ROLE OF DISPERSION AND FUNCTIONALIZATION ON MECHANICAL PROPERTIES IN CARBON NANOTUBE - POLYMER COMPOSITE

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Mechanical Engineering

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2017
ABSTRACT

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Polymer composites with carbon nanotubes (CNT) as filler material is an exciting research area, having a huge potential of offering superior mechanical properties. One of the main challenges of using CNT as a filler material is the control of the dispersion of CNTs within the matrix material, as this dispersion determines the strength of the composite. Some of the methods being researched for enhancing dispersion are chemical, mechanical and surfactants. Many studies have suggested ultrasonication as the preferred way for better dispersion, but challenges exist with finding the proper solvent which can be used for ultrasonication and at the same time doesn’t react with the base polymer. Furthermore, the solvent selection is limited by viscosity, evaporation rate and stability after ultrasonication. Functionalization of CNT may also affect the mechanical properties of the composite as it is supposed to help in distribution of CNTs in polymer matrix. For this study multiwalled carbon nanotubes (MWCNT) with different functionalizations (COOH & OH) and polydimethylsiloxane is selected as CNT polymer composite.

The objective of this study is to determine an effective solvent for ultrasonication and investigate the role of dispersion on the mechanical properties of the CNT polymer composite.
Additionally the secondary objective of this study is to examine how the functionalization helps in enhancing the mechanical properties of CNT polymer composite.
PUBLIC ABSTRACT

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Medisetti Sai Praveen Kumar

Polymer composites with carbon nanotubes (CNT) as filler material is an exciting research area, having a huge potential of offering better mechanical properties. One of the main challenges of using CNT as a filler material is mixing of CNTs within the matrix material, as this mixing determines the strength of the composite. Some of the methods being researched for improving mixing are chemical, mechanical and surfactants. Many studies have suggested high frequency mechanical stirring as the preferred way for better mixing, but challenges exist with finding the proper solvent which can be used for stirring and at the same time doesn’t react with the base polymer. Furthermore, the solvent selection is limited by viscosity, evaporation rate and stability after stirring. Functionalization of CNT may also affect the mechanical properties of the composite as functionalization is supposed to help in distribution of CNTs in polymer matrix. For this study multiwalled carbon nanotubes (MWCNT) with different functionalizations (COOH & OH) and polydimethylsiloxane is selected as CNT polymer composite.

The objective of this study is to determine an effective solvent for stirring and investigate the role of dispersion on the mechanical properties of the CNT polymer composite. Additionally the secondary objective of this study is to examine how the functionalization helps in enhancing the mechanical properties of CNT polymer composite.
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Dr. Nicholas A. Roberts for providing the opportunity to work with him. His guidance, patience and support was invaluable to complete this research. I would like to convey my special thanks to Dr. Thomas H. Fronk for supporting me during my coursework and research.

Special thanks to Christine Spall for her invaluable guidance in helping me complete my masters. I would like to thank Dr. Ling Liu for willingness to serve on my committee. I would also like to thank the entire Mechanical and Aerospace Engineering Department for providing this opportunity.

I would like to thank my family for supporting me through my schooling career. Special thanks to Swathi Ramanathan for being an inspiration to do masters. I would also like to thank my friends Sudesh Mukhami, Silpika Borra and Nilesh Gudape for giving the right advise and continuous support during tough times. I would also like to thank Abhishek Manjunath for his help during this research.

Medisetti Sai Praveen Kumar
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<td>Carbon Nanotube</td>
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<tr>
<td>DMF</td>
<td>Dimethylformamide</td>
</tr>
<tr>
<td>IPA</td>
<td>Isopropyl alcohol</td>
</tr>
<tr>
<td>MWCNT</td>
<td>Multi Walled Carbon Nanotube</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
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<td>SWCNT</td>
<td>Single Walled Carbon Nanotube</td>
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<td>TIM</td>
<td>Thermal Interface Materials</td>
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CHAPTER 1
INTRODUCTION

1.1 Motivation

Polymers have a wide range of applications in the commercial industry due to properties like flexibility, cost and processability. Polymers can be used as thermal interface materials (TIM) by using polymer carbon nanotube (CNT) composite, and nanofabrication in soft lithography [2]. For the above mentioned applications even though the mechanical properties are not of primary importance, wider usage is limited by the low strength of the polymers [3]. Despite flexibility being a critical criteria for the usage of polymers, higher flexibility can be detrimental to certain applications. There has to be a balance between the flexibility and other desired properties like thermal, mechanical and processability.

For TIM, flexibility is one of the important requirements but low modulus leads to lesser stress transfer rates and raises the issue of long term reliability. Therefore, an optimum level of strength is required for an ideal TIM. In the recent years, there has been a substantial increase in the cooling requirement for processor units in the micro-electronic industry. A lot of research has been done to efficiently transfer heat generated by processing chips while often sidelining mechanical properties. Currently, there is a need for TIM which has good mechanical properties along with thermal properties.

In soft lithography, polymer stamps having features to transfer the pattern are nanofabricated using conventional methods like molding with the help of polydimethylsiloxane (PDMS) [4]. Nanofabrication enables a generation of reproducible patterns with size larger than 500nm [3]. This commercial application of nanofabrication is widely used in semiconductor industry and recently there has been demand for sizes below 100nm in pattern making [4] [3]. The application of a polymer for sizes below 100nm is limited partially by the low elastic modulus of polymers as the low strength inhibits better release of the
element from the stamps [3]. This inherent limitation raises the need for better mechanical characteristics for nanoscale fabrication without deforming [3].

For the purpose of finding a balance between flexibility and strength, a composite is needed where in the flexibility of the polymer can be utilized with the strength of a filler material. Since the discovery of carbon nanotubes by Iijima in 1991 [5], vast amount of research has been done to utilize their superior mechanical and thermal properties. Along with their superior mechanical properties, CNT are known for their ease of fabrication. With the processability and flexibility of polymer and mechanical strength of CNT, CNT polymer composite is an ideal composite to study.

The advantages of the filler material property can be best utilized when there is good dispersion and homogenization of filler material in the composite. Good dispersion leads to a better interface between the polymer and CNT and a better interface leads to better strength [6]. Furthermore functionalization is also expected to be important at the polymer CNT interface [7]. The objective of this research is to investigate the role of dispersion and functionalization on CNT polymer composites in enhancing the mechanical properties.

