Material	Young's Modulus	Tensile Strength
MWCNT	900 GPa	150 GPa
Steel	200 GPa	1.5 GPa
Kevlar	150 GPa	3.7 GPa
Carbon fiber	180 GPa	4.0 GPa

Table 1: *For the MWCNTs these values were measured using only a single perfect nanotube, in the axial direction. Theoretical models show that this is only slightly less than the the upper limit for CNTs as it should be.[7] CNTs are much less stiff in the radial direction, especially SWCNTs. The values for steel and Kevlar are for the highest grade materials available.*

Also carbon fibers are mentioned, carbon fiber is a composite made from carbon fiber are epoxy (see below). The high values for CNTs are quite amazing in itself but coupled with the low atomic weight of carbon this means the specific properties of CNTs are (by relative standards) even better, over 300 times that of steel.[6] Under excessive tension CNTs will undergo plastic deformation instead of elastic like any other material. Plastic deformation is the kind that is not reversible when the load is taken off, as opposed to elastic deformations which are reversible. Materials that only or mostly undergo elastic deformation are normally preferred. For CNTs this plastic deformation is thought to be mediated by the so called Stones-Wales deformation; here 4 hexagons deform into 2 pentagons and 2 heptagons, releasing some tensile strain.[12] Such deformations are not before 50 GPa however.[12] Naturally under more extreme loads higher order deformations will occur too.[12] This very high strength is the main reason for using carbon nanotubes as a new structural material.

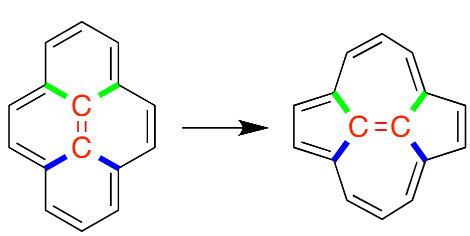

Figure 2: *Stone-Wales deformations are involved in the plastic deformation of CNTs. After such a deformation the lattice has more freedom.[12]*

I.3. Electrical Properties

Not only structural but also electrical properties of CNTs are unlike any other material. Others have described the electrical properties of carbon nanotubes in depth, here we only look at it only superficially.

The carbon tubes can carry current incredibly well, some studies reported as high as 10^9 A/cm^2, higher than most superconductors.[8] CNTs do not exhibit the Meissner effect however, and are not superconductors in name. Small scale CNTs are good conductors because of ballistic transport.[8] Ballistic transport is when the mean free path for electrons is comparable to the dimensions of the medium. Meaning on average it will simply follow a ballistic path from one end to the other. The very few scattering centers in the hollow carbon nanotubes means it has excellent electrical conductivity in the axial direction.

I.4. Thermal Properties

Added to the special electrical and structural properties is also excellent thermal conductivity. The thermal properties stem from phonons, for much the same reason in regard electrons and ballistic transport.[9] For a single carbon nanotube experimental values as high as 3500 W/mK have been reported, almost ten times that of copper.[9] Such high thermal conductivity means that temperature differences will equilibrate very quickly and unequal thermal expansion is not a big concern. Interestingly in the radial direction it has only 1.5 W/mK, rather poor conductivity.[9] In a bit of irony we will see that one of the applications mentioned (aerogels) are in fact thermal insulators, not conductors. This seeming contradiction is mostly due to simply the very low conducting volume and density in aerogels.

I.5. Carbon Fibers

Carbon fibers are closely linked to carbon nanotubes and are already used in commercial applications such as in high-end aerospace engineering solutions. Such products could also be made with the superior carbon nanotube versions to reduce weight and increase strength. Carbon fiber is a composite material, this means that it is made out of a matrix, usually epoxy materials, and the carbon fibers themselves.[10] The matrix acts as the glue to hold the fibers together, while the fiber provides the actual strength of the whole material.[10] CNTs can be added to a matrix material to make composites out of. Some of this has already been done, where CNTs were added to the epoxy matrix of carbon fibers.[14] Although still prohibitively expensive and relatively little benefits yet. Pure CNTs based composites have not yet been used in any commercial application.

