Proceedings of the 3rd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2023), Part II
DOI: 10.54254/2755-2721/7/20230454

An overview of current status, application, and future development about carbon nanotube

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Abstract. Carbon Nanotube (CNTs) could cause inflammation respiratory and blood vessels in the human body. The limitation of arc discharge, laser ablation and CVD hinders the support of large scale demands for technology innovation and civilization-level engineering project,which also encourages and promotes the investment of research and commercial development. This paper discusses the discovered properties, recent application, and production of CNTs by collecting recent open literature. The high-performance machinal properties, electric conductivity, and thermal conductivity of CNTs with related application are experimented and explained. The current problems faced, including toxicity and mass production challenges, are stated, and how they reflect prospects and future directions of CNTs are pointed out in this paper. This study shows that mass demand created by pioneering and breaking construction can accelerate the process of material development.

Keywords: carbon nanotube, nanometre material, material physics, material application, material production.

1. Introduction

Carbon nanotube (CNT)was firstly discovered by Sumio lijima in 1991 [1]. In CNT, carbon atom adopts sp^2 hybridization and combines with each other by carbon-carbon σ bond to form honeycomb structure composed of hexagons. “Nanotube” shows that single-atom thick graphite is rolled into a tube with radius 0.5 nanometres, which means it is supposed to have both abilities of graphite as high conductivity of electricity and thermal and properties of nanomaterial as high-level mechanical performance [2]. So, CNT is valuable in research and application till now. The nanoscale and high conductivity of CNT makes it could be used in extreme tiny electronic component [3]. CNT with high mechanical properties is often mixed with other material to strengthen stiffness and fatigue resistance of composite material [4].

In addition to those outstanding performances, the future of carbon nanotube is quite challenging. CNT can harm human in different level, depending on its shapes, length and so on [5]. The mass production by industry is also problem because of the density, purity, chirality and environ mentality about CNT production requirement [6].

This paper aims to summarize some recent researches on CNT properties and application, then points out its future direction from the bottom up according to its own dangers and production efficiency.

2. Analysis of the current status, application, and future development about carbon nanotube

2.1. Properties and application

To sort out reasons why carbon nanotube can be applied to different demands, the analysis is classified by mechanical, electrical, thermal properties although the application always considers them all.

2.1.1. Mechanical property. CNT's strong mechanical properties show on its 1TPa high young's modulus and around 11-63 GPa adjustable tensile strengths [4]. So, CNT is considered as an excellent reinforce material to mix with polymer. In the report, the mechanical behaviour of poly methyl-methacrylate (PMMA) matrix composites reinforced CNT was tested [4]. It firstly built PMMA model as base and set a region for compositing CNT to get data of PMMA, CNT/PMMA and region (see Figure 1). Then, the young's modulus and stress were calculated in Table 1 as the results. Obviously, Young's modulus of material was successfully reinforced by applying CNT. Therefore, CNT has great prospects for application as reinforcement in composite materials.

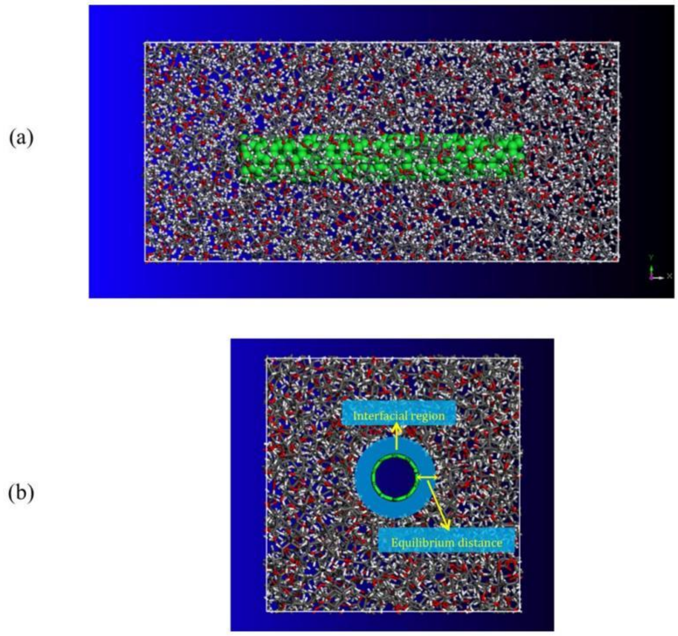

Figure 1. PMMA matrix reinforced with CNT (green) in simulation (a) side view (b)cross section view [4].