1.2 Literature Review

PDMS is one of the most commonly used elastomeric polymer for applications like soft lithography. The process of fabricating PDMS polymer is mixing the base and crosslinker and then curing at a set temperature [8]. The base-crosslinker ratio and curing temperature determines the strength of the polymer. It was found that elastic modulus of the PDMS is maximum at the ratio of 9:1 and thereafter the modulus decreases as the mixing ratio increases [1]. As represented in Table 1.1 it has been determined that modulus increases with the increase in the curing temperature [1].

Since the discovery of carbon nanotubes by Iijima [5], carbon nanotubes with their superior properties have been huge interest in the research as a filler material for composites. Composites with CNT as the filler material have shown increase in mechanical and thermal properties [9]. Carbon nanotubes are categorized into two types, single walled carbon nanotubes (SWCNT) and multiwalled carbon nanotubes (MWCNT) [10]. SWCNT is a
sheet of graphene rolled to form a cylindrical shape as shown in Figure 1.2, MWCNT consist of two or more concentric cylinders [10] as shown in Figure 1.3.

Due to agglomeration, the application of CNT as a filler material in composites is a technical challenge [6]. Various studies have been done for dispersing the CNT in the polymer and keeping it stable. The two most widely used approaches for CNT dispersion are mechanical and chemical. The mechanical approach includes using the method of ultrasonication with high shear mixing to disperse CNT in low viscous solvent [11] [12]. The chemical approach includes functionalizing carbon nanotubes with carboxyl (COOH) and hydroxyl (OH) groups [6]. Through functionalization, limitation of interfacial interaction between CNTs and polymer due to low Van der Waals forces can be overcome by surface modification. In chemical functionalization the covalent bonds of the functional groups like

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**Fig. 1.1: Stress vs Strain plot at different curing temperature [1]**

**Table 1.1: Curing Temperature vs. Young’s Modulus [1]**

<table>
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<th>Temperature (°C)</th>
<th>Young’s Modulus</th>
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<tr>
<td>25</td>
<td>1.32 ± 0.07</td>
</tr>
<tr>
<td>100</td>
<td>2.05 ± 0.12</td>
</tr>
<tr>
<td>125</td>
<td>2.46 ± 0.16</td>
</tr>
<tr>
<td>150</td>
<td>2.59 ± 0.08</td>
</tr>
<tr>
<td>200</td>
<td>2.97 ± 0.04</td>
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COOH and OH are formed at the places of defects, open ends and end caps [13] [7].

A composite material can be defined as a combination of two or more materials that results in better properties based on the application. [14]. Composite basically constitutes two materials, one is matrix material other is a reinforcement. Role of matrix material is to maintain orientation of reinforcement, transfer loads and protect the reinforcement from abrasion. Reinforcement is usually a fiber or a particulate which provides strength and critical properties to the composite [14]. The type and quantity of the reinforcement determines the final properties of the composite. In comparison with alloys, composites retain their separate thermal and mechanical properties. Composites have repeatedly proved to be a better alternative to the conventional materials where in the properties of both the matrix and reinforcement material can be effectively used. The strength of the composite depends on various factors like [15],

1. Orientation of the reinforcement in the matrix material
2. Dispersion of the reinforcement

3. Bonding between matrix material and reinforcement material

4. Load transfer ability of the matrix material

5. Length of the fiber (reinforcement)

Composites are classified into two main groups, continuous and discontinuous. The CNT composite comes under discontinuous randomly aligned fiber reinforced composites. CNT are assumed as fibers in the polymer matrix [14]. Theoretically the strength of the composites are calculated by using rule of mixtures and inverse rule of mixtures based on the direction of loading with respect to fiber orientation. If the loading and orientation of fibers are in same direction then the modulus of the composite using rule of mixtures can be defined as Eq. (1.1) [16].

\[ E_c = fE_f + (1 - f)E_m \]  \hspace{1cm} (1.1)

Where, \( E_c \) is elastic modulus of composite, \( f \) is volume fraction of fibers, \( E_f \) is elastic modulus of fiber, \( E_m \) is elastic modulus of matrix.

If the load and orientation of fibers are perpendicular to each other, then the modulus of the composite using inverse rule of mixtures can be defined as Eq. (1.2) [16].

\[ E_c = \left( \frac{f}{E_f} + \frac{1 - f}{E_m} \right)^{-1} \]  \hspace{1cm} (1.2)

Where, \( E_c \) is elastic modulus of composite, \( f \) is volume fraction of fibers, \( E_f \) is elastic modulus of fiber, \( E_m \) is elastic modulus of matrix.

While calculating the Young's modulus of the composite using the rule of mixture we assume [16],

1. Fibers are uniformly distributed throughout the matrix

2. Perfect bonding between fibers and matrix

3. There are no voids in the composite

4. Lamina is in initially stress free state
5. Loads are applied in the direction of the fibers

The fiber length is one of the important parameter for the strength of the composite. The assumption in the principle of composites is that, the fiber carries more load than the matrix. As the fiber carries more load, the longer fibers give better strength. However, it is inconvenient to use continuous fibers due to fabrication like in injection molding [17]. Therefore, a critical fiber length has to determined which can take the load with the minimum possible fiber length. This critical fiber length is determined using the Eq. 1.3 [15].

\[ L_c = \frac{\sigma_f \cdot d}{2 \cdot \tau_c} \]  

Where, \( L_c \) is the critical fiber length, \( \sigma_f \) is the ultimate tensile strength of fiber, \( d \) is the diameter of the fiber and \( \tau_c \) is the shear strength of fiber-matrix composite. In the case of fiber length being less than critical fiber length, the failure of the composite can happen either due to fiber-matrix interfacial bond or due to matrix. Therefore, it is ideal for the composite to have the fiber length more than the critical fiber length.

The critical fiber length of MWCNT used in our research were determined to range from 0.084nm - 0.969nm. For calculation of critical fiber length, ultimate tensile strength of MWCNT was assumed to be in a range of 11Gpa to 63Gpa [18], diameter of the MWCNT ranging between 10nm and 20nm [19] and shear strength of the PDMS as 1.3MPa [20]. This critical fiber length value of 0.084nm to 0.969nm is well below the MWCNT fiber of length 10nm to 30nm [19] which are used in our study indicating a potential failure of the composite due to fiber strength rather than matrix or fiber-matrix bond strength.