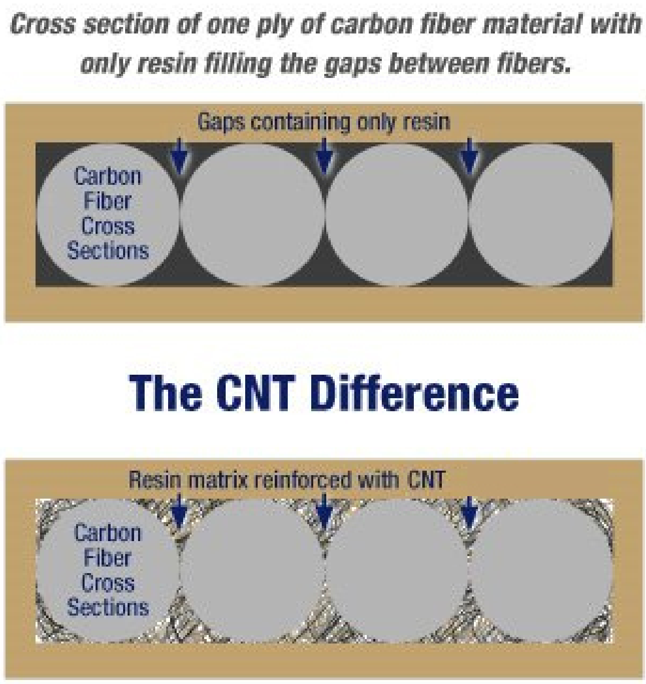

Figure 3: *Shows how CNTs can be added to the epoxy matrix of already existing carbon fiber composites for added strength. This technology was used to make a lighter bicycle that went on to win the Tour de France.[14]*

I.6. Health Risks

One can't talk about CNTs without mentioning at least some of the risk involved. One of the biggest problems with carbon nanotubes is the possible danger to human health. Just this possibility is already cumbersome as research with dry carbon nanotubes has to be performed in controlled areas.

The carbon nanotubes are somewhat similar to other high aspect ratio fibers such as asbestos, which are known to cause cancer. Research has shown that CNTs can also be the cause of cancer through the same mechanism of strained phagocytosis.[11] This can be especially scary if CNTs are airborne and breathed in where the white blood cells in the lungs try to break down the CNTs.[11] However luckily CNTs strongly tend to aggregate, this clumping can make particles much larger than cells and thus no strained phagocytosis occurs.[24] This is still a risk of course, statistics dictate some percent will enter the lungs as a single tube. Free multi walled nanotubes have been found to be more carcinogenic than asbestos fibers.[11] Asbestos has been banned for its danger, the hope is such drastic measures do not have to be implemented for CNTs as well.

II. Applications

Here we will describe only the most prominent applications for CNTs. With all these apparent amazing properties for pristine CNTs there are a plethora of possible uses for it. Trying to sum up all possibilities would be a waste of time.

Most of these different applications have thus far only seen limited research however and it remains to be seen if most of these will become actual commercial products. Furthermore with other advances in the field of nanotechnology and science in general it's very difficult to know if the CNTs will pan out in the end as the best solution. Especially in electronic devices, such as transistors, there is a lot of parallel research. Besides the applications below there are even more possible uses for CNTs, including but not limited to: hydrogen storage, terahertz polarization, near-ideal black body absorption, artificial muscles.[23] In a bit of irony, research is also done for using CNTs against cancer, because of its strong absorption in the infrared part of the spectrum.[22]

II.1. Transistors

Transistors are the building blocks for all micro electronics. Transistors effectively are small switches, either letting current through or not. To make a good transistor you need a semi-conductor material, for carbon nanotubes this means chiral SWCNTs.[1] Single transistors made with SWCNTs easily outperform any silicon based transistor to date because of higher electron mobility, high current density and smaller size.[1] However to create fully functioning integrated circuits a much higher level of control over the chirality and deposition of individual SWC-

NTs is needed than has been attained thus far. One upshot here is that in weight only a small amount of CNTs are needed. In the most ideal case of only one SWCNT per transistor, even with a trillion transistors per square centimeter, this is still only on the order of a microgram per CPU. Thus for this application no mass production would be needed.