Table 1. Mechanical properties of PMMA polymer, PMMA polymer matrix reinforced by CNT and their interfacial region [4].

	PMMA polymer	CNT/PMMA	Interfacial region
Young's modulus (Gpa)	2.86	3.90	0.73
Yield stress (Mpa)	-	35.06	6.60
Yield strain (%)	-	0.9	0.9

In addition, the carbon layer on the sidewall of CNT can vary to suit different mechanical requirement, like signal-wall carbon nanotube (SWCNT), double-wall carbon nanotube (DWCN) and multiwall carbon nanotube (MWCNT) [7]. From article "Fatigue resistance of aligned carbon nanotube arrays under cyclic compression", MWCNT was experimented to show great fatigue resistance. The test used cyclic compression which to stress cyclic the material structure till fatigue. The admissibility of this article is the comparison for stress level and fatigue life of MWCNT and human muscle (see Table 2). MWCNT arrays have stronger stress level, strain, and longer lifecycles, which mostly approaching those of human muscle. The potential of CNTs to contribute to human medicine cannot be ignored, even needs priority research.

Table 2. The stress properties and lifecycles of several materials [7].

Class	Subclass	Example	Stress level (MPa)	Strain (%)	Strain rate (s^{-1})	Lifecycles
Muscle	Skeletal	Human	0.35	>40	5	$>10^9$
Piezoelectric	Polymer	PVDF	3	0.1	>1	$>10^6$
Polymer	Conducting	Polyaniline	180	>2	>1	$>10^5$
Polymer	Gel	PVA–PAA	0.3	>40	0.1	$>10^5$
CNT arrays	Multiwalled	Carbon	>2	>35	>0.75	$>10^6$

The mechanical properties of CNTs still have improvement space. A latest achievement was to research on new CNT fibre by high temperature annealing and molecular coalescence [8]. From different initial temperature, CNT fibre's final mechanical properties and structure varied huge. From Figure 2, with higher temperature, tensile strength in GPa increased sharply by slight growing elongation. However, from 1700°C to 2700°C, the tensile strength decreased 6.57±0.43 GPa to 2.89±0.1 GPa, which closely to graphite. This leads to a new production way on CNT fibre because setting certain temperature annealing could fit certain mechanical demand of market. Higher performance allows it to be used in some extreme environments, like structural materials on space elevator and space station [9].

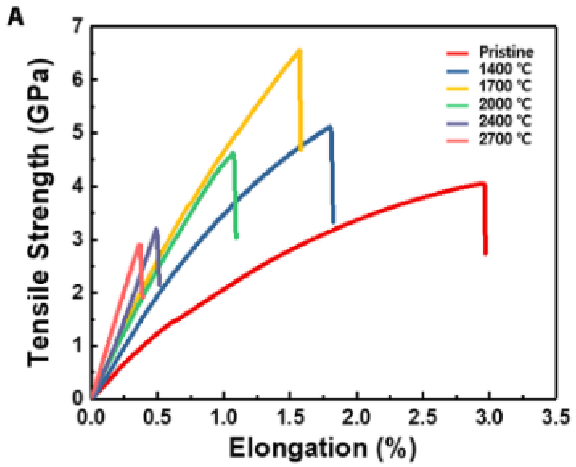

Figure 2. Different annealing temperature affects the stress and strain performance of CNTs [8].

2.1.2. Electrical property. CNT has high performance of electrical property, and it changes by adjusting the rolling direction in the carbon network. The chiral vector shown in Figure 3, CNT's metallic conductivity shows on n=m while n=0 or n≠m point to semiconducting [9]. The semiconducting property is very important because it means CNT could be applied in electronics. Scientists tried to figure out how to efficient use of CNTs on integrated circuits through arraying and density adjustment [10]. They applied high density semiconducting CNTs on field-effect transistors (FETs) with close arrangement (around 100-200 CNT/μm), resulting on higher performance than silicon FET see in Figure 4 [10]. From figure 4, with longer gate length (L_g), the much larger magnitude of transconductance ($g_{m,}$) in the research work than that in silicon FETs. All these work and results point out CNTs can make an important role in semiconductor material revolution.