1.3 Hypothesis

Better distribution of CNTs in the polymer matrix and the use of functionalized CNTs will reduce the amount of agglomeration and modify the CNT-polymer bond. These effects will in turn lead to enhanced Young’s modulus of the composite.
1.4 Objectives

The objectives of this thesis were,

1. Study and understand the role of CNT in the PDMS.

2. Enhance the dispersion of CNT in the polymer matrix by finding a suitable solvent for ultrasonication

3. Optimize the sample fabrication method for CNT polymer composite to include higher weight percentage of CNT.

4. Investigate the role of CNT in the polymer matrix on the mechanical properties of the CNT polymer composite.

5. Investigate the role of dispersion on the mechanical properties of the CNT polymer composite.

6. Investigate the role of functionalization (COOH and OH) on the mechanical properties of the CNT polymer composite.

1.5 Approach

Based on the objectives mentioned in the previous section, research was done in the following way,

1. The process limitation of CNT polymer composite sample fabrication were studied with respect to the maximum weight percentage of CNT which can used in the polymer and duration of sample fabrication.

2. To enhance dispersion by ultrasonication, the effective use of solvents like DMF, Ethanol, IPA and Methanol were investigated.

3. The sample fabrication method adopted is shown in Figure 1.4. The challenges faced and parameters analyzed for optimizing the method are,
(a) Selection of solvent based on the critical parameters like stability of solvent with polymer, evaporation time, dispersion ability and viscosity.

(b) Optimum time required for sonication.

(c) Minimum amount of solvent to be used for sonication.

(d) Efficient method for evaporating solvent from CNT Polymer solution.

(e) Optimize the method to include higher percentage of CNT (1%).

4. Samples were made as per ASTM D638-02a Type IV standards for tensile testing.

5. Fabrication of dispersed and non-dispersed samples for tensile testing with three different weight percentage of MWCNT.

(a) Fabrication of dispersed and non-dispersed samples for tensile testing with three different weight percentage of COOH and OH and unfunctionalized MWCNT.

(b) Tensile testing of fabricated samples using INSTRON to capture stress, strain data.

(c) Determine Young’s Modulus using stress strain data of the linearly elastic region.

6. Determine storage and lost modulus of dispersed and non-dispersed unfunctionalized MWCNT.

1.6 Thesis Overview

This thesis is organized in four main chapters and conclusion in the following way,

- Chapter 2 discusses about the study and selection of solvent for ultrasonication and the optimized sample fabrication method for CNT-polymer composite.

- Chapter 3 discusses the dispersion characterization and quantifying the enhanced dispersion rate achieved by optimized sample fabrication method.

- Chapter 4 provides the principles of dynamic mechanical analysis and calibration method for DMA 242 machine.
Stage 1: Sonication of CNT in Solvent

Stage 2: Mixing CNT Solvent and Polymer

Stage 3: Evaporating the Solvent

Stage 4: Mixing CNT Polymer solution with cross linker

Stage 5: Degass the solution

Stage 6: Polymerization at set temperature

Fig. 1.4: Sample Fabrication Method

• Chapter 5 lists out the tensile testing results by Instron and DMA. This chapter also provides the methodology involved in the determination of Young’s modulus.

• Chapter 6 concludes this thesis by discussing the results and contribution of our research. This chapter also discusses the future work based on these results.
CHAPTER 2
SAMPLE FABRICATION METHOD

In order to achieve uniformly dispersed CNTs in the PDMS material, a proper fabrication method had to be adopted. The primary challenge for the fabrication of the CNT-PDMS composite is agglomeration of CNTs in the polymer. This agglomeration may lead to reduced mechanical and thermal properties. There are different methods to avoid or reduce agglomeration of CNTs like use of functionalized CNTs and high shear mixing. Functionalized CNTs like COOH and OH have better dispersion properties. Effective dispersion of CNTs requires overcoming van der waals forces between the CNTs. For this, high shear mixing is done using the method of ultrasonication. Ultrasonication is a process of applying sound waves at ultrasonic frequencies to agitate particles. Effectiveness of ultrasonication increases with liquids having low viscosity. The silicone elastomer polymer has a very high viscosity of 5100cP [8], which reduces the effectiveness of sonication. Even though mixing crosslinker with the PDMS polymer reduces the viscosity, the curing process starts as soon as the crosslinker is mixed and the high temperature generated during sonication fastens the process of curing. This method of sonicating the solution of polymer, CNTs and crosslinker proved to be ineffective as the solution was cured even before the completion of sonication. For this purpose a solvent is required for dispersing CNTs and thereafter the solution of solvent of CNTs is mixed with PDMS.

2.1 Solvent for Sonication

Four different solvents for sonication were chosen based on prior research done by Kintak Lau [21] for epoxy based composites. The four selected solvents are DMF, ethanol, methanol and IPA. These solvents were evaluated and the right solvent for sonication was selected based on important parameters like viscosity, stability and evaporation rate.
Table 2.1: Viscosity of Solvents and PDMS

<table>
<thead>
<tr>
<th>Name</th>
<th>Viscosity(cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimethylformamide (DMF)</td>
<td>0.79 [22]</td>
</tr>
<tr>
<td>Ethanol</td>
<td>1.07 [22]</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.54 [22]</td>
</tr>
<tr>
<td>Isopropyl alcohol (IPA)</td>
<td>2.04 [22]</td>
</tr>
<tr>
<td>Polydimethylsiloxane (PDMS)</td>
<td>5100 [8]</td>
</tr>
</tbody>
</table>

2.1.1 Viscosity

Viscosity as a parameter was chosen as it aids in sonication. Solvents with lower viscosity are better for dispersion. As shown in Table 2.1, it can be noted that all the solvents when compared to PDMS have very good viscosity numbers. In Figures 2.1 to 2.6 left bottle for each group of solvents show non-dispersed (hand stirred) and the right one shows dispersed (sonicated). As shown in Figures 2.1 to 2.6 all the solvents dispersed using ultrasonication showed good dispersion even after five hours which is well within the processing time for fabrication of CNT-PDMS polymer composite. For viscosity as a parameter for solvent selection, it was concluded that all the selected solvents are good for sonication.