Single walled carbon nanotubes have also been proposed for usage in new organic solar panels. Here it can have more than one function: simply as a good flexible conductor, or even as part of the optically active component.[23]

II.2. Conductor

Another promising electrical application for CNTs is simply as conductor. There are hundreds of kilometers of electrical wires everywhere. Potentially this could be replaced by wire made from carbon nanotubes. For this application large scale production would be needed. Especially the cost per kilometer is important for high-voltage power cables. For small scale and low-voltage the advantages of using a CNT wire over a copper wire are much smaller.

Bulk metallic SWCNT can have electrical conductivity superior to copper with orders of magnitude higher specific current carrying capacity.[4] Current high-voltage power cables have diameters of 20 cm or so, these heavy cables could be replaced by paper thin (0.1 mm) CNT cables. Currently there are already efforts for a copper-carbon-nanotube alloy, although being an alloy it will never give the big benefits of pure CNT cables.[15] Bulk pure single walled carbon nanotubes cables with electrical properties akin to the values of single SWCNTs have not been made to date. As a conductor it will also be an excellent electromagnetic (EM) shielding material, especially where weight and thickness is a concern.[23] This has already been used for EM-shielding in satellites.[23]

II.3. Composites

The main use for carbon nanotubes will likely be in composites (also see 3). Composites form a large family of materials, most of which are fairly new. For this reason the possibilities are very exciting in this area of research, even more so with the introduction of trying to combine already existing composites with CNTs.

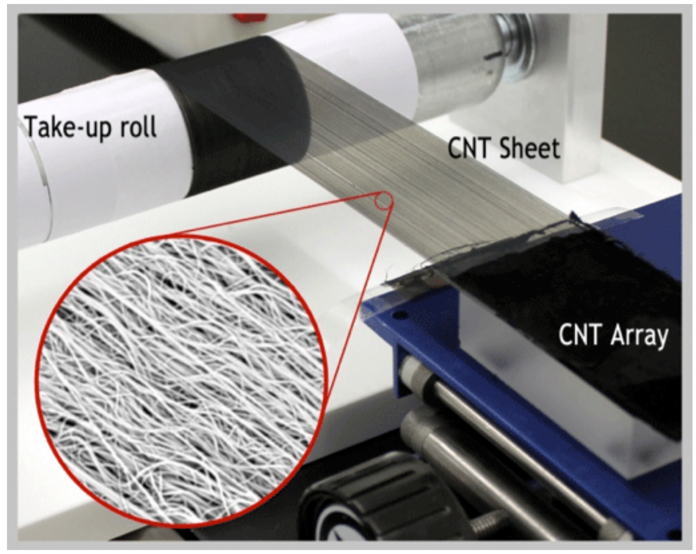

Figure 4: *The CNT array is a mat of aligned carbon nanotubes that were made by CVD process. The mat is simply drawn and a super thin sheet is pulled off and rolled. In this way sheets and yarns can be made. The deposition state of the CNT array is characterized by so called "forest-like growth".[19][25]*

Already CNTs composites have been used with carbon fibers for the strongest lightest material in the world.[14] Given the price however it will stay for use only in high-end applications for the foreseeable future, just like carbon fiber itself (still is at least). Currently airplanes and space rockets are slowly switching from aluminum to carbon fiber composites (The largest single composite is the Vega first stage).[33] Mass is one of the most important characteristics for these craft, material costs are often secondary. Especially in these aerospace applications one would expect to see CNT composites incorporated in the near future. This will mean a large increase in producing CNTs, on the scale comparable to that of carbon fiber composites now. Structurally speaking CNT enhanced carbon fiber composites are some of the toughest materials we have, but singular MWCNTs have very much better mechanical properties than any bulk material produced thus far. Carbon fiber composite are less strong than individual carbon fibers.[19] The losses in material properties from pure MWCNTs to a bulk composite with epoxy as matrix materials remains to be seen.

Instead of making composites purely from CNTs, often just a few percent CNTs added to existing materials already gives a significant boost in structure. One area where CNTs might be considered is in gas turbines. Gas turbines power much of our modern world and the blades have to be made from "superalloys" operating at extreme temperature and tension, perfect for CNT materials.[32] The efficiency of these gas turbines (as well as most jet engines) are limited by the rotational speed and temperature at the tip of the blades.[32]

II.4. Aerogels

Aerogels have been made out of carbon nanotubes. These are the lightest solids in existence, much lighter than even air.[15] However since it is completely porous it is normally filled with air and does not float. These carbon aerogels are like a foam, as opposed to some other (silica) aerogels that are more like brittle bricks. Cool as it may be, there haven't actually been many real world uses for these aerogels yet. Given their porousness they are very good thermal insulators and have been implied as material for heat shields and the like.

