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Stretchlon Film Enhanced Fabrication of Nanocomposites with the Resin Infusion Between Double Flexible Tooling

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STRETCHLON FILM ENHANCED FABRIACTION OF NANOCOMPOSITES WITH THE RESIN INFUSION BETWEEN DOUBLE FLEXIBLE TOOLING

By

DIVYESH BHAKTA

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ABSTRACT

Recent studies have shown that the incorporation of carbon nanotubes (CNT) into carbon fiber composite parts significantly increase mechanical as well as thermal properties. Polymer nanocomposites are polymer matrix composites that consist of reinforcements that have at least one dimension in the nanometer range. The polymer nanocomposite fabricated parts achieve greater mechanical, thermal, electrical and other properties with a low CNT reinforcement volume fraction. Nanocomposites achieve improved properties because of the higher properties of the nano-reinforcement and provides greater interfacial interaction with the matrix.

The fabrication of nanocomposites is primarily by the liquid composite molding (LCM) processes that can be complex process with many challenges. These challenges include poor CNT dispersion, poor bonding between resin and CNT, and blocking or filtration during the infusion process. The Resin Infusion between Double Flexible Tooling (RIDFT) however offers some advantages over other LCM processes. The preservation and extended use of the mold can result in higher productivity and profit. In addition, a significantly lower pressure that translates to lower equipment cost, will be required to drive the high viscosity CNT-rich resin through the two-dimensional flow in a RIDFT process compared to the three-dimensional flow in the RTM. The RIDFT process may also be used for out-of-autoclave fabrication of composites from pre-pregs.

The RIDFT process however has a number of fabrication issues militating against its wide use. These include long production cycle time due to the bottle neck associated with the setup time for cleaning the silicone membrane and the high cost of replacement of the flexible silicone membranes of the RIDFT machine. The introduction of Stretchlon Bagging 800 film may reduce the time that is expended on cleaning the silicone membranes and at the same time reduce the damage that is made to the silicone membranes. The goal of this thesis is to evaluate the performance of the Stretchlon bagging technique with the RIDFT process with the aim of significantly reducing the production cycle time as well as the production cost of composites and nanocomposites without adversely affecting the mechanical properties of the fabricated parts.

The results show that the use of the Stretchlon bagging film resulted in reduction in the production cycle time of GFRP and CNT-GFRP parts of 32 % and 42 % respectively. It also resulted in production cost reduction for GFRP and CNT-GFRP parts of 49 % and 72 % respectively. It resulted in increased durability and service life of the silicon mold thereby helping to reduce the production cost. In addition, the use of the Stretchlon bagging film did not adversely
affect the mechanical properties of the fabricated GFRP and CNT-GFRP parts. It resulted in an increase of 31.94% and 12.62% in the mean UTS of the GFRP and CNT-GFRP respectively. The Stretchlon film however resulted in reduction in the flexural properties of the fabricated GFRP and CNT-GFRP parts by 30.12% and 18.69% respectively.

The use of the Stretchlon bagging film enhanced the in-plane properties of the fabricated parts by helping to increase the fiber volume fraction. The lower resin contents in the parts fabricated with the Stretchlon film may have had an adverse effect in the interlaminar properties resulting in lower flexural strengths. Furthermore, thermal analysis confirmed that there was no change in the glass transition (T_g) temperature of the fabricated parts. Parts fabricated with the Stretchlon bagging film also exhibited better surface finish than those fabricated without using the Stretchlon bagging film.
CHAPTER 1
INTRODUCTION

Composites have superior desirable properties such as high strength, high modulus, and low density [1] that make them particularly attractive for aerospace applications [2, 3]. In addition, they possess outstanding chemical resistance and long-term durability such as corrosion resistance, high thermal conductivity, insulation and fatigue life that engender their wide use in many industrial applications [4, 5].

Recent studies have however shown that the incorporation of carbon nanotubes (CNT) into carbon fiber composite parts significantly increase mechanical as well as thermal properties [6]. Polymer nanocomposites are polymer matrix composites that consist of reinforcements that have at least one dimension in the nanometer range. The polymer nanocomposite fabricated parts achieve greater mechanical, thermal, electrical and other properties with a low CNT reinforcement volume fraction [7]. Nanocomposites achieve improved properties because of the higher properties of the nano-reinforcement and the high ratio of surface area to volume (aspect ratio) that provides greater interfacial interaction with the matrix [7].

The fabrication of nanocomposites is primarily by the liquid composite molding (LCM) processes such as VARTM [8, 9], RTM [10, 11] and RIDFT [12-14] that are used for regular composites fabrication. The use of these LCM processes for nanocomposites fabrication is however a complex process with many challenges. These challenges include [5, 7, 15]: poor CNT dispersion, poor bonding between resin and CNT, and blocking or filtration during the infusion process.

The RIDFT process however offers some advantages over the other LCM processes. While the CNT-rich resin may come in contact with the mold and damage it in the VARTM and RTM processes, the silicone membranes in the RIDFT process prevent this. The preservation and extended use of the mold can result in higher productivity and profit. In addition, a significantly higher pressure that translates to higher equipment cost, will be required to drive the high viscosity CNT-rich resin through the three-dimensional flow in a RTM process compared to the two-dimensional flow in the RIDFT [14].

Another potentially viable application of the RIDFT process is for out-of-autoclave fabrication of composites from pre-pregs. Traditionally, high quality composites for critical applications such as that for aerospace are produced from pre-pregs processed in an autoclave. The
fabrication of composites with an autoclave is however a very expensive process. Many applications do not necessarily require the extremely high quality demands of the aerospace applications but can enjoy the superior properties obtainable from using pre-pregs while also benefiting from the low cost associated with an out-of-autoclave process.

1.1 Problem Statement

The RIDFT process however has a number of fabrication issues militating against it wide use. These include long production cycle time due to the bottle neck associated with the setup time for cleaning the silicone membrane. Another issue is the high cost of replacement of the flexible silicone membranes of the RIDFT machine. The introduction of Stretchlon Bagging 800 may reduce the time that is expended on cleaning the silicone membranes and at the same time reduce the damage that is made to the silicone membranes. Stretchlon bagging is a plastic that will expand 450% its size allowing the silicone membrane to stretch with it and still cover most of the area needed to be cleaned after infusion. The goal of this thesis is to evaluate the performance of the Stretchlon bagging technique with the RIDFT process with the aim of significantly reducing the production cycle time as well as the production cost. This thesis seeks to find creative ways to make the RIDFT process a highly competitive nanocomposites fabrication process by overcoming the problems of high production cycle time and high production cost.

In addition, the thesis will investigate the unique properties of the RIDFT in order to redesign to elevate production capacity to a competitive level in nanocomposite fabrication. This new design seeks to innovate with regard to the curing time with the incorporation of lamps to the properties of the composite with an additional pressure.

1.2 Objectives

In order to achieve the above, two main approaches will be employed. Firstly, an inexpensive sacrificial material (Stretchlon 800) will be used in the RIDFT process during nanocomposites fabrication to protect the expensive silicon membranes. Secondly, an infra-red heating system will be used in the original RIDFT process and an additional pressure to produce a better finish and property for the composite.

i. To reduce the fabrication cycle time for the RIDFT process by investigating the use of the Stretchlon 800 bagging film. Eliminating the cleaning of the silicone membrane may reduce the production cycle time to about half.
ii. Characterize and compare the properties (mechanical tests and morphological characterization) of parts made using the conventional RIDFT process and parts made with the new Stretchlon 800 bagging film. It is important to assess and ensure that the proposed new process does not adversely affect the properties of the fabricated composite parts.

iii. Assess competitive nanocomposites fabrication platforms for RIDFT process by the redesign of the RIDFT to increase the qualities from nanocomposites produced from present RIDFT.
CHAPTER 2
LITERATURE REVIEW

2.1 Fiber Reinforced Composites

Fiber-reinforced composite materials consist of fibers with high strength and high modulus embedded in or bonded to a matrix between different interface [7]. Reinforced fibers and the polymer matrix work together to produce the unique properties of composites. Some of the fibers being used are fiber glass, carbon fiber and Kevlar. The advantages of using composite materials include high strength and stiffness, non-corrosive, low weight and desirable electrical and thermal properties [7].

2.1.1 Resin

Resin is commonly used to maintain fiber orientation and dissipate loads to the fiber network. They also help to protect the fiber network from damage due to environmental conditions such as humidity and high temperature. Resin is typically used as a matrix due to its versatility, excellent adhesion, high strength, fatigue resistance, chemical resistance, corrosion resistance and electrical resistance [16]. The matrix of the composite could either be a thermoplastic or thermoset polymer. Table 2.1 presents some disadvantages and advantages of given resins. Thermoset resin are crosslinked while thermoplastic are not crosslinked which mainly shows how they differ in their molecular structure [17]. When selecting a matrix, one of the main consideration is selecting due to the desired mechanical properties. Thermoset also known as resin is used as the matrix material on fiber reinforced composites. Thermoset polymers are known for their thermal stability and chemical resistance. High tensile modulus, high tensile strength, high thermal stability, chemical resistant, less creep and stress relaxation, and high fracture toughness may be achieved with thermoset resins. [7]. The most common known thermosetting resin is polyester. Polyester is inexpensive and fast processing resin. [18] This resin is commonly used to bond fiberglass fabrics into hard membranes. Vinyl ester resin has the same characteristics as the polyester resin, but vinyl ester have superior corrosion resistance and mechanical properties. [18]. Another common thermoset resin is epoxy. Epoxy resins are thermosetting resins that generate an internal heat in order to cure. Epoxy are generally used on pre-pregs and structural adhesives. Some advantages of epoxy are high strength and modulus, low shrinkage, low level of volatile and some
disadvantages are brittleness properties reduction when moisture is present [18]. Most epoxy require accurate measuring and mixing in order to achieve proper cure.