![Fig. 2.1: Immediately after Sonication (A-DMF, B-Ethanol, C-Methanol, D-IPA)](image)

2.1.2 Evaporate Rate

Evaporation rate is one of the important parameters for solvent selection as it directly
Fig. 2.2: 10 Minutes after Sonication (A-DMF, B-Ethanol, C-Methanol, D-IPA)

Fig. 2.3: 30 Minutes after Sonication (A-DMF, B-Ethanol, C-Methanol, D-IPA)

Fig. 2.4: 1 Hour after Sonication (A-DMF, B-Ethanol, C-Methanol, D-IPA)

Fig. 2.5: 2 Hours after Sonication (A-DMF, B-Ethanol, C-Methanol, D-IPA)

Fig. 2.6: 5 Hours after Sonication (A-DMF, B-Ethanol, C-Methanol, D-IPA)
affects the processing time for sample fabrication. 12ml of each solvent with 0.2% unfunctionalized CNTs for 10 grams of PDMS was taken in small bottle and heated at 135°C on hot pad. All the bottles were observed for 210 minutes on their respective rate of evaporation. As shown in Figures 2.7 - 2.10, DMA and IPA did not show any reduction in volume where as ethanol and methanol exhibited very good results. Table 2.2 shows the time taken by each solvent to evaporate fully at 160°C. On these observations it was concluded that solvents in order of methanol, ethanol, IPA and DMF are best suited for sonication on the parameter of evaporation.

Fig. 2.7: Heating of solvents at 130°C - Initial Position (1-DMF, 2-Ethanol, 3-Methanol, 4-IPA)

2.1.3 Stability

Stability of the solution after mixing PDMS and solvent is a critical parameter for selection of the solvent. 25ml of each solvent was mixed with 10 grams of PDMS to understand how each solution behaves. Furthermore after mixing the solution was heated at 150°C till the solvent evaporates from the solution. DMF-PDMS solution required more time and as shown in Figure 2.11 left some white particles in the solution. Figure 2.12 shows before and after heating images of methanol and IPA solution. IPA-PDMS solution after heating
Fig. 2.8: Heating of solvents at 130°C - After 30 Minutes (1-DMF, 2-Ethanol, 3-Methanol, 4-IPA)

Fig. 2.9: Heating of solvents at 130°C - After 60 Minutes (1-DMF, 2-Ethanol, 3-Methanol, 4-IPA)
Table 2.2: Evaporation Time for Solvents

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Time taken for Evaporation (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimethylformamide (DMF)</td>
<td>18</td>
</tr>
<tr>
<td>Ethanol</td>
<td>5</td>
</tr>
<tr>
<td>Methanol</td>
<td>3</td>
</tr>
<tr>
<td>Isopropyl alcohol (IPA)</td>
<td>9</td>
</tr>
</tbody>
</table>

Fig. 2.10: Heating of solvents at 130°C - After 210 Minutes (1-DMF, 2-Ethanol, 3-Methanol, 4-IPA)

showed different characteristics of viscosity and color. Ethanol and methanol showed good stability after heating and evaporating the solvents.

After evaluating the solvents on three different parameters, ethanol and methanol were selected as the right solvents for sonication. But as the CNT weight percentage was increased to more than 0.3% methanol based solution behaved differently and methanol could not be evaporated even at high temperatures. Therefore, ethanol was selected as the solvent for sonication.

2.2 Process Optimization

After numerous trials and improvements, the scalable process of sample fabrication is adapted which minimized the time and effort. As shown in the flowchart the process in
Fig. 2.11: a) PDMS-DMF and PDMS-Ethanol mixed solution before heating b) PDMS-DMF and PDMS-Ethanol mixed solution after heating

Fig. 2.12: a) PDMS-Methanol and PDMS-IPA mixed solution before heating b) PDMS-Methanol and PDMS-IPA mixed solution after heating
brief involves dispersion using sonication, evaporating the solvent, degassing the solution and polymerization.

2.2.1 Dispersed Sample Fabrication Method

Dispersion

To minimize the evaporation time, a small amount of ethanol was used for sonication. 25ml of solvent for sonication was chosen to aid in dispersion of CNTs at a higher weight percentage of 0.9. The measured amount of CNTs was calculated using Equation 2.1 and mixed with ethanol. As shown in Figure 2.13, Qsonica Q500 sonicator was used for sonication and dispersing CNTs in the solvent. 1/8" micro-tip probe was used for sonication at 35% of 20kHz frequency amplitude. The solution is sonicated for 10 minutes with 10 seconds of pulse on and 30 seconds of pulse off setting.

\[
CNT = \frac{wt\% (PDMS + Crosslinker)}{1 - wt\%}
\]  

(2.1)

Fig. 2.13: Ultrasonication of 0.2 Unfunctionalized CNTs in Ethanol
Evaporation

After sonication, CNTs in the solution start agglomerating and it is ideal to start mixing the polymer in the solution to minimize losing dispersion. After mixing, the CNT-solvent-polymer solution was heated on a hot pad at 120°C for 90 minutes. For the first hour the solution is stirred every 20 minutes to let the ethanol evaporate. Figure 2.14 shows the hot pad used for heating the solution.

![Fig. 2.14: Hotpad for evaporating solvent from the solution](image)

Degas

Once the ethanol has evaporated out of the solution, cross linker is mixed at the ratio of 10:1 and hand stirred for 3 minutes. This ratio of 10:1 is recommended by the manufacturer of PDMS. As shown in Figure 2.15 air bubbles are created during the mixing of the PDMS and cross-linker. To remove the air bubbles, the solution is degassed in a vacuum chamber for 40 minutes.

Curing

As mentioned by DOW CORNING in the data sheet, curing time is dependent on temperature [10]. For this study we considered a curing temperature of 100°C. As discussed by Johnston [10], the amount of time required for the mold to reach the desired temperature
depends upon the oven and the material of the mold. In our case the time taken by the mold to reach the desired temperature was determined as 15 minutes at 100°C and the same was added to 35 minutes of curing time recommended by DOW CORNING.