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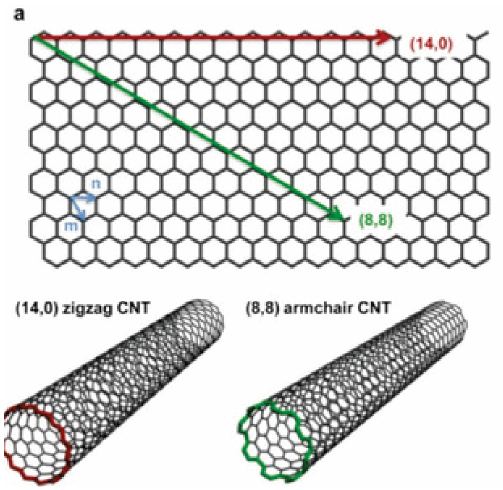

Figure 3. The chiral vector and different orientation structure of CNTs [9].

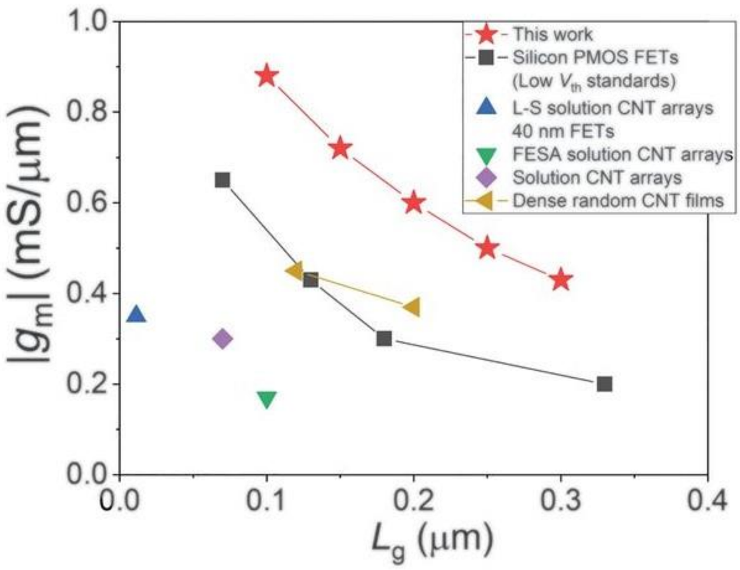

Figure 4. The magnitude of transconductance versus experimented FETs gate length for different types of FETs [10].

Besides as element in integrated circuit, high electrical conductivity of CNTs solve the power output problem and time-revolution instability of biofuel cell [11]. Enzymatic fuel cells can generate energy from organism through the ability of enzyme. It is renewable and low energy supply because of enzyme catalysis, but material of bioelectrodes is difficult to select. This problem is reflected from glucose biofuel cells, which needs consider not only the conducting efficiency but also time-revolution stability [11]. Multiwall carbon nanotube (MWCNTs) here was utilized for high electrical conductivity (total electrode experimented up to 3300 Sm^{-1}) and porous matrix. Porous matrix provides a suitable environment for connection between current to enzyme and enzyme substrate diffusion [11]. The overall performance of glucose biofuel cells has been improved. So, CNTs also could be used in high electrode performance requirements of battery cells.

In addition to satisfy the special demand of biofuel battery, MWCNTs can improve the power and efficiency of energy converter. An interesting article introduced such new energy harvester made by MWCNT yarn [11]. This can effectively receive the mechanical energy (stretch & twist) and output electrical energy. The function of MWCNT here includes powerful mechanical properties as its high

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fatigue resistance and large young's modulus and high electrical conductivity & capacity. That energy harvester named "Twistron" was tested to receive the mechanical energy from sea wave with temperature 13°C and 0.31 M NaCl content and output 1.79 μW average power limited by 25% deformation [12]. It is significant that "Twistron" successfully and totally uses both high-performance mechanical and electrical properties in energy transferring. This thought could be applied to solve the machine which has the mechanical lifetime and energy conducting power.

2.1.3. Thermal property. The high-performance thermal property of carbon nanotube is its high thermal conductivity so that it is frequently used to make up composite material, especially shape-stabilized phase-change composites (SSPCCs). SSPCCs has excellent thermal energy storage and thermal management, but trouble in thermal output efficiency and some thermal conductive filler may affect thermal storage of SSPCCs lower [13]. So, 3D SSPCCs with the interact network made by 1D CNTs and 2D h-BN successfully made up for thermal conductivity defects and side effects. From Figure 5, SSPCCs based on polyethylene glycol (PEG) has much higher thermal performance than pure one by 153.6% increasing [13]. Then, its thermal charge rate could be faster with environment temperature changing. This reflects the prospect of carbon nanotubes as high thermal conductivity auxiliary materials in composite materials.