Differentiating from thermoset resin, thermoplastic resin have high strain to failure and a higher impact strength and fracture resistance that makes the composite have a high damage tolerance characteristic [7]. Thermoplastic materials have and advance processing speed and are capable of been softened repeatedly by increasing their temperature and hardened by decreasing the temperature [18]. Some of the known thermoplastic resin are polyether ether ketone (PEEK), polyphenylene sulfide (PPS), and polyether imide (PEI). Table 2.1 provides the advantages and disadvantages from using thermoplastics and thermoset for production of different composites. This advantages and disadvantages are provided regarding the properties after and before it is handled.

| Table 2.1 Thermoplastics vs thermoset advantages and disadvantages [19, 20] |
|---------------------------------|-------------------------------------------------|-----------------------------------------------------------------|
| **Advantages**                  | **Disadvantages**                               |                                                                  |
| Thermoplastics                  | • Easy to handle                               | • Poor creep resistance                                         |
|                                 | • Shorter fabrication time                      | • Poor thermal stability                                        |
|                                 | • Recyclable                                   | • Poor melt flow characteristics (high viscosity)               |
|                                 | • Easy to repair by welding                    |                                                                  |
|                                 | • Better delamination resistance               |                                                                  |
|                                 | • Postformable                                 |                                                                  |
| Thermosets                      | • Low resistance viscosity                     | • Brittle                                                      |
|                                 | • Good fiber wet-out                            | • Long fabrication time                                        |
|                                 | • Good thermal stability                       | • Non-recyclable                                               |
|                                 | • Chemically resistant                         | • Not postformable                                             |
|                                 | • Creep resistant                              |                                                                  |

Table 2.2 provides typical properties of cast resin at 23 °C comparing the different properties from density, tensile strength and modulus and other factors between the different types of matrix.
### Table 2.2 Typical properties of cast resin (at 23°C) [19]

<table>
<thead>
<tr>
<th></th>
<th>Density (g/cm$^3$)</th>
<th>Tensile strength, MPa (psi)</th>
<th>Tensile modulus, GPa ($10^6$psi)</th>
<th>Cure shrinkage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermoset</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy</td>
<td>1.2–1.3</td>
<td>55–130 (8,000–19,000)</td>
<td>2.75–4.10 (0.4–0.595)</td>
<td>1–5</td>
</tr>
<tr>
<td>Polyester</td>
<td>1.1–1.43</td>
<td>34.5–103.5 (5,000–15,000)</td>
<td>2.1–3.45 (0.3–0.5)</td>
<td>5–12</td>
</tr>
<tr>
<td>Vinyl Ester</td>
<td>1.12–1.32</td>
<td>73–81 (10,500–11,750)</td>
<td>3–3.5 (0.44–0.51)</td>
<td>5.4–10.3</td>
</tr>
<tr>
<td><strong>Thermoplastic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyether Ether Ketone (PEEK)</td>
<td>1.30–1.32</td>
<td>Yield (14.5)</td>
<td>3.24 (0.47)</td>
<td></td>
</tr>
<tr>
<td>Polyphenylene Sulfide (PPS)</td>
<td>1.36</td>
<td>Strength (12)</td>
<td>3.3 (0.48)</td>
<td></td>
</tr>
<tr>
<td>Polyether Imide (PEI)</td>
<td>1.27</td>
<td>Yield (15.2)</td>
<td>3 (0.43)</td>
<td></td>
</tr>
</tbody>
</table>

**2.1.2 Fibers**

Fibers are threads woven into textile and used to fabricate fiber-reinforced composites. Fibers constitute the largest volume fraction of the composite laminate. There are different kinds of fibers available and each with its unique properties. Most of the fibers differ either by their tensile strength and modulus, compressive strength and modulus, fatigue strength, electrical and
thermal conductivity among other characteristics that are influenced by the type of fibers and their orientation [3, 7]. Fibers are composed of small diameter filaments. Due to the diameter sizing, these small diameter filaments are commonly bundled together. The bundle is formed by the collection of continuous filaments either twisted (called yarn) or untwisted (called strand for glass and Kevlar - yarn for carbon) [3, 7]. Table 2.3 provides information on the properties of some of the commercially available fibers. Fiberglass is considered to be one of the most common reinforcing fiber in composites. There are two different types of fiberglass. E-glass, also known as electrical glass, has a high resistance to current flow.

Table 2.3 Properties of some commercial reinforcing fibers [7]

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Typical Diameter (µm)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Density (g/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Tensile Modulus GPa</th>
<th>Tensile Strength GPa</th>
<th>Strain-to-Failure (%)</th>
<th>Coefficient of Thermal Expansion (10&lt;sup&gt;-6&lt;/sup&gt;/°C)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass</td>
<td>10 (round)</td>
<td>2.54</td>
<td>72.4</td>
<td>3.45</td>
<td>4.8</td>
<td>5</td>
</tr>
<tr>
<td>S-Glass</td>
<td>10 (round)</td>
<td>2.49</td>
<td>86.9</td>
<td>4.30</td>
<td>5.0</td>
<td>2.9</td>
</tr>
<tr>
<td>PAN</td>
<td>7 (round)</td>
<td>1.76</td>
<td>231</td>
<td>3.65</td>
<td>1.4</td>
<td>-0.6 (longitudinal)</td>
</tr>
<tr>
<td>Carbon T-300&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10 (round)</td>
<td>2.0</td>
<td>380</td>
<td>1.90</td>
<td>0.5</td>
<td>-1.3 (longitudinal)</td>
</tr>
<tr>
<td>Pitch</td>
<td>10 (round)</td>
<td>2.15</td>
<td>758</td>
<td>2.41</td>
<td>0.32</td>
<td>-1.45 (longitudinal)</td>
</tr>
<tr>
<td>Carbon P-55&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10 (round)</td>
<td>1.45</td>
<td>1.31</td>
<td>3.62</td>
<td>2.8</td>
<td>-2 (longitudinal)</td>
</tr>
<tr>
<td>Pitch</td>
<td>11.9 (round)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>59 (radial)</td>
</tr>
<tr>
<td>Carbon P-100&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aramid</td>
<td>1.45 (round)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> µm = 0.0000393 in., b m/m per °C = 0.556 in./in. per °F., c Amoco., d DuPont.
S-Glass is produced from magnesia-alumina-silicate. Fiberglass are low cost, are galvanic corrosion resistant and do not conduct electricity [18]. Aramid Kevlar is another type of fiber. Aramid have a high strength, high modulus, high toughness and high thermal stability [21]. There are two types of aramid utilized in aviation industry. Kevlar 49 with a high stiffness and Kevlar 29 with a low stiffness [18].

2.1.3 Pre-Preg

Pre-preg involves a reinforced material which is pre-impregnated with a resin matrix that is controlled to a precise fiber-resin volume ratio. The resin is partially cured, also known as B-staged. Fabric and unidirectional are two reinforcement types commonly used in a pre-preg. There are two main processes for producing pre-pregs namely hot melt and solvent dip. Hot melt produces unidirectional and fabric pre-pregs in two different stages. In the first stage, the heated resin is layered onto a paper substrate into a thin film. This resin film and the reinforcement are combined with the pre-preg machine. Using the heat and pressure induced from the nip rollers, the impregnation of the resin into the fiber is completed. In the solvent dip process, the reinforcing fabric is dipped into the resin that is dissolved in a bath of solvent.

Pre-pregs require elevated temperature (heat) and pressure for curing. Usual curing temperatures for pre-pregs range from 60 °C to 180 °C. The most commonly used curing temperature is 100 °C in the out-of-autoclave process [22]. This high temperature results in the curing of the impregnated resin to convert the pre-preg into a solid material with desirable properties such as high durability, lightweight and high temperature resistant.

There are two different types of resin utilized on pre-pregs: thermoset and thermoplastic. Thermoset pre-preg is composed of a thermosetting resin which initially impregnates the fiber reinforcements and any excess resin is removed. The resin and fibers will go through a partial curing stage, known as B-Stage. B-Stage is composed of a resin which is partially cured and tacky that requires cold temperature storage in order to prevent full curing. This resin when heated returns to a liquid state just before it completely hardens or cures. Thermoset pre-preg, when cured, cannot be remolded or reshaped. Thermoplastic pre-pregs are often unreinforced. Thermoplastic pre-pregs resins are stable at room temperature meaning they are in a solid state at room temperature. Heating thermoplastic pre-pregs will allow the pre-pregs to be reformed and reshaped. Table 2.4 represents the advantages and disadvantages of using a pre-preg.
<table>
<thead>
<tr>
<th>Advantages of Pre-preg</th>
<th>Disadvantages of Pre-preg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled resin content</td>
<td>Resin ratio to fiber is controlled on pre-pregs. Pre-preg contain from 30-35% resin weight</td>
</tr>
<tr>
<td>Part uniformity</td>
<td>Elimination of resin rich areas and bubble formation as well as increased probability of uniformity (thickness, weight, finish, etc)</td>
</tr>
<tr>
<td>Manufacturing process</td>
<td>Eliminates hand lay out process, could be handled at room temperature, no extra resin or fiber required, no rush required before it cures.</td>
</tr>
<tr>
<td>Reduction of curing time</td>
<td>Curing time is not the usual 24 to 48 hours. After heating, part is completely cured.</td>
</tr>
</tbody>
</table>
2.2 Composites Fabrication Processes

Manufacturing methods for fiber-reinforced composites evolved from the hand layup process. Due to slow rate of production and high labor requirements, other composites manufacturing techniques have been developed. These manufacturing techniques include liquid composites molding (LCM), compression molding, pultrusion and filament winding. Research increased during the mid-70s with respect to not only mass production but also towards process optimization. The increased research interests in LCM is due to its short cycle time, good quality control, low part cost, and the capability to manufacture high performance composites with a complex geometry [8].

