Formability Characterization of Fiber Reinforced Polymer Composites Using a Novel Test Method

Reference

ABSTRACT
Fiber reinforced polymer composites are often used as a replacement for metal alloys because of the superior strength to weight ratio. However, a major drawback of these materials is the lack of formability caused by the low strain to failure ratio that does not allow the material to follow tooling contours into deep drawn shapes or tight radii. Composite materials have a multiscale hierarchical structure where micro and meso scale effects (fiber and tow scales) contribute to the macro structural response (laminate scale). In particular, during forming, different deformation occurs simultaneously at every scale. Currently, the amount of quantifiable and comparable forming data for both continuous and discontinuous fiber reinforced polymer composites, including a multi-scale understanding of the deformation response, is limited because of the lack of a testing system. This article proposes a novel test method and an apparatus called “the forming fixture” for testing the tow formability of fiber reinforced polymer composites by determining the required load to form an uncured resin impregnated fiber tow sample into a stretch drawn profile. Test results from forming of Hexcel (Stamford, CT) IM7-G continuous carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin system, in the temperature range of 21°C–121°C, are discussed to demonstrate the use of the proposed apparatus including representative data. Results showed consistency and repeatability, validating the reliability of the novel method. The test aided in defining the forming behavior of the material in real time both visually (e.g. sample failure location) and as forming load versus displacement curves. A novel forming metrics, relating the maximum drawing depth with no failure and the maximum forming load, is defined to compare and select different fiber and resin formulations. Widespread adoption of the forming fixture will reduce reliance on a “trial and error” approach during the forming process.
Keywords
forming, fiber reinforced polymer composite, tow, pre-preg, carbon fiber, uncured, forming test fixture

Introduction

Formability is defined as a material’s capacity to undergo deformation without being damaged and without compromising the mechanical properties. It is a key factor in composite parts design because it defines the ability to create complex shapes. Continuous fiber reinforced polymer composites are often used as a replacement for metal alloys because of the high strength to weight ratio. However, the major drawback of these composites is the lack of formability because of the low strain to failure ratio of the fibers, which does not allow the material to follow the contours of the tooling into deep drawn shapes or tight radii. Instead, fibers tend to either bridge, misalign, or fail under forming loads, negatively affecting the behavior and durability of the final products.

Recently, composite technology research and development efforts have focused on discontinuous fiber composites, such as aligned chopped fibers and stretch broken carbon fiber (SBCF). The main advantages of this material are in the ability of the fibers to move independently in the uncured resin matrix. This mobility enables a pseudo-ductile deformation response, which allows the material to be molded in complex geometries, reducing manufacturing costs, as compared to continuous fiber composites.

Regardless of the selected fiber reinforcement, many composite structures are made of laminates obtained by stacking individual plies with different fiber orientations. This process creates a multiscale hierarchical structure where micro and meso effects (fiber and tow scales) contribute to the macro structural response (laminate scale). The final component characteristics are generally complex because of the intrinsic orthotropic or anisotropic nature of the material. When discontinuous reinforcement is used, this complexity is more pronounced as the material does not behave like either a conventional composite or an isotropic material. During a forming process, the hierarchical structure becomes relevant as different deformations occur simultaneously at the micro, meso, and macro scales.

Traditional metal formability tests can be divided into three main categories, namely intrinsic tests, simulative tests, and tests to determine Forming Limit Diagrams (FLD). Intrinsic tests provide information about the basic mechanical properties of the material, which can be related to formability independent of other characteristics like thickness and surface conditions. However, the strain state is simplified and not representative of industrial processes. In addition, intrinsic tests do not account for the effect of the processing variables. The most common example of an intrinsic test is the uniaxial tensile test, which is widely used to determine tensile strength and strain at failure. The simulative tests aim to reproduce the stress and strain conditions experienced during specific forming operations, and include the effects of variables, such as friction with the forming tool, that are not taken into account in the intrinsic tests. Simulative tests are identified according to the forming process they aim to replicate, specifically bending, stretching, drawing, and stretch-drawing. Examples of simulative tests are the cupping tests (e.g., Erichsen and Olsen) used to evaluate material stretchability. The major drawback of simulative tests is that they tend to be less reproducible when compared to intrinsic tests and must be performed under carefully controlled testing conditions to minimize variability in the results. Tests to determine FLD are stretch tests producing out-of-plane or in-plane deformation. Sheets of materials are clamped between a die and a sheet holder and stretched by the action of a punch. Examples of FLD tests include the Nakajima test, which uses a hemispherical punch, a circular die, and rectangular sheets, and the Marciniak test that uses punches of different shapes (circular, elliptical, rectangular) with a central hole and sheets of different widths. Despite being widely employed, the reliability of test results is affected by the bending effect because of the punch curvature, limitations in sample thickness, and the need for elevated and reproducible clamping force.

