Diamond & Related Materials 50 (2014) 135–150

Contents lists available at ScienceDirect

Diamond & Related Materials

journal homepage: www.elsevier.com/locate/diamond

Arc discharge synthesis of carbon nanotubes: Comprehensive review

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ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 24 September 2014
Accepted 3 October 2014
Available online 13 October 2014

Keywords:
Arc discharge
Carbon nanotube synthesis

ABSTRACT

In quest to synthesize high quality carbon nanotubes in bulk, different routes have been proposed and established over the last two decades. Arc discharge is the oldest and among the best techniques to produce high quality carbon nanotubes. Though this synthesis technique has been explored for a long time, the nanotube growth mechanism is still unclear and the growth conditions lack strong correlation with the synthesized product. In this review, we attempt to present the mechanism of nanotube growth in arc discharge and the factors affecting its formation. In order to understand the physics of this mechanism, the effect of experimental parameters such as setup modification, power supply, arc current, catalyst, pressure, grain size, electrode geometry and temperature on size and yield of the nanotubes has been detailed. The variation in synthesis parameters employed in literature has been presented along with challenges and gaps that persist in the technique.

Contents

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http://dx.doi.org/10.1016/j.diamond.2014.10.001
0925-9635/

1. Introduction

Carbon nanotubes (CNTs) possess excellent mechanical, electronic, thermal, optical and chemical properties which have revolutionized the state-of-the-art in nanotechnology. CNTs have been broadly classified as Single-Walled Nanotubes (SWNTs), Double-Walled Nanotubes (DWNTs) and Multi-walled Nanotubes (MWNTs). Researchers have devised different routes to synthesize CNTs from various carbon precursors. The most popular and widely used nanotube synthesis techniques are: Arc Discharge, Chemical Vapour Deposition and Laser Ablation [1–16]. Apart from these methods, Hydro-thermal synthesis [17], Electrolysis [18,19], and Ball milling [20,21] methods have also been used.

CNTs were first synthesized by Iijima [22] in 1991 using arc discharge method. Over the last two decades, researchers have demonstrated a successful use of this technique in the production of high quality CNTs. A bar graph shown in Fig. A.1(a) (Appendix A) depicts the number of papers published year wise on CNT synthesis using arc discharge. We gained some insights of nanotube growth process and understood the fundamental role of few arc discharge parameters. However, the literature lacks comprehensive study on the mechanism of nanotube formation and needs strong correlation between growth conditions and synthesized nanotubes. The requiem to understand the role of growth conditions lays in selective growth of nanotubes using arc discharge, which remains largely unexplored.

For researchers taking up the nanotube synthesis using arc discharge, the availability of comprehensive review on the process is quintessential. Previously, Ando and Zhao [7] discussed the synthesis of SWNTs and MWNTs using arc discharge. In 2007, Harris [8] investigated the models of nanotube growth in arc discharge and laser ablation processes. In 2010, Ando [10] presented the chronological aspect of arc grown nanotubes in hydrogen atmosphere. In 2011, Tessonnier and Su [12] briefly discussed the nucleation and growth process of nanotube in arc grown CNTs. In 2011, Prasek et al. [13] reviewed the different routes of nanotube synthesis. In 2012, Journet et al. [16] discussed low or medium temperature techniques to synthesize CNTs.

The present review updates and details on experimental attempts to manufacture carbon nanotubes using this technique. The growth mechanism of nanotubes, as explored in literature has been briefed. It further discusses the role of synthesis parameters like setup modification, power supplies, arc current, catalyst, pressure, grain size, electrode geometry and temperature on the nanotube production. Few parameters like pressure and catalyst have been investigated quantitatively in literature but the exact role of the growth conditions still requires extensive investigation. The review has been divided into four sections. Section 2 discusses the nanotube growth in arc discharge. Section 3 outlines the physics of CNT growth in arc discharge process and the role of growth conditions on nanotube formation, which is followed by the conclusion.

2. Nanotube growth in arc discharge

2.1. Arc discharge setup

Arc discharge is the electrical breakdown of a gas to generate plasma. This old technique of generating arc using electric current was first used to produce CNTs by Iijima [22] in 1991. A schematic of an arc discharge chamber is shown in Fig. 1. The chamber consists of two electrodes which are mounted horizontally or vertically; one of which (anode) is filled with powdered carbon precursor along with the catalyst and the other electrode (cathode) is usually a pure graphite rod. The chamber is filled with a gas or submerged inside a liquid environment. After switching on the power supply (AC or DC), the electrodes are brought in contact to generate an arc and are kept at an intermittent gap of 1–2 mm to attain a steady discharge. A constant current is maintained through the electrodes to obtain a non-fluctuating arc for which closed loop automation is employed to adjust the gap automatically. A fluctuating arc results in unstable plasma and the quality of the synthesized product is affected. The arc current generates plasma of very high temperature ~4000–6000 K, which sublimes the carbon precursor filled inside the anode. The carbon vapours aggregate in the gas phase and drift towards the cathode where it cools down due to the temperature gradient. After an arc application time of few minutes the discharge is stopped and cathodic deposit which contains CNTs along with the soot is collected from the walls of chamber. The deposit is further purified and observed under an electron microscope to investigate their morphology.

2.2. Growth mechanism of carbon nanotubes in arc discharge

Over the last two decades, researchers have investigated and suggested growth conditions for nanotube formation based on their experimental observations. Despite seminal studies, no clear understanding of the growth mechanism has been developed and a critical study lies in understanding the physics of this mechanism which certainly helps in predicting the optimum growth conditions of nanotubes. In this section, we present an outline of the synthesis mechanism in the growth of CNTs in arc discharge.

The two electrodes are brought in contact and upon application of voltage, constant current flows through them. The electric current results in resistive heating and raises the temperature of the electrodes.

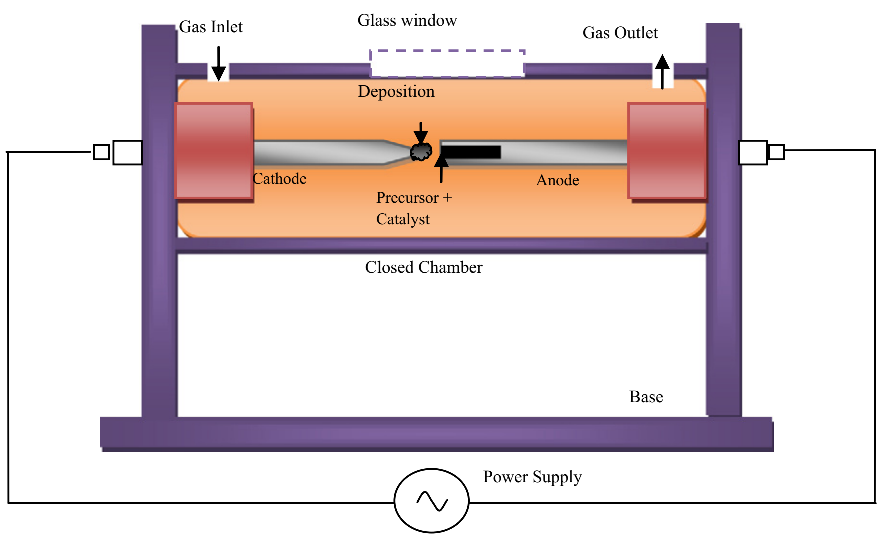

Fig. 1. Schematic of an arc discharge setup.