<table>
<thead>
<tr>
<th>Process</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Layup</td>
<td>Can produce complex shapes; process is well understood</td>
<td>High human exposure to potentially harmful raw materials, Extremely labor intensive, Not cost effective at high volumes</td>
</tr>
<tr>
<td>RTM</td>
<td>Low void content, Produce complex/highly integrated parts</td>
<td>Labor intensive preform preparation, Tooling cost is typically high, 3D resin flow difficult to control</td>
</tr>
<tr>
<td>RIFT</td>
<td>Uses low cost raw materials, Less labor content, bulk deformation, 2D impregnation easier to control</td>
<td>High manufacturing cycle time, High process complexity, Geometry complexity “Formable” shapes [14], Limitations to achieve desirable fiber volume and associated cost, Requires low viscosity resin</td>
</tr>
<tr>
<td>RIDFT</td>
<td>Uses low cost raw materials, 2D impregnation easier to control, Higher quality, Lower cycle time</td>
<td>Tooling membrane may be easily damaged, Requires low viscosity resin</td>
</tr>
</tbody>
</table>

LCM is a group of composite fabrication processes that involves the infusion of a low viscosity resin in a closed mold that holds dry reinforced fibers. LCM techniques include Vacuum Assisted Resin Transfer Molding (VARTM) [7], Resin Transfer Molding (RTM) [10], and Resin
Infusion between Double Flexible Tooling (RIDFT) [13]. These processes have different advantages and disadvantages as highlighted in Table 2.5. The different LCM methods are hereby described.

2.2.1 Resin Transfer Molding (RTM)

Resin transfer molding (RTM) process involves the placement of dry reinforced fiber composites into a mold which is then closed and the resin is injected into the mold cavity. Once the injection has been completed, the part is allowed to cure. The part is removed from the mold during the demolding stage. RTM process allows the production of high quality (with low void content) parts but with a high tooling cost. RTM process is used for aerospace and automobile applications as well as wind turbine and truck panels [10].

![Figure 2.1 Schematic of RTM process [15]](image)

2.2.2 Vacuum Assisted Resin Transfer Molding (VARTM)

VARTM is one of the most commonly used low pressure closed mold composites manufacturing processes. The success of the VARTM process is due to the controlled emission of Volatile Organic Compounds (VOCs) [8]. The VARTM process is a cost effective process for producing uniform and standard quality composite parts. VARTM process uses a single mold and
vacuum with fibers laid on the mold. Dry fibers are bagged and drawn into a vacuum having an inlet and an outlet. The inlet is the location in which a low viscosity resin is introduced and the outlet is the location where the vacuum is applied.

![Figure 2.2 Schematic of VARTM process [8]](image-url)

In the late 1980’s, Bill Seemann invented a variation of the VARTM process called the Seeman Composites Resin Infusion Molding Process (SCRIMP). The SCRIMP is used in diverse applications ranging from turbine blades, boats and bridge decks fabrication. This process can been used to make both thin and very thick laminates. The SCRIMP includes a highly permeable distribution medium which is merged into the surface layer of the preform [9].

### 2.2.3 Resin Infusion between Double Flexible Tooling (RIDFT)

The RIDFT is a variation of a process known as Resin Infusion under Flexible Tooling (RIFT). The RIDFT is a two stages process developed by Dr. Okenwa Okoli. The RIDFT was developed to address some limitations of other LCM processes such as tool wear, high cycle time, high tooling and equipment costs. The RIDFT is a process that facilitates an even and effortless
resin flow making it a way of producing composites economically and quickly while still taking into consideration environmental concerns and safety [14].

One main advantage of the RIDFT with respect to the RTM is that the flow of resin in the RIDFT is two-dimensional, thereby eliminating the complexity of a three-dimensional flow front. The RIDFT eliminates the contact of the resin with the mold surface which leads to longer mold life (multiple uses). The RIDFT does not give itself to tool wear from continuous use.

There are seven major steps in the RIDFT manufacturing process as outlined below and depicted in Figure 2.3.

**Step 1:** Place the fiber into the machine.

**Step 2:** Secure the fiber properly into the machine. Vacuum/Seal the two silicone membrane frames so that the fiber is secured inside.

**Step 3:** Place Flow Channel and turn Flow Channel’s vacuum.

**Step 4:** Infuse resin into machine until fibers are thoroughly wet using the vacuum process.

**Step 5:** Remove Flow Channel.

**Step 6:** Vacuum the chamber so that the fibers are forming around the male mold piece.

**Step 7:** De-mold the part carefully.

![Figure 2.3 Schematic representation of the RIDFT process](image)

Figure 2.3 Schematic representation of the RIDFT process
Thagard [14] developed an industrial RIDFT machine for producing large-sized parts. He also studied and characterized the drapability of different fibers over various geometries to understand the limitations of the RIDFT process in part forming. The need to expand into large scale production of composites required the study of forming and wrinkling of different fibers. In addition, he used a simulation model to predict the interactions between important production factors such as void content, fiber strain, fiber orientation and wrinkling.

According to Kuppusamy [23], mold design and fabrication are key factors responsible for the high cost and time required for producing composite parts on the RIDFT. He studied different materials and created a seven step process for producing an effective mold at reduced cost and production time. His work resulted in the reduction of the production cycle time from about 32 hours to 24 hours. The development of the framework had facilitated the production of new molds and helped in the study of new parts forming.

Nwabuzor [13] worked on reducing the high production cycle time caused by the use of organic peroxide based catalyst in the RIDFT process. Nwabuzor tackled the problem of high curing time by evaluating the feasibility of Cure on Demand (C.o.D.) using Ultraviolet (UV) light with the RIDFT. The need for reducing the curing time led to the development of a different curing system. The C.o.D. uses photoinitiators that are dissolved in the polymeric resin. These photoinitiators will start a polymerization reaction when exposed to ultraviolet light. Nwabuzor results indicated the successful fabrication of UV cured laminates with consistent mechanical and thermal properties.

Parker [24] studied the possibility of infusing high viscosity resin loaded with carbon nanotubes (CNTs). CNTs tend to increase the viscosity of the resin which results in a difficult infusion process. Parker studied different flow distribution channel designs to overcome the infusion limitations. Not only the different flow distribution have been study but also the optimal CNT concentration that will increase the materials properties and still be able to be infused in the RIDFT. Parker was able to infuse resin with maximum viscosity of 10,000 cPs with higher than the 2 wt% CNT in vinyl ester resin. The flow distribution channel designs facilitated the infusion of the high viscosity resin system. The infusion of 2 wt% CNT-dopped vinyl ester resin with the RIDFT has been proved to increase the properties of the composite.
2.2.4 Autoclave Manufacturing

Autoclave is the leading process for the manufacture of most aerospace composites [25]. Autoclave process achieves a high fiber volume fraction and low porosity levels. The autoclave process presents both controlled temperature and pressure. Another curing environment that presents both temperature and pressure is an oven. An oven is usually used for flat parts. Other curing environments that have less control in curing is using heating lamps. Heat lamps are capable of achieving high temperatures required for curing.

Initially, the pre-preg is removed from the storage freezer, cut into piles and stacked together. After stacking the fibers the bagging process is completed. Figure 2.4 represents a schematic of the bagging process for the autoclave manufacturing.

![Figure 2.4 Bagging setup for autoclave [25]](image)

After the bagging is completed, it is placed in the autoclave for curing. The autoclave offers additional pressure for consolidation and as well as heat. Ramp phases of pressure and heat could be achieved to obtain the optimal quality properties for the composite. During the first ramp, the fibers are consolidated together and resin flow begins with the reduction in the viscosity of the resin. During the second ramp, crosslinking is observed. The resin reaches the gelation point. After this, the pre-pregs could also be taken through a post cure process that will help to increase the degree of cure.
2.2.5 Out of Autoclave

Some limitations associated with the Autoclave process used on pre-pregs for production of composites have led to numerous studies to develop an Out-of-autoclave method. Out-of-Autoclave (OOA) is a solution to solve the key issues that the Autoclave presents. High energy consumption and the associated high cost is a negative with processing pre-preg composites with the Autoclave [26]. The issue is not only the energy consumption, but also the Autoclave process requires constant supervision and a high tooling investment [26]. There are different manufacturing approaches to producing parts with qualities close to that obtainable from parts processed in the Autoclave. They include the LCM processes previously mentioned but they will require either an oven or some type of heating device.

Recently, having to create large composite structure require a high investment. Large-size autoclave is costly. The need to tackle the costly production associated with using Autoclave has increase the search for a way to replace the Autoclave. One of the methods currently being used is the VARTM. The VARTM has been known as one of the out-of-autoclave processes used for numerous aerospace systems and composites [27]. The maximum pressure during the vacuum-bag-only curing in an oven is 1 atm and the pressure might not be enough to eliminate the voids [28]. Due to the pressure issue, OOA pre-pregs interest has been increasing. There are some key factors needed to be taken into consideration when finding a replacement for Autoclave production of composites using pre-pregs. These key factors include achieving desirable fiber content (resin to fiber ratio), minimum number of voids, close mold system, high surface finish, processing temperature of 120 to 230 °C and a high vacuum force.

2.2.6 Quickstep

Quickstep process is a unique technological process in manufacturing polymer composites. Quickstep is used as an out-of-autoclave solution. The quickstep process involves the use of a heat transfer fluid (HTF) such as polyalkylene glycon to heat the laminate. Quickstep reduces labor cost, consumes less energy and requires less processing time [29].