III. Production

The Production of the carbon nanotubes will naturally be one of the most important things for the future of CNTs. The focus will lie on chemical vapour deposition as it is simply much more promising than other alternatives.

For most materials the production costs determine how much it is used in practice. Given that the raw material cost of carbon is extremely low, the ease of production and thus the method is easily the most important for the widespread adoption of CNTs. This is often true for not just the adoption in real world applications, but also concerning research. Cheap materials are simply easier to research. Of course for research the quality is very important and must be strictly controlled, while less so for most applications. This means that the scientific methods for producing CNTs don't line up perfectly with the commercial methods. It is clear that for any commercial application the CVD approach will be the best in cost and production, since it is scaleable. While especially in research the arc discharge method is still used a lot, and to a lesser extend laser ablation as mentioned below.

III.1. Aggregates versus Aligned

There are a variety of ways for making carbon nanotubes of various quality. Apart from differences in making single walled versus multiwalled there's also the issue of making aggregates as opposed to aligned nanotubes. Sometimes aggregates versus aligned CNTs are referred to as cooked and uncooked spaghetti. Since CNTs are much weaker in compressive stress than tensile stress the aggregates fall short of the aligned CNTs in strength. Given a certain uniform catalyst density and temperature, the forming tubes will coalesce and self-assemble into the aligned state.[20] Since we usually want the carbon nanotubes to align, this puts some restrictions on the geometries that can be used.

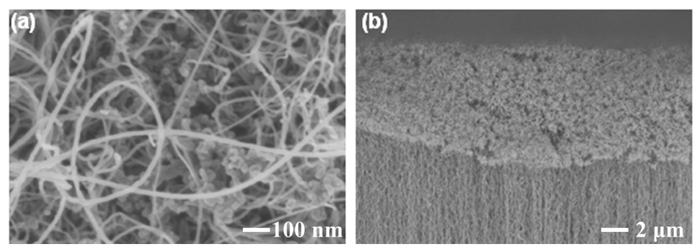

Figure 5: *Shows the microscopic difference of aggregates of CNTs against aligned CNTs. Getting the aligned state was done for (b) by having a uniform spread of iron particle catalyst instead of randomly sputtered for (a).[19]*

III.2. Laser Ablation

Laser ablation was one of the first successful methods of making CNTs. Because the parameters for laser ablation are controlled very well this gives a good reproduceability for separate batches. Because of the physical nature of this method the CNTs produced are almost purely single walled CNTs with small (1-1.6 nm) diameters.[18] Rather little progress in the method has been made since it was first discovered, and is only used for high quality lab CNTs.

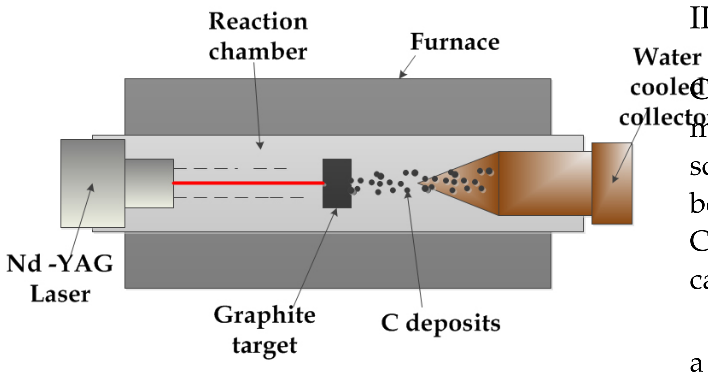

Figure 6: *The reaction chamber is heated and an inert gas flow is added to carry the particles. The graphite target also contains some catalyst (cobalt and nickel). The CNTs form on the water cooled collector.[17]*

III.3. Arc Discharge

The arc discharge method for making CNTs works by passing a high current through a pair of carbon electrodes that evaporate and deposit in the reaction chamber.[30] The reaction chamber is evacuated and usually a catalyst gas such as iron or cobalt is added.[30] Because of the simplicity, and the much higher efficiency compare to laser ablation this is used quite often for labs still. Concerning commercial production this still doesn't produce nearly as much as CVD though.