In the fiber composites industry, most formability characteristics are determined by a “trial error approach,” along with empirical evaluations of the target shape. In most cases, the tooling and the forming process for the final product are limited by the geometric profile of the part being produced. For example, if continuous fibers are considered and the geometry has deep cavities or tight radii, the ability to use either vacuum forming, or
compression molding is very limited. Hand lay-ups are a suitable alternative but the process is expensive, labor-intensive, less consistent, and time-consuming.

During the last decade, the demand for stamp and press forming of composite materials has increased because of its suitability for mass production. Such processes, although being established for thermoplastic composites, are not well suited for thermosetting composites as the material flow is hindered by the chemistry of the resin. Recent studies were conducted on the formability of thermoplastic composites using cupping tests. It was found that forming rate, tool temperature, and sample holding force have the strongest effect on the structural behavior and the service life of products. Recently, studies conducted on the formability of thermosetting composites using cupping and stretch bending tests revealed that the composite shows sufficient ductility for press forming at elevated temperature (100°C). Analytical modeling aided in relating the phenomenon to the resin crosslinking density and the consequent variation of its mechanical properties.

Currently, the amount of quantifiable and comparable forming data for both continuous and discontinuous fiber reinforced polymer composites, including a multi-scale understanding of the deformation response, is still limited. The availability of a quantitative, repeatable, and predictive experimental tool is highly desirable to reduce the reliance on the “trial and error approach” and highly tooling-specific empirical responses during the forming process.

Research Significance

During the last decade, the application of multi-scale modelling to investigate the complex mechanical response of heterogeneous materials like composites has increased. The underlying assumption behind multiscale modelling is that, at the structural scale, the material appears to be homogeneous. With this assumption, the properties for the macro scale can be formulated by investigating the behavior of a suitably “small,” heterogeneous statistically representative volume of material at the micro scale. It has been shown that the representative volume needs to be at least one order of magnitude smaller than the size of the macro domain.

Based on the hierarchical multi scale composite structure and the modeling approach, this work presents a novel experimental method to characterize the mesoscale formability of uncured fiber reinforced polymer composites. In the uncured state, the composite exhibits viscoelastic properties that determine the pseudo-ductile deformation response of the material. When a load is applied during forming operations, the fibers move independently in the resin matrix and may bridge, misalign, or fail, compromising the quality of the final cured products. The investigation of the forming behavior of the uncured composite therefore becomes important to characterizing the deformation response while optimizing the forming process variables that generated it, thereby preventing the development of defects.

The experimental apparatus was designed to evaluate the composite behavior by measuring forming load versus displacement in a stretch drawing process. Several variables relevant to the forming process (e.g., temperature and load) can be controlled during testing (see “Proposed Test Method” below). With a sequential approach, the material is first tested at the tow scale and then the results can be used to improve understanding of larger scale problems such as laminate deformation phenomena during dome (hemispherical) forming tests or for validating multiscale modelling results. Better knowledge of composite formability can potentially allow for reduced material waste, cost-effective processing techniques and more complex and advanced structures.

Test results from the forming of Hexcel (Stamford, CT) IM7-G 12K continuous carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 proprietary epoxy-based thermosetting resin system are presented in this study to demonstrate the use of the proposed testing apparatus and data collection.