Quickstep is a fluid filled mold developed by an Australian company known as Quickstep. The Quickstep process involves a suspended laminate which is cured in a two part molds composed of elastomer bladders that include HTF to give a rapid and controlled thermal curing [30].

The main component of the Quickstep is the two pressure chamber that includes a silicone membrane that forms on the part and the fluid pressurizing the part and transferring the heat. Figure
2.5 is a schematic of the quickstep process. An older version of the quickstep process consisted of three tanks (high, medium and low temperature) that contain the HTF which were preheated for curing [31].

![Figure 2.5 - Quickstep schematic [32]](image)

Quickstep achieves faster heating and cooling rate which helps in the elimination of voids in the laminate. A faster heating will produce a lower viscosity resin faster thereby facilitating the exit of air or voids from the laminate. Quickstep provides a faster curing cycle than autoclave process because of the more effective heat transfer by the HTF compared to heat transfer by gas in the Autoclave [33].

Some of the advantages of the quickstep process include faster heating ramps, low pressure, higher Tg, low viscosity processing, green process, exotherm control, low cost, low energy consumption, low void content, and capability for processing resin films and pre-pregs [32]. The rapid heating produces a low viscosity resin that facilitates fiber wetting. The low viscosity results in the removal of air in the laminate, resulting in a void level of less than 1% that is equal or better than that required by the aerospace quality standard [34].
2.3 Nanomaterials

2.3.1 Nanoclay

Organic modified silicate nanolayers are referred as nanoclays [5]. Layered silicate clay mineral is the reinforcement used in nanoclay composite. Graphite possess a similar layered structure as nanoclay. There are many techniques used for dispersing layered silicate to make nanoclay-polymer composites. The most common techniques are in situ intercalative polymerization, exfoliation-adsorption, and melt intercalation.

In situ intercalative polymerization can be achieved by the following method: in-solution swelling of the silicate in a liquid monomer. This is initiated through heat/radiation treatment, diffusion of an initiating reagent, or an organic initiator [35-40]. The basis of exfoliation-adsorption is a solvent system where polymer is soluble and the silicate layers are swellable. The layered silicate could be dispersed in a different solvent having in mind that increasing the amount of solvent will be a disadvantage [41]. After dispersion, the polymer is absorbed onto the delaminated membranes. Following solvent evaporation, the similarity of sandwiching could be observed [42]. Melt intercalation process is a unique process that does not require any solvent, and the dispersion process occurs at very high temperature (molten) state. Dispersion can be achieved at an increased temperature state via conventional methods (extrusion, injection molding, etc.) with organophilic clay [39, 43-45].

Alignment of clay particles in the polymer matrix resulted in more remarkable shear thinning [46]. An increase of 35% in the tensile modulus was observed in the nanocomposite when compared to the neat nylon 6. There was also an increase in strength of the nanocomposite due to the complete dispersion (exfoliation) of the clay in the polymer matrix [47]. Figure 2.6 displays the three types of composite for layered silicate materials, during fabrication of layered silicate composites. Three main scenarios can occur: a. Phase separated (when polymer is unable to penetrate the layered silicate), b. Intercalated (when a single polymer chain penetrates the silicate layers, c. Exfoliated (when there is a complete and uniform distribution).
2.3.2 Carbon Nanofiber

Carbon nanofibers are defined as a sp\(^2\) based linear filament with typical diameter around 100 nm and are also characterized by their flexibility and aspect ratio [48]. Carbon nanofibers are produced in two different forms: vapor-grown form or electro-spinning. Vapor-grown carbon nanofibers (VGCNF) frequently have a diameter ranging from 20 to 200 nm and a length from 30 to 100 µm [7]. VGCNF are formed in vapor phase by decomposing carbon containing gases (methane, ethane, carbon monoxide etc.) inside a high temperature reactor. Ultratine particles of catalyst are carried by a flowing gas traveling into the reactor or they could be produced directly in the reactor by decomposition of a catalyst precursor [7]. On the other hand, carbon nanofibers could also be produced with the right combination of electrospinning of organic polymer and thermal treatment in an inert atmosphere. Electro-spinning form is well-thought-out for being one of the most advanced fiber formation technique from polymer solution using electrostatic forces [48]. The structure of a vapor-grown nanofiber TEM is shown in Figure 2.7 in which a hollow core is surrounded by cylindrical fiber grown catalyst particle and comprised of graphite basal planes stacked at 25° from longitudinal axis of the fiber [49].
2.3.3 Carbon Nanotubes

Carbon Nanotubes (CNTs) are graphite membranes that have been rolled into tube-shaped materials with nanometer radius scale. CNTs vary from 1 nm to 50 nm in diameter and are characterized by their structures into single-wall nanotubes (SWNT), multi-wall nanotubes (MWNT), and double-wall nanotubes (DWNT). Since the discovery of carbon nanotube in 1991 by Iijima, its many outstanding properties that include mechanical, electronic and thermal conductivity properties have been highlighted in several studies [5, 6, 50].

Carbon nanotubes have attracted large interest due to their capability for enhanced and desirable properties in different fields. Multiple applications have been anticipated for carbon nanotubes, including conductive and high-strength composites; energy storage and energy conversion devices; sensors; field emission displays and radiation sources; hydrogen storage media and nanometer-sized semiconductor devices; probes and interconnects [5, 51]. Carbon nanotubes structures provide them with extraordinary mechanical, thermal, electrical, and optical properties. From previous research, carbon nanotubes have recorded an elastic modulus greater than 1 TPa, that is about 3-4 times higher than that of carbon fibers. Carbon nanotube are thermally stable up to 2800 °C in vacuum and with thermal conductivity twice that of diamond, and electric conductivity 1000 times higher than copper [7].
There are different methods to measure the elastic properties of individual nanotubes. These include micro-raman spectroscopy, thermal oscillations by TEM, and the application of a force to a nanotube rope suspended across a pit using an atomic force microscope cantilever. Different groups have conducted experiments measuring the properties of a rope and obtained an average value for each tube by the number of nanotubes in a rope. Some of the results showed a tensile modulus of 270 GPa and a tensile strength value of 1 TPa for singlewall CNT and a tensile modulus of 11 GPA and a tensile strength of 200 GPa for multiwall CNT [52].

Figure 2.9 demonstrate the significant difference in tensile strength between different materials which have led to the increased interest in carbon nanotubes. Researchers used the vibration of carbon nanotubes as a function of temperature to calculate a Young’s modulus of 1 TPa [53].

Figure 2.8 Schematic – Comparison of diameter dimensions on log scale for different types of fibrous carbons[48]
Carbon nanotubes are described using three different morphologies: armchair, zigzag, and chiral [5, 54]. The structure of a SWNT is characterized by its chirality or helicity defined by the chiral angle and Chirac vector [7]. Chiral vector (n,m) is defined by the packing of carbon hexagons in the graphitic membranes as expressed below:

$$c_h = na_1 + ma_2$$  \hspace{1cm} (1)$$

Where \(a_1\) and \(a_2\) are the unit vector and \(n\) and \(m\) are chirality numbers.
The integers \( m \) and \( n \) determine the manner in which graphite membrane are rolled to produce a nanotube. Nanotubes with \( n \neq 0 \) and \( m = 0 \) are known as zigzag tubes while \( n = m \neq 0 \) are known as armchair. Some variations in the morphology (chirality) produce changes in the properties of a carbon nanotube making it behave as a metallic or semiconducting material. The electronic properties of armchair nanotube are metallic; electronic properties of zigzag and chiral nanotubes are semiconducting [56]. All armchair and one-third of zig-zag nanotubes are considered to have metallic behavior while the other two-third of zig-zag nanotubes are semiconductors [57].

![Figure 2.11 Different morphology of carbon nanotube. (a) armchair (b) zig-zag (c) chiral][5]

2.3.3.1 Carbon Nanotube Production

There are three methods of production of nanotubes namely: electric arc discharge, laser ablation, and chemical vapor deposition (CVD) [6]. For electric arc discharge and laser ablation, the evaporation of solid carbon is utilized to condense carbon gas. CVD production could be
considered a mass production method to produce large quantities of carbon nanotubes. CVD-produced CNTs’ structure differs from those produced with the other two methods. MWNTs which are produced by CVD are less crystalline, contain more defects, are longer and less straight than those produced by the electric arc discharge process [7].

Figure 2.12 is a representation of an arc discharge chamber. Electric arc discharge is considered to be the first production method for SWCNTs and MWCNTs. This method utilizes a low voltage (12 to 15 V), high-current (50-120 amps) power supply. An arc is produced across 1-mm gap between two graphite electrodes of 5-20 mm diameter. An Inert gas, Helium or Argon, is used as atmosphere for the reaction at a pressure of 100 to 1000 torr [6].

![Figure 2.12 Schematic of an arc discharge chamber [6]](image)

Figure 2.13 is a schematic of a laser ablation furnace. Laser ablation uses a 1.2% cobalt/nickel with 98.8% of graphite composite target placed in 1200 °C quartz tube furnace in an inert atmosphere (0.066661185 Mpa of He or Ar) and then vaporized with a laser pulse [6]. Laser ablation is composed of a pulsed or continuous-wave laser used to vaporize a graphite target under controlled temperature and atmosphere. The yield of SWNTs varies from 20 to 80% by weight [6].

![Figure 2.13 Schematic - laser ablation furnace [6]](image)
Figure 2.14 represents a schematic for the CVD furnace. CVD is a simple method in which carbon nanotubes are produced either by pyrolysis of carbon-containing solids (polymers) at high pressure inside a furnace or either by decomposition of carbon containing gas (carbon monoxide and hydrocarbon gases) [7]. Gaseous carbon feedstock flow over transition metal nanoparticles at a temperature between 500-1200 °C and react with nanoparticles.