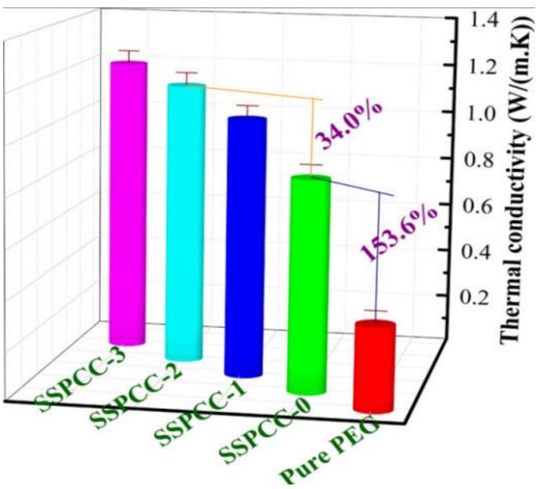

Figure 5. Thermal conductivity of pure PEG and CNTS-hBr-PEG SSPCCs [13].

It is normal for CNTs to combine with other material for developing thermal property and stable structure, called as synergy effects. Excepted hBr as active agents and stabilizers mentioned before, graphene oxide is another enhancer [13, 14]. A typical material "microencapsulated phase change materials (MEPCM)" also trouble in low thermal conductivity, which applied in solar thermal storage [14]. Different that in SSPCCs, the synthesis of MEPCM is modified by graphene oxide (GO) and CNT. In Figure 6, it was easily found out the progress GO-CNT made in thermal conductivity and latent heat for energy storage [14]. When mass ratio of GO:CNT is 3:1, its thermal conductivity is highest as 0.3821 W/mK and increasing with more addition of filler. This points out CNTs is necessary to try to combine with other material because higher performance properties. It is also proved in figure 6.b that the latent heat of MEPCM/GO-CNT is totally larger than that of MEPCM/CNT with filler added [14].

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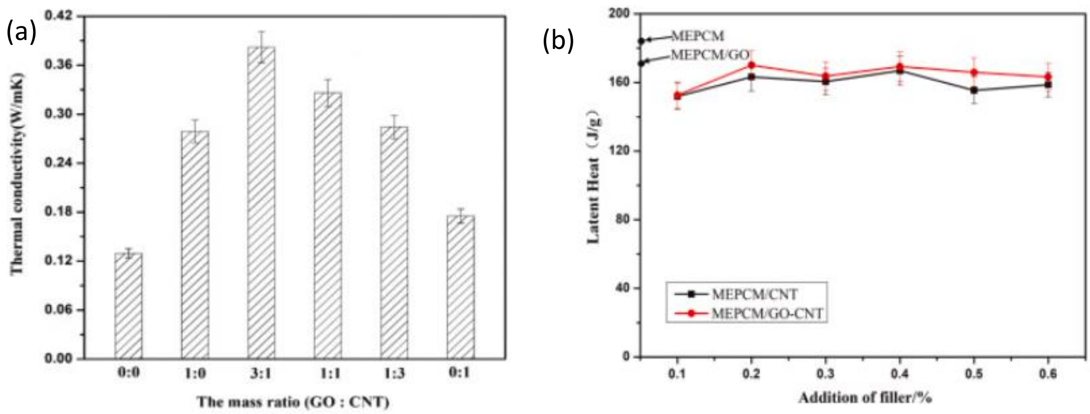

Figure 6. (a) The thermal conductivity influenced by different mass ratio of GO and CNT; **(b)** The latent heat of MEPCM contained CNT or GO-CNT [14].

2.2. Disadvantages and problems

As the saying goes, each coin has two different sides. CNTs also have its shortage and improvement space, including toxicity and mass production.

