Design of VACUUM CHAMBER for CNT Fabrication using Finite Element Method

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Abstract

Carbon Nanotube (CNT) is a cylindrical graphene sheet of sp2-bonded carbon atoms with special electronic, molecular and structural properties. Many researchers are exploring the manufacturing of CNT’s and different methods are proposed. The literature is lacking in giving details of apparatus design for CNT fabrication, which makes the development of fabrication facility for CNT a state of art technology. The present work attempts to design a pressure vessel (vacuum chamber) for CNT fabrication using finite element modeling. The FE models are developed using ANSYS. A comprehensive analysis of developed models is done and first optimal dimensions of the vacuum chamber unit for fabrication facility of CNT are presented.

Keywords: Carbon Nanotubes Fabrication Facility, Pressure Vessel Design, Finite Element Method.

1. INTRODUCTION

Since the discovery in 1991 [1], many researchers all over the world have investigated carbon nanotubes (CNTs). The large length (up to several microns) and small diameter (a few nanometers) resulting in large aspect ratio is captured as one-dimensional model of fullerenes. CNTs possess extraordinary electronic, mechanical and molecular properties [2-4]. Thermal properties due to unique structure and small size make CNTs ideal material for the study of low-dimensional phonon physics, and for thermal management, both on the macro-and the micro-scale. CNTs show metallic and semi-conducting electrical behavior as a function of configuration. The tensile strength of a Multi-Walled CNTs (MWCNT) is as high as 100 times that of steel and depends on many parameters like pressure and temperature, structural defects and imperfections.

Carbon nanotubes are generally produced by three main techniques, arc discharge, laser ablation and chemical vapor deposition. In arc discharge, vapor is created by an arc discharge between two carbon electrodes with or without catalyst and nanotubes self-assemble from the resulting carbon vapor [5]. In the laser ablation technique, a high power laser beam impinges on a volume of carbon containing feed stock gas of methane or carbon monoxide. Laser ablation produces a small amount of clean nanotubes, where as arc discharge methods generally produce large quantities with higher impurities. In Chemical vapor deposition (CVD), synthesis is achieved by a carbon source in the gas phase and an energy source, such as plasma or a resistively heated coil [6]. The diffusion and binding of carbon to a heated and catalyst coated substrate results in formation of CNTs for proper choice of process parameters. The carbon arc discharge method, initially used for producing C_{60} fullerenes, is the most common and easiest way to produce CNTs. The drawback of the arc discharge method is the product, which a mixture of many components like catalytic metals and requires separating CNTs from the soot.
The literature is lacking in giving details of apparatus design for CNT fabrication, which makes the development of fabrication facility for CNT a state of art technology. The US patent (6149775) provided the schematic diagram for fabrication facility of the carbon arc discharge method [7]. The fabrication setup as a product is neither analyzed nor explored for optimization in the process description given in [7]. In order to design the fabrication facility, comprehensive mechanical and thermal analysis is required for detailed dimensional optimization of the units of fabrication facility. The critical unit in the process schematic in [7] is a vacuum chamber for which static and modal analysis is done in present work using finite element method. The present work optimizes the design for the Vacuum chamber and works out optimal dimensions using ANSYS 8.0 [8].

The work is organized in four more sections: In the next section, the schematic of the arc discharge method given in [7] is detailed, Section 3 contains FE analysis of Vacuum chamber and results. In section 4, discussion on the results obtained in FE analysis is presented and optimal dimensional drawing of vacuum chamber is given. Section 5 gives conclusions and future scope of the work.

2. PROCESS LAYOUT FOR CNT FABRICATION FACILITY

The schematic in Fig. 1 [7] details the arc discharge apparatus for CNT fabrication. A vacuum chamber 1 is attached with a rotary pump 2 for creating vacuum and constitutes of metal-added carbon electrodes 3, 4 arranged opposite to each other. The position controlling apparatus 5, 6 for changing the distance between these electrodes, a distance power source 7 (AC/DC) for applying a voltage between the electrodes to generate discharge and simultaneously for controlling a discharge current, and a digital oscilloscope tube for observing a waveform of discharge current is placed giving a customized structure to vacuum chamber.

The vacuum chamber is provided with a gas inlet 9 for introducing a gas into the vacuum chamber, a hole for observing the preparation of soot 10, attachment for cooling tube 11 and a soot recovering filter 12 for recovering soot mounted near to an exhaust vent 13.