![CVD furnace schematic](image)

**Figure 2.14 Schematic – CVD furnace [6]**

2.3.3.2 Carbon Nanotube Characterization

There have been numerous challenges as far as characterization of nanotubes. Some Carbon Nanotubes structured materials have at least one dimension which is less than 100 nanometers, making the sample size one of the challenges for characterization. The alignment and distribution techniques for carbon nanotube have been observed to be among the biggest challenges with carbon nanotube characterization [58]. Some characterization techniques include Scanning Electron Microscopy (SEM), X-ray Scattering (SAXS), and Transmission Electron Microscopy (TEM) [59].

SEM is a type of microscope that provides images created with high-energy beam of electrons. There are two microscopes that stand out. Scanning probe microscopy (SPM) and scanning tunneling microscopy (STM) [59]. SPM uses the interaction between a sharp tip and surface to obtain an image. In STM, sharp conducting tip is held closed to a surface so electron can “tunnel” across the gap and provide the surface’s structural and electronic information at an atomic level [6].
2.4 Nanocomposite Fabrication

Figure 2.15 shows the production of nanocomposites by plastic vacuum bagging infusion. CNTs are dispersed in resin and then infused through the fibers. It is observed during infusion of the CNT resin, the difficulty of the flow through the fibers during the vacuum bagging process. Some significant issues in the processing of CNT polymer composites include uniform dispersion [60-62], wetting and alignment of carbon nanotubes [61, 63] in the polymer matrix and functionalization [58].

![Figure 2.15 Nanocomposite fabrication](image)

In order to study the thermal properties and cure behavior of the nanocomposites, the commonly used techniques include thermogravimetric analysis (TGA), thermomechanical Analysis (TMA) and Dynamic modulus Analysis (DMA).

2.4.1 Functionalization

Due to the initial surface property of CNTs in which the reinforcing CNTs are inert and interact with the surrounding matrix through the van der Waals interaction, chemistry functionalization of CNTs is required [64]. Functionalization of CNT is achieved by submerging CNTs in aqueous solutions that attack the CNT’s surface causing a chemical change in the material [24]. Functionalization is the modification of a material’s surface by either chemical, and or physical means. Functionalizing process of CNTs affects the properties of the material. Depending on the dispersion of the CNTs, the performance of CNT/polymer nanocomposite will vary [64].
Table 2.6 Pros/cons of different CNT functionalization methods [64]

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Possible damage to CNTs</th>
<th>Easy to use</th>
<th>Interaction with polymer matrix</th>
<th>Re-agglomeration of CNTs in matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Method</td>
<td>Side wall Hybridization of C atoms from sp$^2$ to sp$^3$</td>
<td>✓</td>
<td>X</td>
<td>S</td>
<td>✓</td>
</tr>
<tr>
<td>Defect</td>
<td>Defect transformation</td>
<td>✓</td>
<td>✓</td>
<td>S</td>
<td>✓</td>
</tr>
<tr>
<td>Physical Method</td>
<td>Polymer wrapping Van der Waals force, π-π</td>
<td>X</td>
<td>✓</td>
<td>V</td>
<td>X</td>
</tr>
<tr>
<td>Surfactant adsorption</td>
<td>Physical adsorption</td>
<td>X</td>
<td>✓</td>
<td>W</td>
<td>X</td>
</tr>
<tr>
<td>Endohedral method</td>
<td>Capillary effect</td>
<td>X</td>
<td>X</td>
<td>W</td>
<td>✓</td>
</tr>
</tbody>
</table>

2.4.2 Dispersion Techniques

There are two essential requirements for optimal reinforcement in composite systems: filler dispersion and orientation [5]. There have been challenges on the concentration of multiwall carbon nanotubes (MWNTs) and dispersion of single-wall carbon nanotubes (SWNTs) due to the aggregation of the nanotubes due to the Van der Waals interaction between each individual tube [65]. SWNTs agglomerate more easily than MWNTs due to their larger surface area. MWNTs demonstrate lower mechanical, electrical, and thermal properties than SWNT due to the ability of concentric nanotubes. MWNTs tend to have a larger diameter compared to SWNTs.

Good dispersion of the nanotube is required to improve the properties of a composite, as well as the alignment or orientation. Without proper dispersion of the nanomaterial it will be
difficult to develop enhanced mechanical properties over the conventional composites. Poor dispersion of nanomaterials could degrade the mechanical properties [66].

When the particle is oriented in a direction other than the direction of the applied force, the full potential of the particle cannot be realized. Having the particles oriented in the same direction will allow for easier transfer of energy (electrical or thermal). Achieving consistent dispersion and orientation will allow optimal property improvements. Four main methods for dispersing CNTs will be discussed.

_Ultrasonic_

Ultrasonication entails applying ultrasound energy for agitating the particles in a solution. Ultrasonication is usually achieved with either a bath ultrasonic or an ultrasonic probe/horn known as a sonicator (Fig. 2.16). The idea of this technique is basically a series of compression is achieved during the propagation of ultrasound producing shockwaves. These shockwaves will enable detaching of individual nanoparticles that are found at agglomerations or at the outer part of nanoparticle bundles. Ultrasonication is mainly utilized to disperse CNTs in liquids having low viscosity (water, acetone, etc.). If the CNTs are in a viscous liquid like polymer, a solvent that will dilute the polymer system is used to obtain a lower viscosity system before dispersing the CNTs in it. During sonication it is recommended not to be sonicated too aggressively or for too long because it could easily damage the CNTs.

![Figure 2.16 Ultrasonication method a) bath sonication and b) ultrasonic probe sonicator](image)

Figure 2.16 Ultrasonication method a) bath sonication and b) ultrasonic probe sonicator [64]
**Calendar**

Calendaring, also known as three roll mills method, is the combination of two different gaps with an angular velocity. Calendaring is composed of 3 rollers forming two gaps (Figure 2.17). The first gap is known as the feed roller in which the material is fed. The first roller has the slowest rotation per minute (RPM). The rotation of the rollers helps the mixing process. The speed of each roller could be controlled making it possible for the mixture to flow out regardless of the viscosity [24].

![Figure 2.17 Schematic – 3-roll mill [64]](image)

**Stir**

Stirring is a technique utilized to disperse particles in a liquid system as well as disperse CNT particles in a polymer matrix. Results of the dispersion will depend on the shape, size and speed of the propeller and mixture. MWCNTs tend to re-agglomerate due to frictional contacts and elastic interlocking mechanism while the sliding forces and weak attractive forces have minor effects [67]. If CNT agglomeration is present, a higher shear force is required to achieve a fine dispersion in the polymer matrix with setting of 10,000 rpm [64]. Figure 2.18 demonstrates an advance high shear mixer system for dispersion.
Figure 2.18 Possible combinations of high shear mixer (HSM) and conventional impellers [68]

Planetary Centrifugal Mixer [69]

Planetary Centrifugal Mixer “Thinky Mixer” (Figure 2.19) is a machine that provides simultaneous processing of mixing, and dispersing of high-viscosity materials. The container in the thinky mixer simultaneously revolves around the center of the mixer while at the same time rotating. The two contradictory forces help with the dispersion in the container.

In order to modify the surface of the CNT, plasma treatment or chemical oxidation is utilized to attach functional groups. These functional groups will enable the CNT to achieve a better bond to the matrix defying the van der Waals interactions [76]. Gelation/Crystallization is the technique in which after the nanotubes are dissolved in a solvent and polymer solution is added, a gel is formed. This gel is formed into a film which then the solvent is evaporated [80]. Table 2.7 demonstrate a comparison of different CNT dispersion techniques.

Figure 2.19 Thinky mixer [69]
<table>
<thead>
<tr>
<th>Technique</th>
<th>Damage to CNTs</th>
<th>Suitable polymer matrix</th>
<th>Governing factors</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonication</td>
<td>Yes</td>
<td>Soluble polymer, low viscous polymer or oligomer, monomer</td>
<td>Power and mode of sonicator, sonication time</td>
<td>Commonly used in lab, easy operation and cleaning after use</td>
</tr>
<tr>
<td>Calendaring</td>
<td>No, CNTs may be aligned in matrix</td>
<td>Liquid polymer or oligomer, monomer</td>
<td>Rotation speed, distance between adjacent rolls</td>
<td>Operation training is necessary, hard to clean after use</td>
</tr>
<tr>
<td>Ball Milling</td>
<td>Yes</td>
<td>Powder (polymer or monomer)</td>
<td>Milling time, rotation speed, size of balls, balls/CNT ratio</td>
<td>Easy operation, need to clean after use</td>
</tr>
<tr>
<td>Shear Mixing</td>
<td>No</td>
<td>Soluble polymer, low viscous polymer or oligomer, monomer</td>
<td>Size and shape of the propeller, mixing speed and time</td>
<td>Commonly used in lab, easy operation and cleaning after use</td>
</tr>
<tr>
<td>Extrusion</td>
<td>No</td>
<td>Thermoplastics</td>
<td>Temperature, configuration and rotation speed of the screw</td>
<td>Large-scale production, operation training is necessary, hard to clean after use</td>
</tr>
<tr>
<td>Planetary Centrifugal Mixer</td>
<td>No</td>
<td>Liquid polymer</td>
<td>Rotation speed, and time</td>
<td>Commonly used in lab, easy operation</td>
</tr>
</tbody>
</table>
CHAPTER 3
RESEARCH METHODOLOGY

3.1 Sample Fabrication

The RIDFT process was used to produce all composite and nanocomposite parts. Before the infusion process, dry fibers of fiberglass were cut into 8 x 12 inch rectangular shape and laid in the same direction. For all the samples of fiberglass produced, six layers were used per samples. For the production of GFRP, IVEXC 410 Vinyl ester/DCPD blend infusion resin manufactured by ArmorStar was used. Figure 3.1 includes a representation of dry fiber glass aligned in the same direction on the RIDFT for infusion.

