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Carbon nanotube: A review on its mechanical properties and application in aerospace industry

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Abstract. Carbon nanotube (CNT) is a prominent material that has good potential to be used in numerous aerospace applications. This paper presents a review about CNT on its various aspects such as fabrication methods, mechanical properties and applications in aerospace. The evolution of CNT is discussed to its recent applications. The aim of this review article is to highlight the recent advancements in CNT and its possible applications in aerospace.

1. Introduction

Carbon is the 15th most abundant element in the crust of the earth. Having a tetravalency and hence a hybridization of sp³, carbon can form a vast variety of crystalline structures. The allotropic forms of carbon include graphite, diamond, Buckminsterfullerenes, carbon nanotubes, graphene and about 500 hypothetical allotropes as illustrated in Figure 1. The carbon nanotubes (CNTs) are thin and long tubes that are basically graphene sheets rolled into cylinders (graphene is a hexagonal carbon structure). The CNTs have been known for their extraordinary mechanical, thermal and electrical properties, and they are members of fullerene structural family, with length-to-diameter ratio greater than 10⁶.

CNTs have found applications in a lot of fields including nanotechnology, material science, optics and electricity due to their astonishing properties, and they can also be useful for aerospace industry on multiple grounds. CNTs are categorized into two major types: multi-walled carbon nanotubes (MWNTs) and single-walled carbon nanotubes (SWNTs) [1]. The first discovery of MWNT is made by occurrence of hard deposits on the cathode using electric arc experiments to form fullerenes [2]. On the other hand, the formation of SWNT is first confirmed through two separately published studies in 1993 [3]. SWNT is formed by rolling one sheet of graphene in the form of a cylinder and forming a lattice represented by the vector (m, n) . Depending on m and n values, SWNT can be further classified into three different categories: armchair ($m = n$), zigzag ($m = 0$) and chiral (other values of m and n) as depicted in Figure 2. These naming conventions are used to classify SWNT according to their different wrapping style. m and n are basically integers that are used for representing the mapping.

2. CNT Synthesis Methods

Three main methods for CNT synthesis are arc discharge method, chemical vapour deposition method and laser ablation method. First, the apparatus used in the arc discharge method is a vacuum chamber containing two graphite electrodes with distance of 1-2mm between them, which helps in attaining a steady discharge. The chamber is filled with low-pressure gas before a direct current arc discharge (i.e. electrical breakdown of a gas to generate plasma) is introduced between the electrodes. Gas inside the



chamber ionizes into electron and ions, which in turn result in the hot plasma formation between the electrodes. Arc discharge generates a temperature as high as 4000-6000K that makes the carbon precursor at anode sublime. The carbon vapours produced gets deposited on the cathode and cools down there. When this is observed under the Transmission Electron Microscopy (TEM), a columnar texture with thickness of about 6mm is seen to be formed, which is categorized as MWNTs [4]. Meanwhile, SWNTs are produced through arc discharge method using catalyst [Iron(Fe) or Cobalt (Co)]. SWNTs are produced in the soot and not on the cathode. For bulk production of SWNTs through arc discharge method, metals like Nickel and Yttrium are used [5].

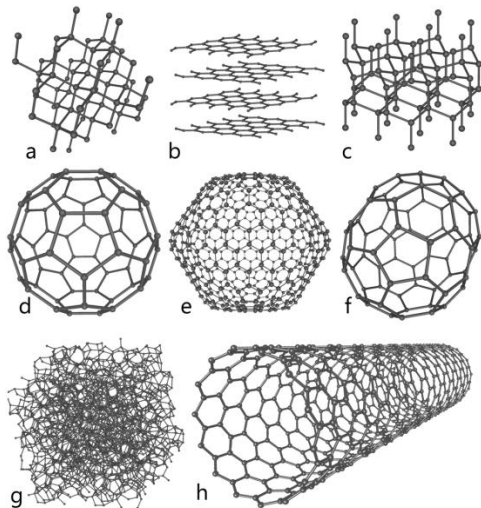


Figure 1: Allotropes of carbon: (a) diamond, (b) graphite, (c) lonsdaleite, (d) C₆₀ Buckminster fullerene, (e) C₅₄₀ fullerite, (f) C₇₀, (g) amorphous carbon, and (h) SWNT fullerenes [6]