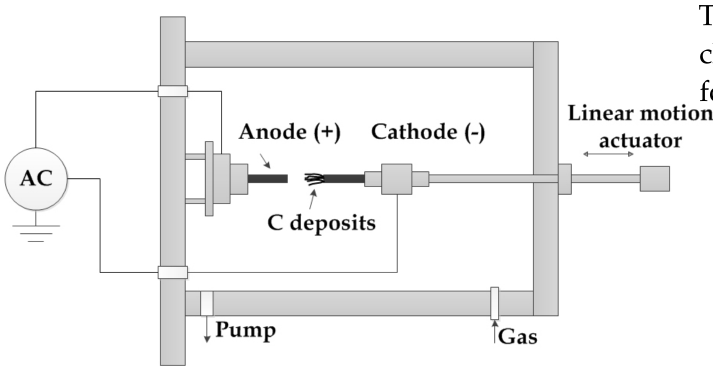

Figure 7: *In arc discharge deposition the carbon nanotubes form on the cathode and the space is filled with an inert gas as well as some (iron, nickel or cobalt) catalyst.[30]*

III.4. Chemical Vapour Deposition

Chemical vapour deposition is the most promising method for commercial production. Here we describe 3 distinct different methods within CVD: fixed bed, fluidized bed, and floating catalyst (HiPCo). CVD is a broad term and the individual executions can vary a lot.

Chemical vapour deposition is a process of letting a gas undergo a reaction of some sort and deposit as a solid. This is done inside a furnace with catalyst particles to actually grow the CNTs. There are many variations on CVD of different kinds of geometry and reactions that are all slightly different.[17] The various CVD techniques are by far the most promising in making large amounts of CNTs, both single walled and multi walled. This is mostly because it is scaleable, the reaction chamber can simply be made as large as needed with essentially the same efficiency. This makes it a very powerful manufacturing technique and has long been used in the silicon and other thin films industry.

In the simplest setup (8) a hydrocarbon gas (usually acetylene) is thermally decomposed near the catalyst metal nano particles that reside there on the substrate.[17] These nano particles then absorb the freed carbon atoms which form the nanotube. The gas that didn't react can be recycled, but for lab conditions is often contaminated too much. The catalyst is of course not directly consumed, but it is slowly passivated by CNTs and other processes.[17] The CNTs that are scraped off the walls have to be chemically treated to get rid of this excess catalyst for purer CNTs.

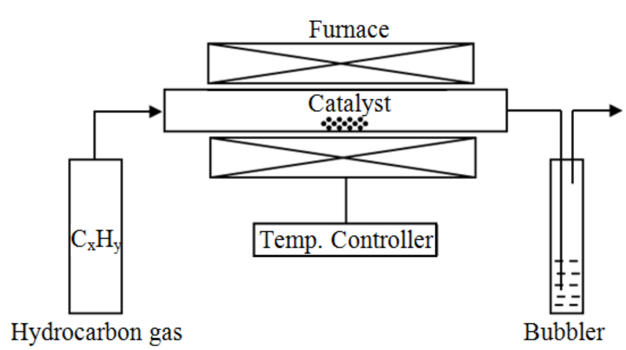

Figure 8: *Simplest CVD setup using only thermal decomposition in a fixed bed geometry.[30]*

III.5. Catalysts

Besides the temperature the catalyst is the most important parameter for CVD grown CNTs. The most active metals for CNTs are transition metals.[21] Especially iron, nickel and cobalt are interesting given their low material price. In the catalytic CVD process the catalyst is "used up" as the CNTs grow on the metal particles, thus new catalyst needs to be added to replace the used.[21] This means there is an efficiency yield of produced carbon nanotube mass divided by catalyst mass. For lowest cost this would be as high as possible, not just for least catalyst material needed but also for less catalyst remnants in the final product (thus higher quality). In practice this will mean growing the longest possible CNTs per catalyst particle.