Fig. 1 Schematic of CNT Fabrication Layout using Arc Discharge Method

The vacuum chamber is the most critical unit of the scheme for fabricating process and is analyzed for designing in next section.
3. FINITE ELEMENT ANALYSIS OF VACUUM CHAMBER UNIT

Design of a vacuum chamber for manufacture of CNT involves the identification of the various parameters. Firstly, the shape of the vacuum chamber was taken as cylindrical. Next the diameter, height and thickness are chosen as parameters for analysis. The features of vacuum chamber configuration to be included in analysis are identified. Since this is a first attempt at designing, the number of features is kept at minimum. The features identified are two holes in the cylinder for insertion of electrodes, one for gas inlet, and one for exhaust vent and vacuum pump.

The dimension and placement of identified features on the cylinder are decided next using a number of design iterations. Assuming material of the vacuum chamber to be cast iron, inside pressure of vacuum chamber equal to 2/3 of atmospheric pressure as given in [7] and neglecting thermal loading, an FE analysis is done using ANSYS for static and modal behavior of the vacuum chamber. The solid model of the vacuum chamber is made in Pro/E. and is extracted in ANSYS for processing.

The results for vacuum chamber diameter and height, both, 10in., thickness 0.5 in. for static displacement and stress distribution and modal behavior are shown in Fig. 2, Fig. 3 and Fig. 4 respectively.

![Fig. 2 Nodal Solution of Displacement for (a) coarse mesh (b) Finer Mesh.](image1)

![Fig. 3 Nodal Solution of improved mesh Using Von-Mises criterion (a) Stress (b) Strain](image2)
4. DISCUSSION

The final design is obtained through an iterative process with many constraints and assumptions. Firstly, the shape of the vacuum chamber is assumed cylindrical, the material is chosen as cast iron and the design parameters and diameter and height are kept at 10 in. and locations of features (the various holes and their dimensions) are identified. The position of hole 1 and hole 2 is kept at a height of 5 in. from the base and position of hole 3 and 4 as height from base, the thickness of chamber wall and diameter of hole 1 to 4 are varied as parameters. Constraining the aspect ratio to the default value for element, the static structural analysis is done in ANSYS refining the mesh using default tetrahedral element. The model parameters are altered a number of times in order to obtain minimal stress concentration with least material for the constraint of user defined aspect ratio. After numerous iterations, the dimensions with least stress are chosen for the vacuum. Maintaining the hole diameters and their respective locations as constant, the thickness is varied from 0.3 to 0.5. It is observed that the stress values decrease as thickness increases. Next, the thickness is kept constant at 0.5in and position of holes varied, with no change in hole diameters. The stress increases if the holes 1, 2, 4 are placed closer together. To further improve the solution, the thickness and locations are maintained constant and the diameter of the holes is varied. Few results are presented in Table 1 of which bold dimensions are optimal results.

Table 1 Results of Stress and Strain in Vacuum Chamber for few Parametric Variations using ANSYS

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>Hole Φ (1 and 2) (in.)</th>
<th>Position from base (in.)</th>
<th>Hole Φ (3 and 4) (in.)</th>
<th>Position from base (in.)</th>
<th>Max. Stress (KPa)</th>
<th>Max. Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.5</td>
<td>5</td>
<td>1</td>
<td>1.9</td>
<td>1360</td>
<td>0.0163</td>
</tr>
<tr>
<td>0.5</td>
<td>1.5</td>
<td>5</td>
<td>1</td>
<td>1.9</td>
<td>1050</td>
<td>0.0120</td>
</tr>
<tr>
<td>0.5</td>
<td>1.5</td>
<td>5</td>
<td>1</td>
<td>1.5</td>
<td>1090</td>
<td>0.0123</td>
</tr>
<tr>
<td>0.5</td>
<td>1.75</td>
<td>5</td>
<td>1</td>
<td>1.5,8</td>
<td>922.9</td>
<td>0.0105</td>
</tr>
<tr>
<td>0.5</td>
<td>1.75</td>
<td>5</td>
<td>1.25</td>
<td>1.5,8</td>
<td>922.9</td>
<td>0.0105</td>
</tr>
</tbody>
</table>

5. CONCLUSION

In the present work, a study of CNT synthesis using arc discharge method was carried out for which a process layout schematic is available. The critical unit of the fabrication facility based on the process layout is identified as a vacuum chamber. The vacuum chamber is chosen for finite element analysis and static stress strain and displacement simulations were carried out using ANSYS. Parameters are varied in wide range in order to obtain thickness of vacuum chamber for least stress development keeping the height and diameter of vacuum chamber fixed. The preliminary results obtained are shown graphically in the present
work. The computational simulation of the vibration behavior at the design stage is also done using modal analysis in ANSYS. The first optimal results are obtained by heuristic variation of parameters over a wide range, which can be further worked for detailed designing. The results are obtained by keeping height of electrode holes fixed. Further work can be done altering height and other dimensions along with various parameters. The model can further be improved using different materials, detailing and refining the features like threads, fillets, rounding corners, before arriving at the optimal values.

REFERENCES