2.2.2 Non-Dispersed Sample Fabrication Method

To observe the changes in properties of CNT polymer composite due to dispersion, non-dispersed samples were also fabricated. As shown in Figure 2.16, a basic method suggested by the manufacturer was adopted. Furthermore, to keep the method similar and control the input parameters for fabrication of dispersion and non-dispersion samples, dispersing solvent was used for both the methods.

2.3 Tensile Sample Fabrication

ASTM standard of D638 02a Type IV was followed for fabrication of polymer specimens for tensile testing. D638 type IV specimen was chosen with a thickness range of 1 - 1.5mm. As shown in Figure 2.17, mold was fabricated to accommodate 11 samples. A syringe was used to pour the solution on to the mold. It was noted that the pot life of sylgard 184 silicone elastomer is 90 minutes, therefore the degassing and pouring of solution for curing was done within 90 minutes. Figure 2.20 shows the dimensional drawing of dog bone shaped tensile sample.
Stage 1: Mixing CNT Solvent and Polymer

Stage 2: Evaporating the Solvent

Stage 3: Mixing CNT Polymer solution with cross linker

Stage 4: Degas the solution

Stage 5: Polymerization at set temperature

Fig. 2.16: Sample Fabrication Method for Non-Dispersed Samples

During trials of initial fabrication, the tensile samples were tested and found to fail at a particular curve. This failure was due to the spilled over polymer material creating a stress raiser. After cutting off the excess material at the curves using a thin blade, the tensile testing of samples gave a better failure rate of breaking in between the gauge length.

Fig. 2.17: Mold used for Making Tensile Samples
Fig. 2.18: CNT-PDMS solution in the Mold

Fig. 2.19: a) 0.1% CNT (COOH) Dispersed Tensile Sample b) 0.1% CNT (COOH) Nondispersed Tensile Sample

Fig. 2.20: CAD Drawing of ASTM D638 - 02a Type IV Specification Tensile Sample
Table 2.3: ASTM D638 - 02a Type IV specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Length</td>
<td>115</td>
</tr>
<tr>
<td>Total width</td>
<td>19</td>
</tr>
<tr>
<td>Distance between grips</td>
<td>65</td>
</tr>
<tr>
<td>Width of narrow section</td>
<td>6</td>
</tr>
<tr>
<td>Gauge Length</td>
<td>25</td>
</tr>
<tr>
<td>Thickness</td>
<td>1</td>
</tr>
</tbody>
</table>
CHAPTER 3
DISPERSION CHARACTERIZATION

Despite technical challenges, there is good amount of research being done on dispersion of CNTs in various mediums. To evaluate the rate of dispersion in PDMS-CNT composite two methods were used by researchers, namely optical microscopy and electron microscopy. Optical microscopy involves observing the dispersion by taking images using optical microscope and then processing it to analyze the CNT clump size and distance between the clumps. Electron microscopy involves using beam of electrons to create an image of the specimen sample and thereafter processing it. In our research, both the methods were used to analyze the rate of dispersion. But images from the electron microscopy were not used for further processing as PDMS matrix is not electron transparent.

3.0.1 Sample Preparation

Using the same fabrication methods mentioned in previous section the PDMS-CNT solution is prepared and using single wafer spin processor a microfilms are fabricated. A solution is poured on 1” x 1/8” quartz disc and placed on the wafer chuck as shown in Figure 3.1, thereafter the chuck is rotated at 200 rpm for 2 minutes. After spinning the quartz disk is cured inside the oven at 100°C for 35 minutes.

Fig. 3.1: Single Wafer Spin Processor and Microfilm of Unfunctionalized CNT Polymer
3.0.2 Optical Microscopy

Two different samples were observed using an optical microscope. Figure 3.2 and Figure 3.3 show the 10x optical images of 0.1% unfunctionalized CNTs dispersed and non dispersed samples. To further process the image for calculation of agglomerates size and spacing the optical images are converted into grey scale images as shown in Figure 3.4 and Figure 3.5. Thereafter the grey scale images were processed using an image processing code.

3.0.3 Optical Microscopy Results

Figure 3.6 and Figure 3.7 show agglomerate clump size and spacing for dispersed sample and Figure 3.8 and Figure 3.9 show agglomerate clump size and spacing for non-dispersed sample.

3.0.4 Optical Microscopy Results

![Fig. 3.2: 10x Optical image of 0.1% dispersed unfunctionalized CNTs](image)
Fig. 3.3: 10x Optical image of 0.1% non-dispersed unfunctionalized CNTs

Fig. 3.4: 10x Grey scale image of 0.1% dispersed unfunctionalized CNTs
Fig. 3.5: 10x Grey scale image of 0.1% non-dispersed unfunctionalized CNTs

Fig. 3.6: Agglomerate clump size for dispersed sample
Fig. 3.7: Spacing between agglomerate clumps for dispersed sample

Fig. 3.8: Agglomerate clump size for non-dispersed sample
Fig. 3.9: Spacing between agglomerate clumps for non-dispersed sample
4.1 Basic Principles

Dynamic mechanical analysis, in simple words, can be described as analyzing the materials response after application of an oscillating force. DMA is a non-destructive test performed by applying periodical force on the sample specimen. Periodic force is controlled by either force or displacement. Target force or target displacement is given as one of the parameter while setting upon the experiment. If the target force is set as the parameter for experiment, DMA monitors and records the displacement with respect the force applied. Similarly, if target displacement is set as the parameter for experiment, DMA monitors and records the force required and applied for a particular displacement of push rod. Figure 4.1 shows the force plot with dynamic force of 6.5N and static force of 7.15N. Force on the sample is calculated using the Equation 4.1 given by the DMA [23].

\[
F_{Sample} = F_{Static} + F_{Dynamic} + F_{Static.Constant} \tag{4.1}
\]

\[
F_{Static} = PropotionalFactor \times F_{Dynamic} \tag{4.2}
\]

Fig. 4.1: Force Plot from the DMA Netzsch Operating Manual
Non-destructive test by DMA gives storage modulus, loss modulus and complex modulus of the material. Complex modulus $E^*$ is the ratio of the stress amplitude to a strain amplitude and represents the stiffness of the material [23]. Storage modulus according to ISO 6721-1 is proportional to the energy stored. Loss modulus according to ISO 6721-1 is proportional to energy dissipated. Storage modulus also represents stiffness of the material and is similar to Young’s modulus but not exactly same. Young’s modulus is an average of the linear slope between stress and strain curve. The storage modulus is the equal to slope of the hysteresis curve [24].