III.6. Fixed Bed Reactor

In a fixed bed reactor the CNTs have two distinct growth modes, it can either happen at the base or at the top. The difference is the adhesion of the metal with the substrate versus the carbon nanotube. i.e. more spread out over the substrate (lower contact angle) means more adhesion, and will more likely have the base growth mode as illustrated in 10. In both cases the growth is thought to stop because of passivation of the catalytic surface.[17]

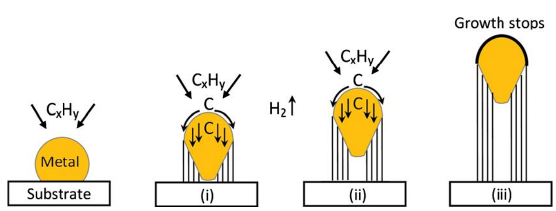

Figure 9: *Tip growth mode as it is currently thought to go, the hydrocarbons are absorbed by the metal catalyst particle and diffuse down to for part of the growing CNT.[17]*

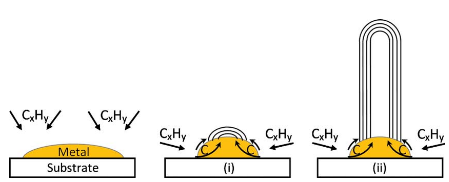

Figure 10: *Base growth mode, here the hydrocarbon are absorbed into the metal catalyst particle that forms the carbon nanotube.[17]*

III.7. Fluidized bed Reactor

In the fixed reactor bed configuration the catalyst particles are simply on a substrate inside the furnace area of the CVD setup (as in 8). However there is another setup that is preferred by large scale chemical industries called fluidized bed reactor. In this setup the reactor is turned ninety degrees and the gas inlet is done via a distributor. The gas is pumped in, causing the solid nano particles of catalyst to behave like a liquid at high enough pressure.[27] This mixing makes sure the temperature is uniform and the mass transfer is maximal.[27] Once the gas has reacted it is pumped off again and possibly recycled. In the case of CNT production the catalyst needs to be replaced continuously as it is used up and the product taken out. The output production of fluidized bed reactors scales easily and already a commercial scale pilot plant has been made with a claimed total production of 15 kg/h.[29] As with the fixed bed type the product has to be purified to get rid of some of the catalyst.

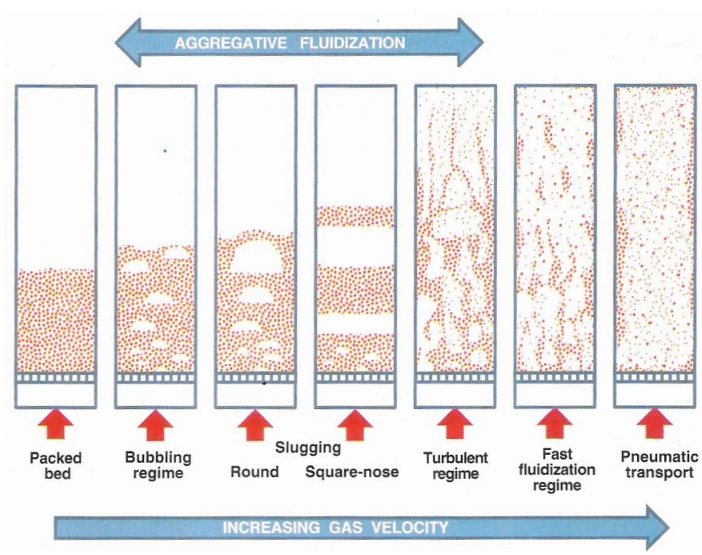

Figure 11: *At higher gas injection velocity the solid particles fluidize more and the catalyst mixes better with the reactant. Aggregate fluidization causes non uniform mixes and vibrations.[27]*

III.8. HiPCo

Currently a different method is popular for produced reasonable amounts of pure SWCNTs, the HiPCo process (High Pressure Carbon monoxide).

