FUNDAMENTALS AND TECHNOLOGICAL ASPECTS OF CARBON NANOTUBES

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1. INTRODUCTION

Since their initial discovery as a by-product of fullerene-synthesis in the arc-discharge process, carbon nanotubes have attracted a very significant amount of attention from the scientific community the world over. The existence of tubular forms of carbon has been known by scientists and engineers working in the fields of chemical reactors and thermal management systems for at least half a century.1,2 These tubes of carbon, typically several tens of nanometers in diameter and several hundreds of micrometers in length, were formed due to the catalytic decomposition of either hydrocarbons or carbon monoxide by nanometer-sized particles of transition metals typically found inside the reactors. Analysis of these tubular forms of carbon showed that they were multi-walled in structure, and the individual sheets of graphite (graphene) that constituted the walls of these tubes were found to be extremely defect laden.

Scientific and technical interest in carbon nanotubes was very significantly revived by the discovery in 1991 by Sumio Iijima4 at NEC of multi-walled nanotubes (MWNT) grown in the plasma of the arc-discharge apparatus used for the synthesis of fullerenes or buckyballs. Similar to the whiskers discovered by Roger Bacon3 at GE in 1960, these MWNT were grown without the aid of a catalyst and formed in the plasma of the arc, where the temperature is estimated to range anywhere from 3000 to 5000 °C. Subsequent work by other researchers at NEC5 demonstrated that the MWNT formed at significantly higher pressures on inert gas (such as helium or argon) than needed for conventional fullerene synthesis. A very significant number of scientific papers and books have been published over the last decade on studies related to the structure, properties, and applications of MWNT, as will be detailed later in this chapter. However, the almost simultaneous discovery in 1993 at NEC6 and IBM7 of the single-walled variants of carbon nanotubes (SWNT) has considerably overshadowed the scientific excitement associated with MWNT. SWNT can be considered as unique materials for several reasons: they are prototype one-dimensional quantum wires that are made up of one element (carbon) that are one atom in wall thickness and tens of atoms in circumference.

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with every atom on the surface of the tube. The theoretical as well as experimentally measured values of the mechanical properties of SWNT, with elastic modulus and tensile strength calculated to be near 1000 and several tens of gigapascals (GPa), respectively, are comparable to those predicted for single sheets of graphene. Perhaps the most exciting characteristics of SWNT are their electronic properties, which depend exclusively on their diameter and chirality (the manner in which the single sheet of carbon atoms is wound). Their electronic properties, in combination with their mechanical properties, render SWNT as a very exciting class of materials for research and for several current and potential applications.

The predecessor to what the scientific community now refers to as carbon nanotubes was discovered in the late 1950s. It was referred to as a graphite whisker and it was synthesized in a graphite arc in an argon atmosphere under high pressure and temperature conditions. These whiskers were large enough to allow the direct measurement of physical properties, and based on structural and mechanical property analyses, it was determined that each whisker consisted of one or more concentric tubes, with each tube being in the form of a scroll extending continuously along the length of the whisker, with the graphitic c-axis being normal to the axis of the whisker. Mechanical property measurements indicated that the tensile strength and elastic modulus of these whiskers were 20 gigapascal (GPa) and 800 GPa, respectively – which are very close to the theoretical values calculated for single crystal graphite.

2. SYNTHESIS OF CARBON NANOTUBES

The discovery of both variants of carbon nanotubes was achieved using the same process used for fullerene synthesis – the evaporation of graphitic electrodes in an arc-discharge set-up. A schematic of an arc-discharge unit is shown in Figure 1.

Figure 1. Schematic of the arc-discharge apparatus used for the synthesis of fullerenes and carbon nanotubes.