Storage and loss modulus variables are determined when either force or displacement is applied in a set frequency. In our study, we have determined complex modulus of the CNT-PDMS polymer composite using tensile testing experimental setup. In reference to thermal parameters, there are two types of experimental setups, isothermal and dynamic. In isothermal, the tensile testing is done under constant temperature where as in dynamic mode, the temperature increases at set rate till the target temperature is achieved. To understand the affects of temperature on the storage modulus of CNT polymer composite, the samples were also tensile tested under dynamic temperatures parameters.

4.2 DMA Calibration

Netzsch, the manufacturer of DMA 242, requires five different calibrations over a set frequency [23]. Furthermore, these calibrations are also recommended if the machine is moved. The five calibrations are dynamic mass calibration, empty system calibration, system stiffness calibration, rotational tuning calibration and temperature calibration. Netzsch also recommends to calibrate the machine in the following particular order as represented in Figure 4.2 [23].

4.2.1 Dynamic Mass Calibration

In this dynamic mass calibration, the measuring system is subjected to a known dynamic force at the room temperature. This force is applied with a known mass accurate to thousandth of a gram coupled to the system. Furthermore, measurement is is also done
without any mass coupled to the system at the room temperature. Both the measurement are compared to determine dynamic system constant. This calibration is carried out without placing the sample holder on the measurement system.

### 4.2.2 Empty System Calibration

Empty system calibration is done after dynamic mass calibration with a sample holder on the measurement system. This calibration determines the spring constant at the room temperature starting from the lowest frequency and stepping up to the highest frequency. Sample specimen is not required to be placed on the sample holder while conducting this calibration.

### 4.2.3 System Stiffness Calibration

System stiffness calibration is done after empty system calibration with a sample holder on the measurement system. For each type of material testing, the sample holder differ and before using a particular sample holder this calibration is required. This calibration is done at seven different temperatures and 19 different frequencies recommended by the manufacturer. This calibration tests the internal stiffness of the DMA instrument life and components like push rod, sample holder, measurement system at different temperatures.
and frequencies.

4.2.4 Rotational Tuning Calibration

System stiffness calibration is the pre-requisite and this calibration is recommended for testing very stiff materials like metals and ceramics. This phase angle is determined by assuming that loss factor is low for steel and constant for frequencies, DMA operates.

4.2.5 Temperature Calibration

For the isothermal and dynamic material testing at temperatures other than room temperature, temperature calibration is required. For the accuracy of temperature measurements by thermal components like thermocouple this calibration is needed. This calibration is done with penetration sample holder and three different sample specimens.
5.1 Intron 5542

The tensile properties of PDMS-CNT polymer composites were evaluated using Intron 5562 tensile tester. Intron 5542 is a single column table top 500N capacity model having maximum crosshead travel of 490mm. Table 5.1 shows the technical specifications of Intron 5542. In the tensile testing method of Intron, the experiment is controlled by either load or extension.

For determining the effect of percentage change in CNT weight on the Young’s modulus three data points under 0.9% were randomly selected. Due to the limitation of the sample fabrication process, the percentage weight with respect to the polymer was kept below 0.9%. For COOH and OH functionalized, the data points are 0.3, 0.6 and 0.9% CNT weight. For unfunctionalized CNTs, it was observed that the density was lower, therefore for same percentage of CNT weight, unfunctionalized CNTs were more in number than COOH and OH functionalization. Due to this density difference, the percentage data point for unfunctionalized CNT polymer composite was taken as 0.1, 0.35 and 0.6%. Furthermore, for each functionalization two different data sets of dispersed and non-dispersed were fabricated to observe the effect of dispersion on the Young’s modulus of the CNT polymer composite.

5.1.1 Calibration

If the load cell is changed or disturbed, the Bluehill software which runs the Intron tensile tester prevents testing and directs the operator for calibration. The Figure 5.1, shows the process of load calibration. Once the calibration is performed, the software restores the previous calibration whenever the the system is restarted.
Table 5.1: Instron 5542 technical specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load capacity</td>
<td>500 N</td>
</tr>
<tr>
<td>Crosshead speed accuracy</td>
<td>± 0.1% at steady state and no load measured over 100 mm or 30 seconds, whichever is greater.</td>
</tr>
<tr>
<td>Position accuracy</td>
<td>Under no load conditions, equal or less than ± 0.02 mm or ± 0.05% for displayed reading, whichever is greater.</td>
</tr>
<tr>
<td>Load measurement accuracy</td>
<td>± 0.4% of reading down to 1/100 of load cell capacity.</td>
</tr>
<tr>
<td>Strain measurement accuracy</td>
<td>± 0.5% of reading down to 1/50 of full scale with ASTM E83 class B.</td>
</tr>
<tr>
<td>Total crosshead travel</td>
<td>490 mm</td>
</tr>
</tbody>
</table>

5.1.2 Deliverable’s and Experimental Method

Stress, strain and young’s modulus are some of the mechanical properties the Instron can test for. Tensile samples mentioned in chapter 3 were tested under extension control method. An experimental method was created with the following conditions,

- Extension control rate of 20mm/min.
- Gauge length of 25mm.
- End test by either sample specimen failure or max load exertion of 50N.

Extension and load was obtained from the Instron data to determine stress and strain. Thereafter stress and strain was used to determine the Young’s modulus of the specimen sample.

\[
\sigma = \frac{Force \ (N)}{Area \ (mm^2)} \tag{5.1}
\]

\[
\sigma = \text{Stress}
\]

\[
Area = \text{Thickness} \times \text{Width}
\]
Instron 5542 Calibration

Transducer Setup

Calibration

Remove load from load cell

Fig. 5.1: Instron Calibration Sequence

\[ \epsilon = \frac{\Delta L}{L} \text{ (mm)} \]  

(5.2)

\[ \epsilon = \text{Strain} \]

\[ \Delta = \text{Extension} \]

\[ L = \text{Gauge Length} \]

\[ \sigma_{Avg} = \frac{\sigma \text{ (At each data point)}}{\text{Count of data points}} \]  

(5.3)

\[ \epsilon_{Avg} = \frac{\Delta L \text{ (At each data point)}}{\text{Count of data points}} \]  

(5.4)

\[ E_{Avg} = \frac{\sigma_{Avg}}{\epsilon_{Avg}} \]  

(5.5)

\[ E_{Avg} = \text{Average Young’s Modulus} \]

5.1.3 Determining Data Range for Average Young’s Modulus

Average Young’s modulus has to be determined to evaluate the right tensile properties of PDMS-CNT polymer composite. The average Young’s modulus of 0.3% COOH func-
tionalized dispersed sample specimen shown in Figure 5.2 was determined to be 1.03MPa. The total number of data points used for calculation of Young’s modulus were 2389. But as Young’s modulus is defined as the ratio of stress to strain in which Hooke’s law holds i.e., in the linear region of the stress strain curve on the axis. Equation 5.5 holds good for the part of the curve where the stress and strain curve is linear. Therefore there was a need to determine the data point range for linear region of the curve.