![Figure 3.1 Glass fiber positioned and marked for cutting](image)

Four different types of composites were produced and tested. The first composite is to be created using the traditional RIDFT process. The second composite was created with the RIDFT process with Stretchlon bagging. The third composite will be similar to the first composite but CNTs are dispersed in resin using the Thinky mixer ARE_310. The forth composite will be as the third composite but with the incorporation of the Stretchlon bagging. The CNTs utilized for this thesis are Multi-wall nanotubes SMW200 Specialty Multiwall Carbon Nanotubes supplied by SouthWestNano Technologies. SMW200 has been selected due to its diameter and length. Figure 3.2a demonstrates the initial state when producing GFRP-CNT sample before the infusion process while Figure 3.2b is the initial stage when infusing and Figure 3.2c is when the infusion has been completed. The Stretchlon 800 Bagging Film used for this study was supplied by Fibre Glast Developments Corporation.

Stretchlon is a bagging film that can add versatility to a vacuum bagging system. Some of the characteristics of the Stretchlon 800 is that it could be stretched 450% of its original size. When the Stretchlon bagging is stretch, the Stretchlon will stretch over complex shapes and stretch over
the voids of any mold. Another characteristic from the Stretchlon is that it possesses higher durability than other plastic systems with decrease in the possibility of tears and other damages. The tensile strength of the Stretchlon is 10,000 psi. The Stretchlon 800 is also compatible with most resin systems (Epoxy, Polyester, and Vinyl Ester) and will stand up to 400 °F. Figure 3.2 demonstrate different stages in producing nanocomposite utilizing the RIDFT.

![Figure 3.2](image)

**Figure 3.2 a) Initial nanocomposite setup, b) infusion of CNT resin, and c) infused CNT resin completed**

### 3.2 Test Methods

Tensile test, flexural test and burn off test will be conducted as part of mechanical test. For thermal analysis, DMA test will be used to obtain the Tg. During the fabrication of each composite type, an optical hand help microscope was used on the silicone membranes of the RIDFT. SEM will be utilized to understand the test results and to study the effects of the Stretchlon on the silicone membranes. Figures 3.3, 3.4 and 3.5 highlight the different tests to be conducted on the various samples.
Figure 3.3 Overview of different mechanical tests to be conducted on fabricated samples

Figure 3.4 Overview of different thermal analysis to be conducted on fabricated samples

Figure 3.5 Overview of microscopic studies to be conducted on fabricated samples
3.2.1 Tensile Test

Five fabricated GFRP and nanocomposites panels are cut according to the ASTM D3039 standard with a diamond saw. The minimum length required is gripping + 2 times width + gage length. Samples for the tensile tests will be tested using the Landmark MTS universal testing machine servo-hydraulic test system. The tensile test will help determine key composite properties like the ultimate tensile strength, maximum elongation, young’s modulus, poison’s ration yield strength and strain-hardening. Figure 3.6a and 3.6b show the placement of the samples on the landmark MTS tensile machine during one of the tests.

\[ F_{tu} = \frac{p_{\text{max}}}{A} \]  \hspace{1cm} (2)

\[ \sigma_i = \frac{P_i}{A} \]  \hspace{1cm} (3)

Where

- \( F_{tu} \) = ultimate tensile strength, MPa
- \( \sigma_i \) = tensile stress, MPa

To determine the ultimate tensile strength (Eq 2.) and tensile stress (eq 3.), the following equation were used:
\( P_{\text{max}} \) = maximum load before failure, N
\( \sigma_i \) = tensile stress at ith data point, MPA
\( P_i \) = load at ith data point, N
A = average cross sectional area

### 3.2.2 Flexural Test (Three Point Bend Test)

Five samples for flexural test are cut according to the ASTM Standard D790. Samples for the flexural test will be tested using the AGS-J Shimadzu. The specimen length required is six times that of the thickness and the width is equal to two times that of the thickness. Flexural test is conducted in order to study the interlaminate properties of the composite, as well as the flex or bending properties. The fabricated samples were tested under a 3-point bend test loading condition. Figures 3.7a demonstrate initial setup for flexural test sample and 3.7b demonstrate when a force is applied over the sample.

![Figure 3.7 Representation of the 3 point bend test on the Shimadzu with a) before applying force b) after forced applied](image)

To determine modulus of elasticity in bending the following equation was used:

\[
E_B = \frac{L^3 m}{4 bd^3}
\]  

(4)
Where

\( E_B \) = modulus of elasticity in bending, MPa

\( L \) = support span, mm

\( B \) = width of beam test, mm

\( d \) = depth of beam tested, mm

\( m \) = slope of the tangent to the initial straight-line portion of the load-deflective curve N/mm

### 3.2.3 Burn Off Test

In order to obtain the volume fraction results, burn off tests is performed according to the ASTM D2548-68 standard. The first step in a burn off test is to find the burning temperature of the vinyl ester and carbon nanotubes. This way, by separating the different components (CNTs and resin) by burning them off, it is possible to calculate the volume fraction. This way, the fiber content in the composite part can be determined. In order to achieve high temperatures, the furnace – Vulcan 3-1750 NDI will be used. Equation 5 is used to determine the volume fraction

\[
V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f}
\]  

(5)

Where

\( V_f \) = volume fraction of fibers

\( W_f \) = weight of fibers

\( W_m \) = weight of matrix

\( \rho_f \) = density of fibers

\( \rho_m \) = density of matrix

### 3.2.4 Dynamic Mechanical Analysis (DMA)

Dynamic Mechanical Analysis (DMA) is a technique used to study properties of different materials. A sinusoidal deformation is applied to the sample in which a controlled stress and/or strain is applied. DMA can be used to measure the storage modulus, loss modulus, glass transition temperature (Tg), complex viscosity, ultimate strength and other material characteristics that can facilitate better understanding of the behavior of the composite parts fabricated with and without
the use of the Stretchlon with the RIDFT. Three samples are tested using the DMAQ800 by TI instrument to determine the effect of the Stretchlon on the glass transition temperature.

3.2.5 Morphology Characterization

Scanning Electron Microscope (SEM) utilizes a focused beam of high energy electron to scan samples and generate high-resolution and highly magnified images of the observed object or surface. Micro-structural characterization was conducted with a Field Emission Scanning Electron Microscope (JEOL JSM-7401F) to gain insight into the failure mode of the fabricated and tested composites and nanocomposites parts. In addition, DinoLite hand held digital microscope (DinoLite, USA) was also used to study the surface morphology of the composites and nanocomposites.

3.3 Production Cycle Time and Cost Analysis

The Stretchlon bagging 800 film has the potential to reduce setup time for multiple productions of fiberglass/carbon fiber parts. The introduction of the Stretchlon bagging film is expected to result in a small increase in the set up time but a significant reduction in the mold cleaning and preparation time. During infusion, areas that will be impregnated with resin will be covered with the Stretchlon film. The Stretchlon film will prevent the resin from making contact with the silicone molds thereby helps to reduce the silicon mold cleaning time after infusion in preparation for new production cycle. Stretchlon bagging will serve as a cover to the silicone membrane particularly in areas that are difficult to clean. After production, the Stretchlon bagging will be discarded. Utilizing the Stretchlon bagging may also result in a variation in the surface finish of the fabricated composite parts. The time (duration) for each task involved in the fabrication of the composites using the two processes (with or without Stretchlon) on the RIDFT was measured and recorded. Cost analysis was also carried out to determine the economic impact of the use of the Stretchlon process with the RIDFT
CHAPTER 4
RESULTS AND DISCUSSION

4.1 RIDFT with Stretchlon Fabrication Process: Minimizing Wrinkling Effect

The wrinkling effect was studied with a “C” shape mold that offers greater geometrical complexity than a rectangular mold. The drapability of the fibers over the mold were visually observed with and without the use of Stretchlon film bagging on the RIDFT machine. Vacuum was applied to observe the wrinkling effect during forming. Figure 4.1 is a picture of the setup of the Stretchlon film and the “C” shape mold on the RIDFT machine before vacuum was applied.

Visual inspection of the setup after vacuum was applied (Figure 4.2 and 4.3) indicates practically the same extent of wrinkles for the case with no Stretchlon film and the one with Stretchlon film. Good formability with no wrinkling could be observed in the front views of the setup with no Stretchlon (Figure 4.2a) and that with Stretchlon (Figure 4.2b). Similarly, no significant differences could be observed in the wrinkles at the edges of the mold for the setup with no Stretchlon (Figure 4.2c) and the one with Stretchlon film (Figure 4.2d). Naturally, the
flexible silicone membrane of the RIDFT produces wrinkles at the edges of the mold depending on the complexity of the mold shape. The observed wrinkles are minimal and are located at the edges and lower parts of the mold where they would not affect the fabricated parts.

Figure 4.2 Formability of glass fiber on ‘C’ mold on the RIDFT with a) no Stretchlon (front view), b) Stretchlon (front view), c) no Stretchlon (side view), d) Stretchlon (side view)

Figure 4.3 a) Wrinkle effect using Stretchlon with Stretchlon a) completely attached to silicone, b) completely attached to silicone and cut at the corners, and c) partially attached to silicone at the corner edges
4.2 Production Cycle Time

Table 4.1 provides the result for the average time duration of various tasks when using the RIDFT for fabricating GFRP and CNT-GFRP parts of the same size. The table clearly shows the differences in the production time when the Stretchlon is used in the process. All the parts were allowed to cure for 24 hours.