Proposed Test Method

In this section, a novel method is proposed for testing the formability of fiber reinforced polymer composites at the mesoscale (tow). The simulative testing apparatus detailed in this article is called the “forming fixture.” The test method determines the required load to form a dry or uncured resin impregnated fiber tow (here
generally defined as tow sample) into a stretch drawn profile. Limitations of cupping and stretch bending forming tests\textsuperscript{14-20} are related to the sample holding mechanism and to the imposed test geometry. When mechanical clamping is used, insufficient and inconsistent clamping force, during and between experiments, may lead to sample slippage, compromising test repeatability and the reliability\textsuperscript{18} of results, especially when tests are conducted at elevated temperature. Because these tests’ geometries do not offer flexibility, if the need to perform experiments using different sizes or shapes of the forming tool arises, a whole new unit must be machined in most cases. The “forming fixture” is equipped with a sample holding assembly that offers high reliability by completely avoiding sample slippage. The clamping force is controlled and a self-leveling system accounts for variation in the sample thickness. In addition, the forming parts (blocks and tool) can be quickly and easily replaced to accommodate the desired testing geometry.

During industrial forming operations, especially when complex shapes are formed, the material must properly follow the contours of the tooling. The amount of material involved in this process is usually much larger than the size of a complex feature (e.g., drawn profile or a tight radius); therefore, the strain response of the material located in its surrounding region becomes relevant to the quality of the final product. A common trait of the previously established\textsuperscript{14-21} forming tests is the sample being clamped at the edges of the die. Excess material is only used for securing the sample in position. This condition is only partially simulative because it does not account for the strain response of the material in the region surrounding the die. In the proposed “forming fixture,” the clamping system is placed away from the forming tool. Once the sample is secured in place, part of it lays on the blocks next to the forming region during testing and will generate a strain response related to the selected geometric configuration. This test setup is novel as it better simulates the complexity of the industrial forming processes and most importantly, allows for the investigation of the synergistic effects of multiple forming variables.

Figure 1 shows a schematic of the test setup.

During testing, different stress conditions result in the tow sample. The part of the tow sample laying on the top of the forming blocks experiences shear stress. Bending stress (as uniaxial tension/compression) is created around the forming blocks radius of curvature (fig. 1B) and plain strain tension exists on the walls of the stretch drawn tow sample. The stress condition experienced at the bottom of the stretch drawn profile and in contact with the forming tool depends on the nature of the tested sample and on the geometry of the tool. For example, uniaxial stretch is created when a single tow is tested using a semi-cylindrical profile tool, whereas biaxial stretch (deep drawing) can be achieved when a hemispherical forming tool is used to test laminate tape samples manufactured with different fiber orientations (see “Design Recommendation” section).

FIG. 1
Forming fixture test design concept
(A) forming blocks, (B) forming blocks radius of curvature, (C) forming tool, (D) forming tool radius of curvature, (E) tow sample, and (F) stretch drawing depth.
The general setup of the forming fixture when mounted on a Mark-10 ESM303 (Mark-10 Corp. Copiague, NY) universal testing stand is shown in figure 2.

The tow can be tested dry or resin infused. Any material combination of interest for fiber and resin can be used. The following parameters can be adjusted to accommodate a variety of forming processes:

- Forming blocks and forming tool radius of curvature
- Forming blocks and forming tool profile geometry
- Forming blocks and forming tool temperature
- Forming blocks span distance
- Tow sample gauge length
- Loading rate
- Temperature

The forming blocks and tool are removable and are held in place by T-slots. This design allows for fast forming part replacement to accommodate the desired profile geometry during testing. Figure 2 shows the forming fixture equipped with the forming blocks and the tool having a semi-cylindrical profile (figs. 2D and 2F). Figure 3 shows a set of forming tools with semi-cylindrical profile of different sizes and the tool adapters (fig. 2C).

The ability to securely hold the tow sample is a major requirement during testing. Slippage of any kind must be avoided to assure test repeatability and data reliability. For this reason, a sample holding assembly has been specifically designed (fig. 2E) to securely hold the tow ends as follows. When prepared for testing, the ends of the tow sample are secured between two cardstock tabs, using a fast curing ethyl cyanoacrylate adhesive (see "Specimen Fabrication" section). Figure 4 shows the sample holding assembly with one of the tabbed ends of the tow sample held in place by a self-leveling clamp mechanism.

The plate (fig. 4A) aligns the parts of the clamping mechanism. The tightening screw (fig. 4B) on the translating bridge (fig. 4C) forces the self-leveling clamp (fig. 4D) into the tab holding block (fig. 4E). The self-leveling clamp accounts for variation in the tab geometry and tow sample thickness. A 20-N·m torque is applied with a wrench to ensure a consistent clamping force of ~14,000 N. The tabbed ends of the tow sample are constrained in the horizontal direction by a combination of friction and stop features on the front of the tab holding block (fig. 4F).