Figure 5.2 shows stress strain plot of 0.3% COOH functionalized dispersed sample.

For 0.3% COOH functionalized dispersed sample data set, Young’s modulus for different set of data points range was calculated as shown in Table 5.2. As shown in Table 5.2, the data set range till 900 has a relatively similar or small change in Young’s modulus. Therefore for this particular data set 900 was chosen the right data range to determine young’s modulus. Using this method, data point range for each data set was determined and thereafter Young’s modulus was calculated. Figure 5.3 shows the linear curve of 0.3% COOH functionalized dispersed sample with a Young’s modulus as 0.73MPa.
Table 5.2: 0.3% COOH Functionalized Dispersed Sample Data Range Set

<table>
<thead>
<tr>
<th>Data Point Range</th>
<th>Tensile Strain</th>
<th>Young’s Modulus</th>
<th>Standard Deviation</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2300</td>
<td>3.10</td>
<td>1.03</td>
<td>0.34</td>
<td>32.94</td>
</tr>
<tr>
<td>1-1900</td>
<td>2.57</td>
<td>0.91</td>
<td>0.23</td>
<td>25.22</td>
</tr>
<tr>
<td>1-1500</td>
<td>2.03</td>
<td>0.81</td>
<td>0.12</td>
<td>14.49</td>
</tr>
<tr>
<td>1-1100</td>
<td>1.50</td>
<td>0.74</td>
<td>0.04</td>
<td>5.92</td>
</tr>
<tr>
<td>1-900</td>
<td>1.23</td>
<td>0.73</td>
<td>0.04</td>
<td>5.57</td>
</tr>
<tr>
<td>1-700</td>
<td>0.97</td>
<td>0.73</td>
<td>0.04</td>
<td>5.13</td>
</tr>
<tr>
<td>1-500</td>
<td>0.70</td>
<td>0.73</td>
<td>0.04</td>
<td>5.62</td>
</tr>
<tr>
<td>1-300</td>
<td>0.43</td>
<td>0.76</td>
<td>0.04</td>
<td>5.09</td>
</tr>
<tr>
<td>1-200</td>
<td>0.30</td>
<td>0.78</td>
<td>0.03</td>
<td>4.03</td>
</tr>
<tr>
<td>1-100</td>
<td>1.17</td>
<td>0.81</td>
<td>0.02</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Fig. 5.3: Stress Strain Linear Curve of 0.3% COOH Functionalized Dispersed Sample
5.1.4 Tensile Testing Results from Instron

Plain PDMS samples with ethanol were tested to understand the effect of ethanol on the tensile properties of PDMS. It was determined that there is decrease of 4.5% (see Figure 5.24) in the average Young’s modulus when ethanol as a solvent was used in the PDMS.

**COOH CNT**

As Figure 5.25 shows, dispersion method of fabricating samples increased the average Young’s modulus by 7.7% for 0.3% CNT weight, 9.65% for 0.6% CNT weight and 9.04% for 0.9% CNT weight. But the percentage increase in CNT weight dint show any significant increase in Young’s modulus.

**OH CNT**

As Figure 5.26 shows, dispersion method of fabricating samples increased the average Young’s modulus by 6.8% for 0.3% CNT weight, 5.9% for 0.6% CNT weight and 6.3% for 0.9% CNT weight. There is a significant increase of 14.1% from 0.3% CNT weight to 0.9% for dispersed sample.

**Unfunctionalized CNT**

As Figure 5.27 shows, dispersion method of fabricating samples increased the average Young’s modulus by 5.0% for 0.1% CNT weight, 8.2% for 0.35% CNT weight and 45.9% for 0.6% CNT weight. There is a significant increase of 80.2% from 0.1% CNT weight to 0.6% CNT weight for dispersed sample.
Fig. 5.4: Average Young’s Modulus of Plain PDMS CNT Polymer Composite using Instron

Fig. 5.5: Average Young’s Modulus of Ethanol based PDMS CNT Polymer Composite using Instron
Fig. 5.6: Average Young’s Modulus of 0.3% COOH Functionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.7: Average Young’s Modulus of 0.3% COOH Functionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.8: Average Young’s Modulus of 0.6% COOH Functionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.9: Average Young’s Modulus of 0.6% COOH Functionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.10: Average Young’s Modulus of 0.9% COOH Functionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.11: Average Young’s Modulus of 0.9% COOH Functionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.12: Average Young’s Modulus of 0.3% OH Functionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.13: Average Young’s Modulus of 0.3% OH Functionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.14: Average Young’s Modulus of 0.6% OH Functionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.15: Average Young’s Modulus of 0.6% OH Functionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.16: Average Young’s Modulus of 0.9% OH Functionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.17: Average Young’s Modulus of 0.9% OH Functionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.18: Average Young’s Modulus of 0.1% Unfunctionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.19: Average Young’s Modulus of 0.1% Unfunctionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.20: Average Young's Modulus of 0.35% Unfunctionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.21: Average Young's Modulus of 0.35% Unfunctionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.22: Average Young's Modulus of 0.6% Unfunctionalized Dispersed CNT Polymer Composite using Instron

Fig. 5.23: Average Young's Modulus of 0.6% Unfunctionalized Non-Dispersed CNT Polymer Composite using Instron
Fig. 5.24: Average Young’s Modulus Summary Ethanol based PDMS and Plain PDMS using Instron

Fig. 5.25: Average Young’s Modulus Summary of COOH Functionalized CNT Polymer Composite using Instron
Fig. 5.26: Average Young’s Modulus Summary of OH Functionalized CNT Polymer Composite using Instron

Fig. 5.27: Average Young’s Modulus Summary of Unfunctionalized CNT Polymer Composite using Instron
5.2 Dynamic Mechanical Analysis

After tensile testing the fabricated samples on Instron, the same samples were used to cut into specified specimen size as shown in figure. The samples were tested under parameters shown in Table 5.3. The force plot for this experimental setup in shown in Figure 5.28. DMA was used to analyze the effect of dispersion on the unfunctionalized CNT polymer composite. For this purpose two different percentage data points of 0.1 and 0.6% were selected and tested.