The use of the Stretchlon membrane for the fabrication of GFRP parts resulted in 32 % reduction in the production time per part for pristine resin and 42 % per part for CNT resin. During the production of composite parts, the cycle time vary depending on the amount of time a sample is produced using the same silicone sheet. Every time the same silicone sheet is reused it increases the cycle cleaning time due to the older residues. The longer the residues have been there the harder to clean. Most of the time spent on production consisted for cleaning the silicon membranes in preparation for the next production cycle.

Table 4.1 Average part production time for the RIDFT process with or without the Stretchlon 800

<table>
<thead>
<tr>
<th>Task</th>
<th>GFRP, no Stretchlon (minutes)</th>
<th>GFRP, with Stretchlon (minutes)</th>
<th>CNT-GFRP, no Stretchlon (minutes)</th>
<th>CNT-GFRP, with Stretchlon (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infusion</td>
<td>1</td>
<td>2</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Part demolding</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Membrane silicon cleaning</td>
<td>140</td>
<td>60</td>
<td>300</td>
<td>120</td>
</tr>
<tr>
<td>Material layup before infusion</td>
<td>90</td>
<td>97</td>
<td>90</td>
<td>97</td>
</tr>
<tr>
<td>Production time/part (min)</td>
<td>237</td>
<td>161</td>
<td>408</td>
<td>234</td>
</tr>
</tbody>
</table>

Figure 4.4 shows the material deposits on a silicon membrane of the RIDFT after part production. Figure 4.4a shows CNTs deposits on a silicone membrane after nanocomposite part
fabrication with the RIDFT. Figure 4.4b demonstrates what happens after cleaning the silicon membrane after the first time it has been infused. Previously, by a different operator, multiple infusions have been produced reusing the same silicone membrane. Figure 4.4c shows the state of the silicone membrane after multiple infusions (part production) making it no longer suitable for continued use. Figure 4.4d demonstrates some issues that happened when the resin is completely attached to the silicone membrane and when in contact with acetone it starts breaking and puncturing the silicone membrane.

![Figure 4.4](image)

**Figure 4.4** a) Silicone membrane after nanocomposite fabrication, b) cleaning of the silicone membrane after producing one nanocomposite part, c) cleaning of the silicone after producing multiple nanocomposites with vinyl ester and epoxy, and d) particles that tend to break when cleaning and damage the silicone membrane.

### 4.3 Silicone Replacement Cost and Time

One big advantage from utilizing the Stretchlon is how the Stretchlon increases the useful life of the silicone membrane. Silicone membranes are expensive to replace. After multiple infusion the silicone membranes are required to be changed. The replacement of the silicone membrane tends to last from two to three days. After the silicone membrane is placed on the frame, it is sealed with silicone rubber that requires twenty four hour curing time. After the curing, the
frames are placed back in the RIDFT and subjected to a vacuum process for it to stretch. On stretch mode, another coating of the silicone rubber is placed between the silicone membrane and the metal frame that holds the silicone.

When producing pristine carbon fiber or fiber glass composite, the silicone membrane tends to have a longer service life than when producing nanocomposite. The Stretchlon prevents the resin from making contact with the silicone membrane thereby making it easier to clean. It also gives the fabricated composite part a smoother and finer surface finish. Figure 4.5a and 4.5b show how the silicone membranes are cut to fit the frames while Figure 4.5c shows how the holes are made on the silicone membrane to attach them to the frames.

Without the Stretchlon film bagging, the silicone membrane becomes flabby and very difficult to clean after multiple production cycles because of the destructive effects of the resin and cleaning chemicals used after each production cycle. The reduced cleaning made possible with the use of the Stretchlon further helps to protect the expensive silicone membrane from damage caused by the rigors of the cleaning process.
This study shows that to produce 28 GFRP parts (28 production cycles), the silicone membranes on the RIDFT need to be changed twice. With the use of the Stretchlon, 28 parts (production cycles) of GFRP could be produced using the same silicone membranes without replacement. Without using the Stretchlon bagging, the time required for cleaning and the amount of cleaning reagents required increase with each production cycle. Table 4.2 gives a summary of the cost required to produce 28 parts in 28 production cycles on the RIDFT machine, with and without Stretchlon film bagging. The use of Stretchlon film with the RIDFT process for GFRP resulted in 48.78 % reduction in tooling and cleaning materials cost. The use of Stretchlon film with the RIDFT process for CNT-GFRP fabrication resulted in 72.39 % reduction in tooling and cleaning materials cost.

<table>
<thead>
<tr>
<th>Material cost ($)</th>
<th>Pristine Resin (No Stretchlon)</th>
<th>Pristine Resin (With Stretchlon)</th>
<th>CNT Resin (No Stretchlon)</th>
<th>CNT Resin (With Stretchlon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone</td>
<td>2052</td>
<td>1026</td>
<td>4104</td>
<td>1026</td>
</tr>
<tr>
<td>Cleaning Supplies</td>
<td>320</td>
<td>28</td>
<td>394</td>
<td>55</td>
</tr>
<tr>
<td>Stretchlon 800 film</td>
<td>-</td>
<td>161</td>
<td>-</td>
<td>161</td>
</tr>
<tr>
<td>Total ($)</td>
<td>2372</td>
<td>1215</td>
<td>4498</td>
<td>1242</td>
</tr>
</tbody>
</table>

### 4.4 Issues Using Dispersion by Calendaring

Before infusion, CNTs are dispersed in the resin. Dispersion is a critical factor when producing nanocomposites. The dispersion technique first utilized for the production of nanocomposite was calendaring. The calendaring machine utilized was the EXAKT 80 E. Mixture of resin and functionalized CNT underwent seven consecutive passes on the calendaring machine.

During the process of dispersing the CNT in resin by the calendaring process, emission of styrene is present. The emission of styrene turns the resin from a low viscosity to a high viscosity system. Due to the viscosity incident, at the culmination of the calendaring process the amount of styrene that was released during calendaring is re-added at the end and some is added at the beginning. A small percentage of styrene is added at the beginning to minimize the rapid increase
of viscosity and to facilitate the dispersion process. CNTs-rich resin is initially measured by weight and at the end of calendaring process is re-measured. Styrene is re-added until the initial weight is obtained. Figure 4.6a shows the dispersion process while Figure 4.6b highlights the issues when styrene is evaporated resulting in very high viscosity system.

Figure 4.6 a) Low viscosity at the beginning of the calendaring process and b) high viscosity developed after multiple passes through the rollers

4.5 Mechanical Analysis

4.5.1 Tensile Properties

The tensile stress-strain curves for the different sample types tested are as shown in Figure 4.7. All the sample types exhibited similar behavior under tensile loading. The stress-strain curves are characterized primarily by a linear elastic behavior up to the ultimate tensile strength and brittle
failure typical of GFRP. The use of Stretchlon did not alter the stress-strain behavior of either the GFRP (Figure 4.7b) or the CNT-GFRP (Figure 4.7d).

Figure 4.7 Stress-strain curve for a) GFRP no Stretchlon, b) GFRP with Stretchlon, c) CNT-GFRP no Stretchlon, and d) CNT-GFRP with Stretchlon

Figure 4.8a shows the mean ultimate tensile strength for GFRP fabricated without using Stretchlon film (GFRP No Stretchlon) and that produced with the Stretchlon film (GFRP with Stretchlon) on the RIDFT machine. The result indicates an increase in the mean ultimate tensile strength (UTS) of the tested samples with the use of Stretchlon bagging. The mean UTS increased from a value of 292.63 MPa, with a standard deviation value of 31.39 MPa, to a value of 386.11 MPa, with a standard deviation value of 56.87 MPa, with the use of Stretchlon bagging. This corresponds to an increase of about 24% in the UTS value. With regards to the CNT-GFRP we observe an increase from 220.98 MPa from no Stretchlon with standard deviation of 48.79 MPa to 248.87 MPa from Stretchlon with standard deviation of 40.03 MPa. This increase corresponds to a ten percent (10%) in the UTS Values. From the tensile test, the elastic modulus was also calculated. The mean elastic modulus increased from a value of 13.79 GPa with a standard deviation value of 2.13 GPa for GFRP no Stretchlon to 17.54 GPa with a standard deviation value
of 1.24GPa. As far as CNT-GFRP samples, the mean elastic modulus increased from a 0.58 MPa for CNT-GFRP Stretchlon with standard deviation of 13.06 to 0.98 GPa for CNT-GFRP no Stretchlon with standard deviation of 12.33GPa.

![Figure 4.8 a) Mean ultimate tensile strength and b) mean elastic modulus for tested samples](image)

4.5.2 Flexural Test

In order to conduct the three point bend test, five samples from each panels were cut utilizing a diamond saw cutter. The three point bend test was conducted on a Mechanical Test Machine by Shimadzu Co, Japan.

Figure 4.9a gives the mean flexural strength for the different composite parts fabricated. The failures in flexural strength tests are normally dominated by resin and interlaminar properties [1]. Consequently, sample type with lower fiber volume fraction (hence higher resin volume
fraction) has higher mean flexural strength because the resin-rich interlaminar layers enhanced the interlaminar properties such as the flexural strength. The GFRP No Stretchlon samples with the lower fiber volume fraction have a mean flexural strength of 395.01 MPa (Standard deviation of 100.48 MPa) and a flexural modulus of 17.91 GPa (Standard deviation of 5.98 GPa). In the same vein, the GFRP with Stretchlon samples with the higher fiber volume fraction have a lower mean flexural strength of 276.09 MPa (Standard deviation of 17.85 MPa) and a flexural modulus of 10.44 GPa (Standard deviation of 2.00 GPa) because there is less amount of resin in the interlaminar layers to enhance interlaminar properties such as that indicated by the flexural strength. As far as the CNT-GFRP samples, CNT-GFRP no Stretchlon with lower volume fraction had a mean flexural strength of 337.21 MPa (Standard deviation of 18.24 MPa) and flexural modulus of 7.45 GPa (Standard deviation of 0.93 GPa) and CNT-GFRP with Stretchlon samples with higher volume fraction had a flexural strength of 274.36 MPa (Standard deviation of 38.88 MPa) and flexural modulus of 5.80 GPa (Standard deviation of 0.39 GPa).