**FIG. 2**
Overview of the forming fixture assembly when mounted on a Mark-10 ESM303 (Mark-10 Corp. Copiague, NY) universal testing stand.
(A) Universal testing stand, (B) force gauge, (C) forming tool adapter, (D) removable forming tool, (E) sample holding assembly, (F) removable forming blocks, and (G) ball screw for span distance adjustment.
At elevated temperatures, the cyanoacrylate bond between the cardstock tab and the tow sample degrades, causing slippage and inconsistent test results. To address this issue, the tow sample material protruding from the back side of the cardstock tab is secured over a capstan and clamped on the back surface of the tab holding block. Testing efficiency and repeatability is further enhanced by the translation bridge, which can be quickly adjusted in the horizontal x-direction depending on the sample’s gauge lengths. The central channel machined in the sample holding assembly base (fig. 4H) constrains the tab holding block in the horizontal direction. The entire sample holding assembly exerts force only in the vertical direction, eliminating inconsistent and off axis loading of the sample tabs.

Accurate temperature control is another major requirement during testing because it directly relates to the viscosity and curing points of different resins and, therefore, to the formability of different fiber and resin combinations. Each forming block and the forming tool are equipped with a 250-W and a 125-W electrically resistive cartridge heater, respectively. The temperature is controlled by a Watlow (St. Louis, MO) proportional-integral-derivative (PID, part number PM6C1CA-EAAAPWP) controller coupled to a solid-state relay (SSR, part number
SSR-240-10A-DC1) that can switch the power to the 125-W (part number 2165-1904) and 250-W (part number E2A72-L12) cartridge heaters every three electrical cycles, or every 0.05 s. Each heated part is equipped with thermocouple probes (part numbers 20CJFGD036A and 40EJFGB036A) used for feedback and control of the PID system. This system allows for a temperature accuracy of ±1°C of the set value. The tow sample temperature is controlled through the contact with the heated top surface of the forming blocks and the heated forming tool (figs. 1 and 2). Figure 5 shows the cartridge heaters and the thermocouple probes installed in the forming fixture.

Figure 6 shows the complete assembly of the forming fixture equipped with the heating control unit.

Uniformity of temperature within the volume of the forming blocks, forming tool, and the tow sample are predicted by the Biot number (Bi). Bi is the ratio of heat flow resistance within a body caused by thermal conduction, to heat flow resistance at and above the surface of the body by thermal convection. The Biot number is given by the following equation:

\[ Bi = \frac{hL_c}{k} \]  

where \( h \) is the convective heat transfer coefficient (W m\(^{-2}\) K\(^{-1}\)), \( L_c \) is the characteristic length (m), and \( k \) is the thermal conductivity of the material (W mK\(^{-1}\)).

**FIG. 5**
Heating system installed in the forming fixture: (A) forming tool, (B) forming blocks, and (C) electrically resistive cartridge heater and thermocouple probes.

**FIG. 6**
Complete assembly of the forming fixture equipped with temperature control: (A) Mark-10 ESM303 (Mark-10 Corp. Copiague, NY) universal testing stand, (B) forming fixture, and (C) temperature control unit.
In the natural convection condition of the forming fixture, as would be experienced in a laboratory environment, the convective heat transfer coefficient $h$ is 5 W/(m$^2$·K). The forming blocks and the forming tool are made of 6061-T6 aluminum alloy with a thermal conductivity $k$ of 170 W/(m·K). Carbon fiber reinforced polymer (see “Test Method Implementation” section) was used as the tow sample. The thermal conductivity $k$ of resin impregnated carbon fiber is typically 0.8 W/(m·K). Table 1 lists $Bi$ calculated for the heated blocks, forming tool, and tow sample.