![Force Plot](image)

Fig. 5.28: Force plot at 16hertz with 7.15 N static force and 6.5 N dynamic force

7075 - T6 aluminum samples having a known Young’s modulus of 71.7GPa were tested under the same experimental conditions. Total of 8 samples were tested at 1Hz frequency and storage modulus was observed. As shown in Figure 5.29 the average storage Young’s modulus was determined to be 71.750GPa.

5.2.1 Isothermal Tensile Testing Results from DMA

Figure 5.30 shows the average storage modulus of plain PDMS samples. Figures 5.31 to 5.34 show the average storage modulus of unfunctionalized CNT polymer composites for dispersed and non dispersed. From the summary Figure 5.35 it can be noted that from non-
Fig. 5.29: Average Storage Modulus of 7075 - T6 Aluminum Samples using DMA

Table 5.3: DMA Experiment Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Length</td>
<td>7 mm</td>
</tr>
<tr>
<td>Sample Thickness</td>
<td>1.1 mm</td>
</tr>
<tr>
<td>Sample Width</td>
<td>6 mm</td>
</tr>
<tr>
<td>Static Load</td>
<td>0 N</td>
</tr>
<tr>
<td>Dynamic Load</td>
<td>6.5 N</td>
</tr>
<tr>
<td>Absolute Target Amplitude</td>
<td>30 micrometer</td>
</tr>
<tr>
<td>Proportional Factor</td>
<td>1.1</td>
</tr>
<tr>
<td>Frequency</td>
<td>16.67 Hz</td>
</tr>
<tr>
<td>Temperature</td>
<td>25 (Room Temperature)</td>
</tr>
</tbody>
</table>
dispersed to dispersed samples there is 38% increase in average storage modulus. Similarly there is 14% increase in average storage modulus when amount of CNTs in the composite are increase from 0.1% to 0.6%.

![Average Storage Modulus Summary of PDMS using DMA](image)

**Fig. 5.30: Average Storage Modulus Summary of PDMS using DMA**

### 5.2.2 Dynamic Tensile Testing Results from DMA

Figure 5.36 shows the storage modulus for 0.3% COOH functionalized CNT polymer composite. As can seen in the plot, five different tensile tests were performed sequentially on the same sample with dark green, blue and purple plots being isothermal tensile tests while red and light green plot show the curve for dynamic tensile testing. From the plots it can be determined that the storage modulus of the sample increased on repeated tests. This can be attributed to further curing of the polymer material, but this result needs more study on the effects of frequency, stress and temperature on the mechanical strength of the CNT polymer composite.
Fig. 5.31: Average Storage Modulus Summary of 0.1% Unfunctionalized Non-Dispersed CNT Polymer Composite using DMA

Fig. 5.32: Average Storage Modulus Summary of 0.1% Unfunctionalized Dispersed CNT Polymer Composite using DMA
Fig. 5.33: Average Storage Modulus Summary of 0.6% Unfunctionalized Non-Dispersed CNT Polymer Composite using DMA

Fig. 5.34: Average Storage Modulus Summary of 0.6% Unfunctionalized Dispersed CNT Polymer Composite using DMA
Fig. 5.35: Average Storage Modulus Summary of Unfunctionalized CNT Polymer Composite using DMA

Fig. 5.36: Storage Modulus Summary of COOH functionalized CNT Polymer Composite - Dynamic Tensile Testing
6.0.1 Conclusion

The results of the dispersion characterization clearly show marked improvements in rate of dispersion due to ultrasonication. Figure 3.6 and Figure 3.8 show reduction in agglomerate size from non-dispersed to dispersed samples. Similarly Figure 3.7 and Figure 3.9 show huge reduction in spacing between agglomerate clumps.

Figure 5.24 show reduction in Young’s modulus due to presence of ethanol in the PDMS matrix, but this reduction as seen it not significant. It was apparent from the tensile results of Instron that the method of ultrasonication enhanced Young’s modulus of COOH, OH and unfunctionalized CNT polymer composite samples. The enhancement of mechanical property varied with all three functionalization indicating each functionalization behaved differently in bonding with the PDMS polymer. OH functionalization gave higher Young’s modulus on comparison with COOH indicating better bonding characteristics. Furthermore, the results indicated unfunctionalized CNT polymer composite exhibited much higher Young’s modulus for 0.6%. This increase can be attributed to difference in density of CNT for three functionalizations therefore unfunctionalized CNTs with lower density had more number of CNTs at the same percentage weight on comparison with COOH and OH. Tensile testing results from DMA also indicated enhancement of storage modulus in dispersed samples.

These results support our hypothesis that better distribution of CNTs in the polymer matrix will reduce the amount of agglomeration and enhance Young’s modulus of CNT polymer composite. Furthermore, the results also support another hypothesis that functionalization of CNT causes better bonding.
Dynamic tensile testing of CNT polymer composite gave results which need to further studied. Even though isothermal tests showed enhancement of Young’s modulus by ultrasonication and functionality, the dynamic results gave a different results. On repeated testing the storage modulus increased significantly. This significant increase in the storage modulus needs to further studied to understand the effects of frequency, strain and temperature on polymer curing and mechanical properties of CNT polymer composite.

The fabrication method adopted in this research is limited to 0.9% of CNT by weight. More work needs to done in improving the method to use higher percentage of CNTs and the same time achieving better dispersion. This improvement has the potential of further enhancing the Young’s Modulus of the CNT polymer composite. Furthermore, better functionalized CNTs need to studied as the percentage increase in the Young’s modulus was not significant as compared to the Young’s modulus of CNTs.
REFERENCES