Figure 4.9 a) Mean flexural strength and b) mean flexural modulus for tested samples
4.5.3 Burn Off Test

In order to gain further insights into the observed results, burn tests were conducted on the samples to determine the fiber volume fraction. Three samples were tested for each composite type. Following the ASTM standard, samples were placed into a furnace and heated. Resin or any extra filler from samples are completely eliminated. Temperature required to completely burn vinyl ester resin was calculated to be 565 °C. Figure 4.10 shows the volume fraction for the different sample types. It is clear that the use of Stretchlon bagging does not adversely affect the fabrication process for the composite. A fiber volume fraction of 0.52 was achieved for GFRP parts fabricated with no Stretchlon film while a higher fiber volume fraction of 0.59 was achieved for GFRP parts fabricated with Stretchlon film in the RIDFT. For CNT-GFRP samples a higher volume fraction of 0.46 is achieved for CNT-GFRP with Stretchlon while a lower volume fraction of 0.42 for CNT-GFRP with no Stretchlon. Since the tensile strength is a fiber dominated property of the composite, it is not surprising that the composite with the higher volume fraction resulted in higher mean ultimate tensile strength. Figure 4.38 shows the volume fraction of every sample fabricated.

![Figure 4.10 Volume fraction for GFRP and CNT-GFRP fabricated with no Stretchlon film and with Stretchlon film bagging.](image)
4.6 Thermal Analysis

4.6.1 DMA

The values of the tan delta Tg for the various samples tested are given in Table 4.3. The difference in the mean Tg values between the GFRP No Stretchlon and the GFRP with Stretchlon samples is only 2.6%. The mean Tg value increased from a mean value of 118.28 °C for GFRP No Stretchlon samples to a value of 121.34 °C for GFRP with Stretchlon samples. It may be inferred that the use of the Stretchlon film does not adversely affect the thermal property of the composite as evident by the mean Tg values of the tested samples.

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>GFRP No Stretchlon</th>
<th>GFRP with Stretchlon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>118.96</td>
<td>121.98</td>
</tr>
<tr>
<td>2</td>
<td>117.82</td>
<td>121.34</td>
</tr>
<tr>
<td>3</td>
<td>118.07</td>
<td>120.71</td>
</tr>
<tr>
<td>Mean Tg (°C)</td>
<td>118.28</td>
<td>121.34</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>0.60</td>
<td>0.64</td>
</tr>
</tbody>
</table>

4.7 Microscopy

4.7.1 Digital Optical Microscope

The digital optical microscope was used to study the effects of the infusion process on the silicone membranes. After multiple part production and cleaning cycles, the silicone membranes tend to degrade and become unsuitable for further use. Figure 4.11 shows different silicone membranes. In figure 4.11, the “S” represent silicone membranes covered with Stretchlon and “NS” represent silicone membranes with no Stretchlon after contact with resin. It was observed from the image that after multiple production cycles some residues tend to stick to the silicone membrane when the Stretchlon was not used. The Stretchlon prevents the resin or CNT resin to get in contact with the silicone membrane thereby facilitating the cleaning process for new part
production. Figure 4.12 demonstrate how images were obtained with the optical handheld microscope.

Figure 4.11 Samples preparation for morphology characterization

Figure 4.12 Silicone membranes studied with optical handheld microscope
Using the hand held microscope, four different images were taken. Figure 4.13 demonstrate images of the silicone sheet before and after fabricating GFRP parts with and without Stretchlon. Figure 4.14 shows images of the finalized GFRP parts with Stretchlon and without and also shows a close up to the Stretchlon and the silicone.

![Digital optical microscope images on clean silicone membrane, b) digital optical microscope images on silicone membrane after GFRP production, c) digital optical microscope images on silicone membrane after nanocomposite production, and d) digital optical microscope images showing residues of CNT resin particles on silicone membrane.](image)

Figure 4.13 a) Digital optical microscope images on clean silicone membrane, b) digital optical microscope images on silicone membrane after GFRP production, c) digital optical microscope images on silicone membrane after nanocomposite production, and d) digital optical microscope images showing residues of CNT resin particles on silicone membrane.
4.7.2 Fractography

Figure 4.15 shows the optical microscope images of CNT-GFRP parts fabricated with Stretchlon (Figure 4.15 a-c) and those with no Stretchlon (Figure 4.15 d-f). The failure of the nanocomposites initiated at the tension side as expected for specimens under flexural loads. It could however be observed that specimens fabricated with no Stretchlon (Figure 4.15 b and c) experienced significant fiber failure during failure than those fabricated with Stretchlon (Figure 4.15 e and f). It seems that the higher flexural properties observed in nanocomposites fabricated with no Stretchlon are due to effective load transfer from the resin matrix to the fiber. The failure mode in the specimens fabricated with Stretchlon tends to be resin dominated (resin cracking) due to less effective load transfer.
Figure 4.15 Fractography a) intact section of CNT-GFRP no Stretchlon, b) fracture section of CNT-GFRP no Stretchlon, c) fracture section of CNT-GFRP no Stretchlon sample 2, d) intact section of CNT-GFRP with Stretchlon, e) fracture section of CNT-GFRP with Stretchlon, and f) fracture section of CNT-GFRP with Stretchlon sample 2

4.7.3 SEM

Figure 4.16 is a typical scanning electron microscope image of the side view of a fractured nanocomposite (CNT-GFRP). The micrograph shows the failure of the nanocomposite originating with matrix cracking (Figure 4.16a) from the tensile side of the sample. Some fiber breakage (Figure 4.16b) could also be observed closer to the tensile side of the specimen. Delamination failure (Figure 4.16c) is the predominant failure mode observed closer to the compression side.
Figure 4.16 SEM image of failed CNT-GFRP sample a) matrix cracking, b) fiber breakage, c) delamination
CHAPTER 5
CONCLUSION

LCM is known as the most viable technique for composite production. RIDFT is an innovative process with many advantages for the fabrication of both composite and nanocomposite parts. The use of the Stretchlon bagging 800 film with the RIDFT has been demonstrated and shown to improve the production cycle time by reducing the silicon membranes cleaning time.

Stretchlon bagging film resulted in reduction in the production cycle time of GFRP and CNT-GFRP parts of 32 % and 42 % respectively. It also resulted in production set-up (mold preparation) cost reduction for GFRP and CNT-GFRP parts of 49 % and 72 % respectively. The increase in durability and service life of the silicon mold helped to reduce the production cost. In addition, Stretchlon bagging film resulted in an increase of 31.94 % and 12.62 % in the mean UTS of the GFRP and CNT-GFRP respectively. The Stretchlon film however resulted in reduction in the flexural properties of the fabricated GFRP and CNT-GFRP parts by 30.12 % and 18.69 % respectively.

The use of the Stretchlon bagging film enhanced the in-plane properties of the fabricated parts by helping to increase the fiber volume fraction. Thermal analysis confirmed that there was no change in the glass transition (Tg) temperature of the fabricated parts. From simple inspection and images taken with the microscope, fabricated with the Stretchlon bagging film also exhibited better surface finish than those fabricated without using the Stretchlon bagging film.

Further work is however needed to optimize the RIDFT-Stretchlon film fabrication process for nanocomposites. A more detailed microscopy study needs to be performed to gain better insights into the reasons for the enhanced fiber volume content and in-plane properties achieved with the use of the Stretchlon film. In addition, the study needs to be repeated with functionalized CNTs to study the effects of functionalized CNTs on the fabricated parts, the silicon mold and the Stretchlon film. There is also the need to fabricate the new RIDFT design and optimize its performance.
APPENDIX A
LIST OF PUBLICATIONS

Divyesh H. Bhakta, David O. Olawale, Tarik Dickens, and Okenwa I. Okoli; “Stretchlon Film-Enhanced RIDFT Process for Composite Manufacture” SAMPE Baltimore 2015, May 18-21, 2015, Baltimore, Maryland


David O. Olawale, Divyesh Bhakta, Emily Hammel, Jin Yan, Donovan Carey, Tarik Dickens, and Okenwa I. Okoli; “Triboluminescent Composite with In-situ Impact Sensing Capability” The Composite and Advanced Materials Expo (CAMX 2015 conference), Dallax, Texas; October 27-29, 2015


34. Quickstep. The Out-of-Autoclave process for high performance autoclave grade materials.


Divyesh Bhakta was born in Republic of Panama the 18th of February, 1989. During his high school studies, he co-founded a business named Ace of Games. Ace of Games is an internet café located in Panama. He finished his liberal studies in 2009 from Florida State University, Panama campus and transferred to Florida State University, Tallahassee campus. He completed his undergraduate studies in Industrial and Manufacturing Engineering in 2012 from Florida State University.

Divyesh also did an internship at Cerveceria Nacional – SAB Miller, Republic of Panama. After the internship, he worked as a research assistant for the High Performance Materials Institute. Along with his research, he has worked as a teaching assistant for FSU-FAMU Collage of Engineering.

His master’s degree consisted of improving the RIDFT process. He is also a member of professional student organizations such as Institute of Industrial Engineers (IIE) and Society of Manufacturing Engineers (SME). His goal is to combine his entrepreneurial experience with the technical knowledge gained during his master’s program.