The temperature within the volume of the body is uniform when $Bi < 0.1$. The highest number in Table 1 is one order of magnitude smaller than the boundary value (0.1). Therefore, it can be considered that the temperature within the volume of the forming blocks, forming tool, and the tow sample is uniform. The forming blocks and the forming tool can be considered as thermal reservoirs because of their thermal mass (the product of the specific heat and the mass of the considered component), which is much larger than that of the tow sample. In steady state, the temperature of the tow sample is the same as the contacting component (forming block/tool) temperature. Heat transfer calculations estimated that the tow sample reaches steady state within 60 s; this response was also confirmed by thermocouple measurements. The short length (<50 mm) of the tow sample resting on the surface of the sample holder assembly is in proximity but not in physical contact with either of the heated forming fixture parts and a very small gradient (<2°C) may be observed in these locations. This temperature difference has a nonexistent or negligible effect on the resin viscosity. Therefore, the measured thermal gradient is not deemed sufficient to compromise test results.

The test starts with setting the desired span distance between the forming blocks by turning the ball screw. The span can be adjusted from 0 (blocks in contact) to 78 mm. The desired forming tool is then selected and attached to the load cell of the test stand equipped with the appropriate adaptor. To protect the load cell from overheating, a thermally insulative spacer made from polyether ether ketone polymer is used between the heated forming tool and the load cell. This insulation enables operation of the tool at a temperature up to 121°C without damaging the load cell. The prepared tow sample is set evenly across the forming blocks on the forming fixture. The tightening screw is then used to clamp the sample tow tabs; the tow sample material protruding from the back side of each tab is secured on the capstan and clamped on the back surface of the tab holding block. Once the specimen is secured and all other components are ready for testing and the steady state forming temperature is reached, the forming tool can be lowered into the starting position and the forming test can commence. Forming load and displacement data are collected using the Mark-10 MESUR Gauge Plus software.

**Test Method Implementation**

To validate the forming fixture setup performance, an experimental matrix consisting of 25 continuous carbon fiber reinforced polymer tows was designed. This section includes the description of the matrix, the tow sample fabrication process, test results, and discussion.

**TEST MATRIX**

Table 2 presents the test matrix for the forming fixture tow samples, categorized in five groups. Each group contains 5 replicates for a total of 25 samples identified by a code of “Cx-y.” “C” stands for “continuous” and “x” identifies the group number, whereas “y” identifies the sample number in each group.
TABLE 2
Experimental test matrix

<table>
<thead>
<tr>
<th>Number</th>
<th>Group</th>
<th>Fiber Type</th>
<th>Temperature, °C</th>
<th>Specimen IDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1</td>
<td>IM7-G</td>
<td>RT</td>
<td>C1-1, C1-2, C1-3, C1-4, C1-5</td>
</tr>
<tr>
<td>2</td>
<td>C2</td>
<td>IM7-G</td>
<td>57</td>
<td>C2-1, C2-2, C2-3, C2-4, C2-5</td>
</tr>
<tr>
<td>3</td>
<td>C3</td>
<td>IM7-G</td>
<td>82</td>
<td>C3-1, C3-2, C3-3, C3-4, C3-5</td>
</tr>
<tr>
<td>4</td>
<td>C4</td>
<td>IM7-G</td>
<td>107</td>
<td>C4-1, C4-2, C4-3, C4-4, C4-5</td>
</tr>
<tr>
<td>5</td>
<td>C5</td>
<td>IM7-G</td>
<td>121</td>
<td>C5-1, C5-2, C5-3, C5-4, C5-5</td>
</tr>
</tbody>
</table>

Note: Room temperature (21°C).

TABLE 3
Mechanical properties of tow sample constituents

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Carbon Fiber</th>
<th>Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>5,688 MPa</td>
<td>100 MPa</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>276 GPa</td>
<td>3,771 MPa</td>
</tr>
<tr>
<td>Elongation at failure</td>
<td>1.8 %</td>
<td>N/A</td>
</tr>
<tr>
<td>Approximate yield</td>
<td>2.24 m/g</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note: N/A = not applicable.