2.2.1. Toxicity. Carbo nanotube has excellent properties in mechanical, thermal, and electrical. Before mass application, its safety issue should be tested. Based on recent types and composites of CNTs, its toxicity comes from metal impurities, structure, charge, and density [15]. Impurities in CNTs are the main cause as metal contaminants. Different metals and mass ratio can induce respiratory and cardiovascular disease varying degrees. For example, Most MWCNTs sold has Fe, Co, Mo, and Ni which human is possibility induced bronchitis by exposure [15]. In addition, the physical properties of CNTs are also threats. Surface charge and layer number will influence the working active of macrophages, meanwhile longer length and needle shape easily cause granuloma because macrophages only can devour certain objects [15]. Safety assessment of material is important and necessary for further application and production. The hazard on environment and human will significantly drop the investment and research. As a result, the toxicity of CNTs needs to warn and improve before mass popularization in daily life.

2.2.2. Production. The raw material resources of CNTs are easily available as CNTs are just constructed by carbon. The problem is mainly reflected in manufacturing method and function targeting. Currently, the synthesis of CNTs can be divided into two ways which are based on physical process and chemical process. Arc discharge and laser ablation both produce highly pure CNTs through high energy by achieving carbon sublimation with strict condition (low pressure, vacuum, and low inert gas content) [3]. The extreme condition seriously affects the continuous production efficiency although its huge one-time production can make up for this shortcoming. Chemical vapor deposition (CVD) is to form CNTs on the catalyst site with milder condition. This production way can control the CNTs structure (length, radius, and arrays) by catalyst which are always metal and metal oxide, especially Fe and Fe derivatives. For example, some catalysts selected for vertically aligned CNT growth is show in Table 3 [16].

Table 3. Some Selected results of vertically aligned CNT growth [14].

Method	Catalyst	T[°C]	Diameter [nm]
CVD	Fe/mesoporous SiO_2	700	~30
	Co/SiO_2 plate	950	30–50
	Co in AAO	500	~90
	Co/Mo/quartz	800	1.0–2.0
	$Fe/Al_2O_3/Si$	770	6–15
	$Fe/Al_2O_3/Si$	750	10–30

The improvement of CNT industry process has many points from resource to output, including high efficiency catalyst, cheaper resources, multifunction reactor and coupling reaction. These ideas are summed up from the petroleum processing and always classic and useful way to raise industrial production efficiency. In addition, the mass production must pass commercialization threshold, which means CNTs have an extremely large number of application requirements [16]. Therefore, CNTs industry will attract more and more investment about finance, scientists, and other related industry. The breaking point which triggers this explosive development is to create that huge application requirement. Space elevator is an ideal example to detail features of 'Breaking Point'. Mass CNTs needs to be applied to the cable from the earth surface to geosynchronous orbit (about 35800 km) as its high-performance mechanical strength and thermal conductivity [17]. The achievement of space elevator is meaningful for technological leap and future foundation of human civilization. In fact, this idea already pointed out in 20th century and researched so far. It must deal with many other theoretical and practical problems, likes electromagnetic propulsion and space tether [18]. Meanwhile, from 2000 to 2016, the retail price of SWCNT dropped $1500 per gram to $2 per gram as produced 75% [18]. Lower price reflects lower production costs and bigger production scale. This proves space elevator fastens the development of CNTs industry as breaking point doing. Although CNTs are frequently used in various fields, it will ultimately be the cornerstone of cutting-edge aerospace as the breakthrough of the technical upper limit.

3. Conclusion

From the overview, excellent properties of carbon nanotube with application are shown. For mechanical performance, CNTs has high young's modulus and can combine with other materials to continue to improve mechanical properties. Suitable fatigue resistance and stress levels of its multi-layer form MWCNTs totally meet the requirements of artificial human muscle. These properties can be tuned under specific processes as annealing. In addition, high electrical conductivity of CNTs makes that it plays an important role in semiconductor, electrodes for biofuel cell and energy harvester in energy converter (machinal to electricity). In the same way, CNTs are always ideal composition of composite material for improving heat output efficiency because of its high thermal conductivity. These both point out composite-CNTs are never disappointing for higher performance properties in electrical and thermal. However, the metal impurities in CNTs are harmful for human respiratory tract and affect the normal work of macrophages. With the safety problem of production, production method is also a point to improve. Latest processes including arc discharge, laser ablation and CVD can produce high purity and function targeting CNTs, but not mass enough to support large scale construction, like space elevator. This national and even civilized construction can greatly accelerate the process of material popularization though extremely challenging. Attracting a lot of investment from countries and enterprises can develop CNTs further.

The flaws in this study are that not all excellent properties, application and typic construction about CNTs are introduced, like optical performance and orbital mining device for gaseous planets. Nevertheless, they all emphasized the research and practical value of carbon nanotubes.

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