As the name suggests this involves CVD of CO at high pressure (30 atm) and medium temperatures (1050 °C) with an iron catalyst.[24] This process is distinct from bed reactors for it makes the catalyst particles in situ during the CVD process from gas phase $Fe(CO)_5$. This is the biggest upshot of this method that the iron particles are formed in situ thus making it a continuous process. The production rate of this process is about 0.5 g/h, fairly low, and sells for more than 1000$ per gram.[24] One of the biggest problems is purifying the CVD result to take out the iron catalyst. Although the temperature is relatively low compared to some other techniques the pressure is not. High pressure vessels are very expensive, driving up the cost a lot. The maximum length the SWCNTs attain is limited by passivation (by carbon) of the metal catalyst clusters.[24] Since the clusters are created in situ from a precursor gas there is very little control over the catalyst parameters. Because of the small size of the metal clusters, and the consistency given the right parameters, only single walled nano tubes are created.[24]

IV. Discussion

In this discussion section some of the issues with the current situation will be highlighted. Especially with the future in mind to move the field forwards. Especially the metal-free catalyst that will be mentioned is interesting for it might give a very significant reduction in cost for CNTs commercially.

IV.1. Research

Perhaps the biggest gripe with carbon nanotubes is the fact that although we know how to produce them in various ways, we are still not capable of predicting why those certain parameters would work. This means that most productions methods thus far have really been by trial and error, instead of knowing the best solution and implementing that. Doing specific research into making a batch of carbon nanotubes with very precise defined parameters (diameter, length etc) by two separate, different, production methods may be a good way to understand better how CNTs are grown. In this way you would expect that both those methods would use the same kind of reaction for creating the CNTs, and can be compared to each other to find the common ground. Such a thing would obviously require being able to produce not only nanotubes with very precise parameters but also the same precise parameters by two methods, two methods that are beforehand not that well understood. e.g. reliably making SWCNTs with 10 nm diameter and 200 nm length by CVD and by say laser ablation. This would suggest the situation for both of those methods are the same during the CNT growth period, and can be compared.

Somewhat recently metal-free catalysts like nano particle diamond have been successfully used.[17] This suggests there is indeed something deeper about carbon atoms forming nanotubes on particles as the nano diamond was proven to be in solid state the whole way through (meaning no diamond carbon ended up in the CNT).[17] Exactly how this works is unknown, but metal-free catalysts in CVD might not need the chemical treatments afters deposition anymore, making it purer and cheaper.

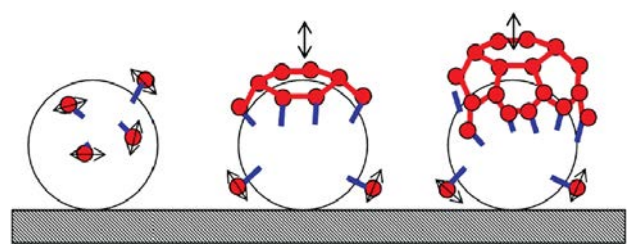

Figure 12: *A model for the starting mechanism of growing CNTs by carbon atoms adsorbed on the surface of a metal catalyst particle. First the carbon atoms try to form a graphene like structure whereby they push themselves up off the metal particle to form the end cap of the CNT.[17]*

One of the biggest problems is the passivation of the (metal) catalyst particles. For most purposes the longer the CNTs are the better. Therefore the exact geometry of the nano particles that are used to grow the CNTs can have a large impact on the average length a nanotube grows before the catalyst particle is passivated. It's very difficult to research because that means making a large amount of nano particles with a very specific geometry, say perfectly spherical versus star-like. Particles that would not suffer from passivation could in theory make CNTs as long as is desired.

IV.2. Microscopic versus Macroscopic

Of course all of this would mean little if the microscopic amazing properties of CNTs don't translate well into actual macroscopic properties. The promises of CNTs are from atomically perfect contaminate free specimens, instead of an average over carbon defects of various sorts. Although materials have been made with superior bulk properties already they aren't really worth the effort or price yet. Presumably this will get fixed by making better cross links between the tubes as well as having longer pristine tubes. A very promising avenue in this is radiating the tubes with electrons to form cross links.[31] In this method high energy electrons force the aligned (MW)CNTs to form covalent bonds between the tubes, strengthening the matrix.[31] If we are to make use of CNTs materials in "everyday" life it needs to not only be cheap enough to manufacture but also have very clear advantage over already existing materials.