Table 3 presents the carbon fiber and resin mechanical properties as detailed in the manufacturer data sheets.30–32

Tow samples were tested in the forming fixture under the following conditions:

- 22-mm span distance between forming blocks
- 6.4-mm forming blocks radius of curvature
- 9.5-mm forming tool radius of curvature
- 21°C–121°C forming temperature range
- 6.4-mm/min loading rate
- Maximum drawing depth 51 mm

SPECIMEN FABRICATION

The fiber reinforced polymer composite tow samples were prepared using Hexcel (Stamford, CT) continuous IM7-G carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin. Prior to resin impregnation, precautions were taken to ensure that all fibers were aligned correctly, and no twists were present. After impregnation, the average volume fraction of the carbon fiber for a tow sample was 50±2 %. After the tow was impregnated with the resin, it was prepared for placement on computerized numerical control (CNC) routed cardstock tabs (32 by 19 mm). The tabs were adhered to the tow sample ends using a cyanoacrylate adhesive. Before testing, samples were clamped and left at room temperature for a minimum

FIG. 7  Schematic of the fiber reinforced polymer composite tow sample fabrication showing the cardstock tabs adhered to each end of the carbon fiber tows.
of 30 min to allow for complete curing of the adhesive. If the specimen was not tested immediately after preparation, it was stored in a freezer at −18°C to prevent the resin from cross-linking. Prepared samples measured 203 mm between the inside of the tabs were 7.6 mm wide and 0.25 mm thick. Figure 7 is an illustration of the tow sample fabrication.

Results and Discussion

In this section, data from the test matrix were collected and analyzed to determine testing reliability, tow sample forming behavior, and failure mode. All tow samples were prepared using the method proposed in this article and tested according to the conditions stated in the experimental matrix. Because experiments were conducted in the temperature range of 21°C–121°C, it is expected that the change in the resin viscosity will relate to the tow sample formability process. Table 3 presents the Huntsman (The Woodlands, TX) RDM 2019-053 resin viscosity values at the selected testing temperatures. Figure 8 displays tow samples after forming test at each selected temperature.

Complete failure (breakage) is observed only for the samples tested at room temperature (21°C, fig. 8A). The resin viscosity at room temperature is very high (>3,500 Pa·s) and leads to a composite material with increased shear resistance, which greatly decreases the formability, causing a clean break close to the middle region of the sample (fig. 8A).

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Viscosity, Pa·s</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>&gt;3,500</td>
</tr>
<tr>
<td>57</td>
<td>791</td>
</tr>
<tr>
<td>82</td>
<td>168</td>
</tr>
<tr>
<td>107</td>
<td>25</td>
</tr>
<tr>
<td>121</td>
<td>11</td>
</tr>
</tbody>
</table>

FIG. 8 Hexcel (Stamford, CT) continuous IM7-G carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin tow samples after the forming test at different temperatures. The lowest temperature, (A) RT, shows complete failure, whereas at elevated temperatures (B–E), partial failure is observed as sample cross-sectional thinning.
All samples tested at elevated temperature show partial failure visible as increased cross-sectional thinning from 57°C to 121°C (fig. 8B–8E). Because the viscosity decreases as the temperature increases (Table 3), the fibers can intertwine after failure inside the resin matrix resulting in the observed thinning.

The forming behavior of the tow samples is expressed as load versus displacement curves during the stretch drawing process (figs. 9A and 10). For all experiments, no slippage of the samples in the sample holding assembly was observed during testing.

Figure 9 shows the forming behavior of the tow samples tested at room temperature. It was observed that the load drops to zero after an average maximum forming of load of 850±29 N (fig. 9A) indicating rapid and complete failure of the tow.

Figure 9B shows how the designed forming fixture allowed for the observation of the sample failure in real time, confirming the mechanism of failure and the inability of the continuous fiber material to follow the contours of the tooling into drawn shapes or tight radii.

Figure 10 shows the forming behavior of the tow samples tested at temperatures of 57°C (fig. 10A), 82 °C (fig. 10B), 107 °C (fig. 10C), and 121 °C (fig. 10D). For all elevated temperatures, a primary peak, corresponding to the maximum forming load, is observed. It is then followed by a secondary peak related to the partial failure process of the fibers within the resin matrix. The secondary peak maximum load decreases from 57°C to 121°C proportionally to the resin viscosity (Table 3). The highest secondary peak values are observed for the tests conducted at 57°C (resin viscosity 791 Pa·s), whereas the lowest correspond to the tests conducted at 121°C (resin viscosity 11 Pa·s). The secondary peak load relates to the ability of the fibers to readjust or intertwine after failing, facilitated by lower resin viscosity.

Figure 11 shows the average maximum forming load for the forming of the tow samples in the 21°C–121°C temperature range. All tests conducted at elevated temperature resulted in a reduced average maximum forming load when compared to the room temperature tests.