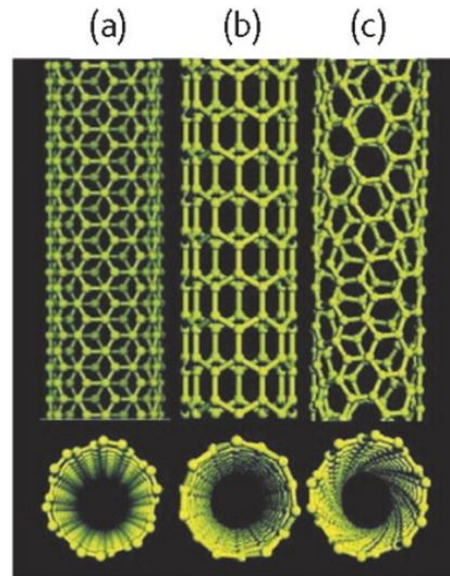


Figure 2: Categories of SWNT: (a) armchair, (b) zigzag, and (c) chiral [1]

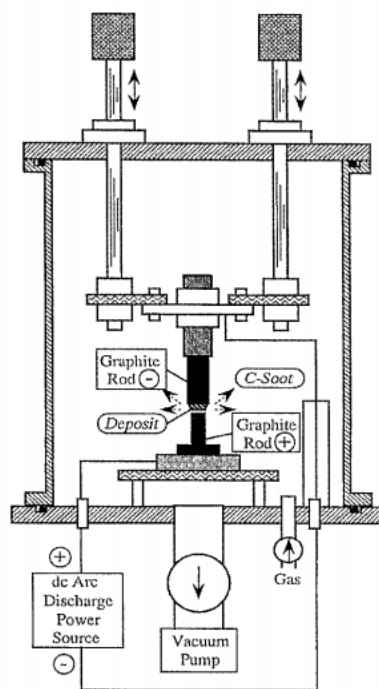


Figure 3: Working process of arc discharge device [4]

The second method, which is chemical vapour deposition (CVD) method, is currently used a lot as it is simpler and costs less in comparison to both arc discharge and laser ablation methods. In the CVD method, pre-treatment of the substrate surface can be done and this helps in controlling multi-walled and single-walled architectures [7]. The other two methods: laser ablation and arc discharge are less effective as they produce nanotubes with a higher amount of impurities. The product through CVD is likely to be more pure and therefore, the desired type of CNT can be obtained [8]. However, although CVD method gives a high yield, the products are more structurally defective. The schematic diagram of the CVD method is shown in Figure 4.

One type of CVD is thermal catalytic. In this method, hydrocarbons or other carbon feed stocks are decomposed at elevated temperature (i.e. ranging between 500-1200°C) by diluting them in continuous flow of noble gas over transition metal catalysts (i.e. iron, cobalt, nickel, etc.) in a furnace [9]. Metal catalysts applied in this method are obtained from sources like organometallobenes (i.e. cobaltocene, nickelocene, ferrocene) [10]. The decomposed carbon will dissolve the metal particles until a point of super saturation is achieved where carbon precipitate in the form of fullerene dorns gets formed. This CVD method is useful in producing CNT in variety of forms. Low temperatures (i.e. ranging between 600-900°C) will yield MWNTs whereas high temperatures (i.e. ranging between 900-1200°C) help in producing SWNTs [11]. The nanotube's diameter and the catalyst particles are correlated. Hence, the diameter of CNT obtained can be controlled by using catalyst of controlled sized [12]. Furthermore, another type of this method is plasma enhanced CVD (PECVD). In PECVD, the thermal energy of the system is substituted by energy sources that can provide energy for hydrocarbon decomposition and support the production of CNT at a comparatively lower temperature. In PECVD, hydrocarbon gas is in ionized state and it is used over transition metal. The sources, which are used as the plasma energy source, are hot filament PECVD, direct current PECVD, radio frequency PECVD and also microwave PECVD [8].

Last but not least, laser ablation or laser vaporization method for CNT synthesis uses a laser beam (Yttrium Aluminum Garnet or CO₂ laser), which is directed on a graphite rod placed inside the reactor. Graphite rod gets vaporized due to the elevated temperature of argon buffer gas that is further cooled and collected to copper collector, as illustrated in Figure 5. This method is advantageous as it helps in production of high quality SWNT (i.e. with minimal defect). This method also offers diameter control, which can be done by changing the temperature, flow rate and catalytic metal [8].