IV.3. Costs

In the ideal case a great amount of CNTs are made per hour per catalyst at low temperature with a high quality end product. But even in the very best of cases the price of CNTs will simply never be able to compete with conventional metal production and manufacturing. This would mean that we shouldn't expect CNTs products at every corner in the future. Although theoretically possible to build bricks from CNT composite materials far superior to either steel or concrete, such a building would be many times more expensive than using current techniques. Similar arguments count concerning everyday clothing made from ultra strong carbon nanotube fibers. That said, it has been shown that even small amounts of CNTs added into other materials can have significant material advantages (see [14] and [15]).

IV.4. Top Down Approach

When speaking of CNTs, essentially always a bottom up approach to making them is assumed. Bottom up meaning the CNTs are made from carbon atoms one by one as described earlier. On the other hand carbon fibers have been made with smaller and smaller fiber thickness by new techniques. One could imagine a pathway of making carbon nanotubes from a top down approach instead. Historically top down approaches have often been cheaper than bottom-up, while giving less control over the process in general. Carbon nanofibers have already been made with diameters in the nanometer range by electrospinning.[22] In electrospinning the material is suspended in a fluid and extracted by high voltage, creating a noodle-like extremely thin wire.[22] As expected from their size the nanofibers have properties somewhere between carbon nanotubes and carbon fibers, essentially an intermediate. Carbon nanofibers by electrospinning are roughly speaking two orders of magnitude cheaper than CNTs per weight currently.[26] A down side here is that these nanofibers are made as aggregates and not in the aligned state.

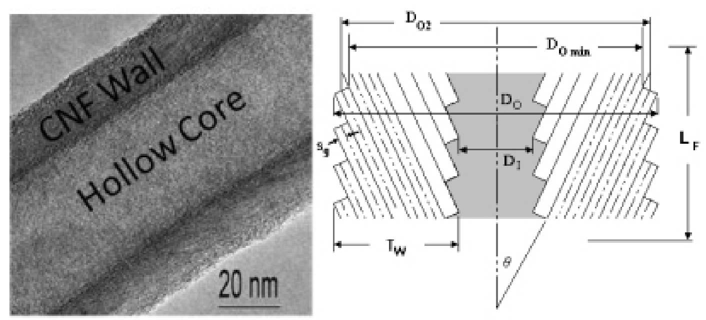

Figure 13: *Shows the exact geometry of the carbon nanofibers, essentially the fibers are made up of a stack of concentric hollow cones of graphene.[26]*

IV.5. Recipes

Whether we understand it fundamentally or not, at some point we'll have a pretty good list of exact parameter/catalyst combinations for making carbon nanotubes with certain properties. Currently it's still a big mess of what exact method is the best in making what exact CNT for a given application. And on top of that often where CNTs are used in the literature it is not stated precisely what kind with what distribution, more transparency in this would help. Needless to say this is an on going process that is getting better as CNTs are studied more.

IV.6. Health

A mayor concern with carbon nanotubes has been its similarity to other tough high aspect ratio fibers. Not only are biological reactions to intruder particles very complex, it is also difficult to do research on the harm to humans and animals without needlessly harming them in the process. Knowing its carcinogenic effect we should look for methods to neutralize its effects.[11] When a certain technology is deemed dangerous to the public eye it is almost impossible to get rid of that reputation, whether true or not becomes irrelevant. For the most part the CNTs are contained inside some other material and the danger effect will be minimal, but for pure materials, the ones with the most promising properties, this will need real attention before they can be put on the market.

V. Conclusion

Nanotechnology is still in its infancy. Easily one of the most promising materials is the carbon nanotube (CNT). Although the strength promised by theoretical arguments thus far has not yet been achieved in bulk form. The main application where industrial scale CNTs are required will be for structural purposes, but there are also plenty of electrical applications. CVD (chemical vapour deposition) is a process for making CNTs as either aggregates or aligned. Industry already has a lot of experience using chemical vapour deposition. CVD is the only scaleable process known for making CNTs, it is therefore favored for commercial production. Nevertheless the process is not well understood at all as can be seen from the fact that metal-free catalyst work as well. There are no obvious reasons why we wouldn't be able to get commercial scale CNT production in the near future however, some of this has already been done (see [29], [24] and [33]). This implies we will see many places where CNTs are used soon, while at the same time they will likely stay as an expensive high-end material. We should stay weary of any negative consequences it has, especially to health, as damage is harder to fix than prevent.

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