From room temperature to 57°C, the forming load decreased 42 % from 850±29 N to 496±13 N. In the range 57°C–107°C, the forming load plateaus suggesting that the effect of the resin viscosity on formability is reduced.

FIG. 9 Load-displacement curves of Hexcel (Stamford, CT) continuous IM7-G carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin. Tow samples during stretch drawing at room temperature show failure as (A) rapid drop in the post-peak force versus displacement curves and (B) visual evidence of sample failure around the forming block. The clearance between the forming tool and each forming block was 1.25 mm and the sample tow thickness was 0.25 mm.
**FIG. 10** Load-displacement curves of Hexcel (Stamford, CT) continuous IM7-G carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin tow samples during stretch drawing at elevated temperature: (A) 57°C, (B) 82°C, (C) 107°C, and (D) 121°C.

**FIG. 11** Average maximum forming load of Hexcel (Stamford, CT) continuous IM7-G carbon fiber impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin tow samples during stretch drawing with increasing forming temperatures.
These results well agree with previous findings, which determined that the formability of carbon fiber thermo-setting composites was increased from room temperature to 100°C. An 8% increase of the forming load from 468±18 N to 506±29 N is observed between 107°C and 121°C. At 121°C, the very low resin viscosity (Table 3) allows the fibers to have an increased mobility within the resin matrix after failing. Under the applied load, failed fiber can intertwine creating a “yarn effect.” This phenomenon in turn can increase the overall tow sample strength, thus resulting in a modest increase in the forming load. This mechanism is well supported by figure 8E, where the smallest cross-sectional area is observed without breakage.

Design Recommendation

The fixture presented in this article offers extensive flexibility for the mesoscale investigation of the formability of fiber reinforced polymer composites. The data shown herein were collected for a single tow sample using the interchangeable forming blocks and a forming tool with a semi-cylindrical profile during uniaxial stretch drawing. The tabs used for manufacturing the tow samples were 19 mm wide and were held by a 20-mm channel within the sample holding assembly. However, part of the tailorability of the setup is that the geometry of each piece (forming blocks and forming tool) can be machined to best accommodate and reproduce the forming process of interest. Custom channel inserts were manufactured to accommodate different sample widths, replacing the one described in detail herein, without the need for any further modification within the holding assembly or the forming fixture. This design allows for clamping larger tabs and enables the testing of multi tow or prepreg samples up to 50 mm (about 6 tows) wide. The sample holding system also self-adjusts to the tow sample thickness. To take advantage of these features, future work will focus on the testing of multi tow and prepreg laminate to investigate the forming behavior of a composite material similar to those used in industrial tape laying machines. In particular, the deep drawing biaxial stretch response of fiber reinforced polymer laminate tape samples, manufactured with different fiber orientations, will be investigated using hemispherical forming tools.

Because the bonding state of the fiber/resin interface and the presence of voids are characteristics of the mesoscale, observations using microscopy will be performed after forming tests to better understand how defect development relates to forming conditions.

Conclusions

The forming fixture discussed in this article successfully evaluated the stretch drawing forming behavior of composite tow samples made from Hexcel (Stamford, CT) continuous IM7-G carbon fibers impregnated with Huntsman (The Woodlands, TX) RDM 2019-053 resin at several forming temperatures (21°C–121°C). Results showed consistency and repeatability as measured by the peak, post-peak, and force versus displacement curves during forming, demonstrating the viability of the forming fixture to evaluate composite forming at the mesoscale. Catastrophic failure was observed only for tow samples tested at room temperature, whereas samples tested at elevated temperature showed partial failure identified by cross-sectional area thinning. The proposed fixture aided in defining the forming behavior of the material in real time both visually (e.g., room temperature tow samples failure around the forming block) and in terms of forming load versus displacement curves. For elevated temperature testing, a primary peak corresponding to the maximum forming load was identified followed by a secondary peak that is related to the decrease of the resin viscosity when the temperature is increased. These results were used to establish novel forming metrics: such as the maximum drawing depth with no failure, the maximum forming load, and post-peak (secondary) loading behavior. These metrics can be used to compare forming behavior with different tooling geometries and selection of different fiber and resin formulations to match desired part and processing specifications.

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References