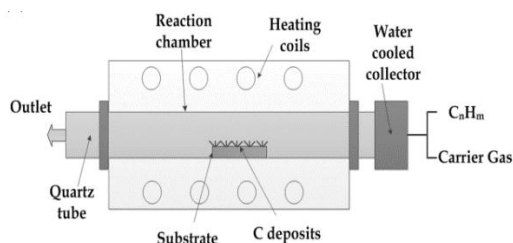


Figure 4: Schematic diagram for CVD [13]

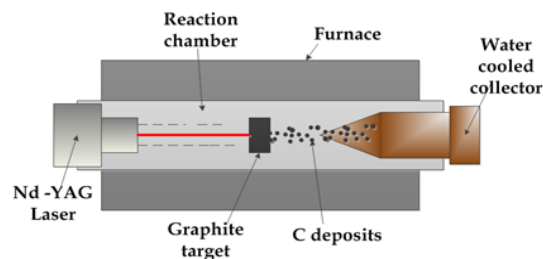


Figure 5: Schematic diagram for laser ablation [13]

3. CNT Mechanical Properties and Composites

Tensile strength of a material is the measurement of the force required to pull something such as rope, wire or structural beam to the point where it breaks. Tensile strength of a multi-walled CNT is found to be 63GPa [14]. CNT shells have been found to have a strength of 100GPa. Theoretically, Young's modulus of CNTs should be similar to Graphene sheet if their diameter is not so small to misshape the bonds. Young's modulus of CNT is found to have an order of 1TPa. This strength of CNT is due to the covalent sp² bonds between the carbon atoms [15]. These results are being observed mainly through Atomic Force Microscopy (AFM) and High-Resolution Transmission Electron Microscopy (HRTEM). The tensile strength and elastic modulus of CNTs make them the strongest and most inelastic materials ever discovered [16]. Young's modulus of MWNTs is found using Transmission Electron Microscopy

(TEM). TEM can measure the mean square vibration amplitudes of arc grown MWNTs over a wide temperature range (i.e from the room temperature to 800°C). The average value obtained for 11 tubes is 1.8TPa, ranging between 0.40TPa to 4.15TPa [17]. For SWNTs, the average for 27 tubes yielded a value of 1.3TPa. However, this result is found to have two systematic errors: one due to temperature measurement and other due to the nanotube length [18].

The real strength of materials is often lower than the theoretical value since the actual strength of a material cannot solely be determined with the help of its modulus. Strength of a material depends on several factors like its history, atmosphere, pressure and temperature. This situation applies to CNTs as well. Temperature is a key factor for checking the strength of a material because dislocation takes place due to temperature. CNTs, like other covalent materials, are very brittle at low temperature. At room temperature, flexibility of CNT is due to its strength and unique capability of hexagonal network to distort for relaxing stress [18].

In the meantime, due to low weight, high aspect ratio and high Young's modulus, CNTs are also ideal for making composites. A common method of producing nanotube composites is by combining the nanotubes dispersion with polymer solution and the solvent is then evaporated afterwards. Various methods are being used to produce CNT composites for mechanical purposes [19]. Nevertheless, there are some difficulties while fusing CNT in the polymer matrix since the CNT does not easily dispersed in it [20]. CNT composites are mostly prepared to get composites that have stiffness and high amount of strength for mechanical use. CNTs effectively enhance the capability of a polymer but some of the initial results were not as successful. For instance, polyvinyl alcohol (PVA)/nanotube composites are made by blending aqueous nanotube dispersion along with aqueous solution of polymer. The mixture obtained is then casted as films and the water is evaporated. The composites are obtained at the room temperature and they have stiffness way lower than that of isolated nanotubes. At room temperature, the modulus of the composites is 150MPa. Composites from MWNTs have been produced by the arc method and then submerged in a copolymer MPC-DEA. The nanotubes and polymers are mixed in the acidified solution, then applied to TEM matrix and dried. To perform the deformation studies, electron beams from TEM at a low accelerating voltage (75Kv) are focused on the film to produce the thermal stress. In turn, this initiates the forming of cracks inside the composites. The cracks grew wider but the tubes did not break. This can be due to better nanotubes that are produced by arc discharge and not by catalytic method [2]. Another effective way of enhancing the mechanical properties of composites is by depositing SWNTs layer by layer and polymer on the substrate, and then they are cross-linked. The layers are stuck together due to Vander Waals forces and electrostatic attraction among SWNTs that possesses negative charge with the polyelectrolyte that is positively charged. The films produced in this method have relatively better mechanical properties. Average tensile strength of films is found to be 220MPa, which is greater than most strong plastics. Thus, this layer by layer approach of making composites can be very promising in future.

4. Aerospace Applications

Being a high strength lightweight material, CNTs are an obvious choice for aerospace industry as they help in reducing the weight. Aerospace organizations and companies such as National Aeronautics and Space Administration (NASA) Ames Research Center, NASA Johnson Space Center and also NoPo Nanotechnologies Private Ltd. have been working on finding the potential roles of these materials. For example, Carbon Nanotube Reinforced Polymer (CNRP) can help serve as radiation protection, heat dissipation on coatings and static discharge. Moreover, CNTs can also be used in electric wirings to help in increasing the conductivity of current.

Space elevator is a revolutionary idea to carry payloads to space, which is conceptually illustrated in Figure 6. The elevators are shown to be using cables to carry the payloads to space. This means that high tensile strength cables are required. If a cable of low carbon density of 1300kg/m³ is assumed with a fixed cross section, then the maximum stress to carry payloads from the earth's surface to the Geosynchronous Earth Orbit is found to be equal to 63GPa [21]. Such high strength can be achieved by CNTs. Nonetheless, even a few vacancies in the SWNTs can lead to a sudden change as suggested by

Quantized Fracture Mechanics criteria (i.e. vacancy defects in CNTs are produced after synthesis and this disorder in the structure makes the material weak) [21]. In such a huge cable structure, the vacancies are inevitable due to statistical reasons [22]. Statistical and different deterministic models to estimate the strength of mega CNT cable have suggested a strength reduction by a factor of at least 70% as compared with theoretical strength of CNT and an increase in mass by a factor of larger than 300% [21]. These results are confirmed by the first observations of long meter nanotube cable strength [23]. This reduction poses a doubt in effective realization of use of such long cables in construction of a space elevator.



Figure 6: NASA's description of artwork by Pat Rawlings [24]

In addition, CNTs can also be used in large satellites and spacecrafts to reduce their weight. Using CNT in satellite can reduce the weight to one third of its current weight [25]. The use of silane grafted MWNTs can result in better mechanical properties and thermal stability compared to neat resin with normal MWNTs [26]. Thermal conductivity of MWNTs is of higher value than diamond [27] and thus they offer an immense potential for thermal protection systems. To reduce the payload, aluminium is replaced with CNRP on the Reusable Launch Vehicle, which has led to reduction in weight by 82%. Furthermore, CNTs can be used as propellant additives for chemical propulsion systems. An electric motor is applied in electric aircraft and in such motors, CNT can replace the iron and copper materials to fulfil the requirements of next generation motors by increasing efficiency and reducing weight. In space exploration, usage of electric propulsion is catching eyes over the usage of chemical propulsion. Electric propulsion has been efficiently utilized in different space missions [28]. In the nano-particle Field Extraction Thruster (nanoFET), thrust is produced by emitting charged CNT particles.

Reduction in weight can also be achieved by replacing the current copper wiring in aircraft by CNT based wires [29], where use of CNT cable known as 1553B can result in 69% weight reduction [30]. The weight of an aircraft is increased many folds due to wiring. For instance, a commercial plane like Boeing 747 has about 217261m of copper wiring that contributes 181.437kg to its weight. Moreover, CNT can be used in International Space Station and other future space settlements for the purification of water since nano materials possess a number of properties that enable them to purify water. The nanotechnology can serve as recyclable ligands for toxic metal ions, organic/inorganic solutes and also radio nuclides in aqueous medium [31].

5. Conclusion

CNT research field has come far from where it started in 1991. New methods of CNT synthesis have been achieved with CVD being the most promising one due to its economic advantages and simple methods, even though CNT obtained through this method is structurally ineffective. In its initial stages

due to its high tensile strength and elastic modulus, CNT seems to be a promising material due to its amazing mechanical properties. However, even after years of efforts, there is still work that need to be done further in the field of CNT composites to increase their practical usages. The application of CNT in reducing the payload of aircraft and space shuttles appears to be really promising as of now. Many researchers have shown that the overall weight of aircraft and space shuttles can be effectively reduced by using CNT based composites or CNT for electric wiring.

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