CARBON FIBER COMPOSITE B-PILLAR REINFORCEMENT MANUFACTURING: AUTOMATED PREFORMING AND MOLDING

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Abstract

To reduce vehicle mass and increase fuel efficiency, carbon fiber composites are being considered for structural body components. As a demonstrator, a B-Pillar reinforcement was designed with continuous carbon fiber prepreg as the material system. Preforming of the carbon fiber prepreg is a critical and often overlooked processing step. It involves three dimensional forming and trimming of ply layups, which is performed in situ resulting in net shape preforms. It is vital the preforms maintain dimensional stability, without post-forming deformation, to allow for subsequent compression molding of the final component. To ensure dimensional stability, key processing parameters must be understood. To support this development, a transient heat transfer model was developed and experimental verification will be presented. The automated preforming and compression molding processes for the B-pillar reinforcement will also be presented and discussed.

Preforming Shape Retention Study: Double Dome Geometry

Introduction

It is generally accepted that preforming is perhaps the most critical step in the manufacture of carbon fiber composites. The preforming process involves transforming two dimensional ply layups into net shape, three dimensional components for compression molding. To conduct experimental preforming trials, a combination forming and trimming tool of the double dome geometry was used (Figure 1). Three dimensional forming of the two dimensional ply layups was achieved using matched metal tooling. The tooling incorporates a draw ring to control material flow during forming and a shear edge to perform trimming when forming is completed (Figure 1).

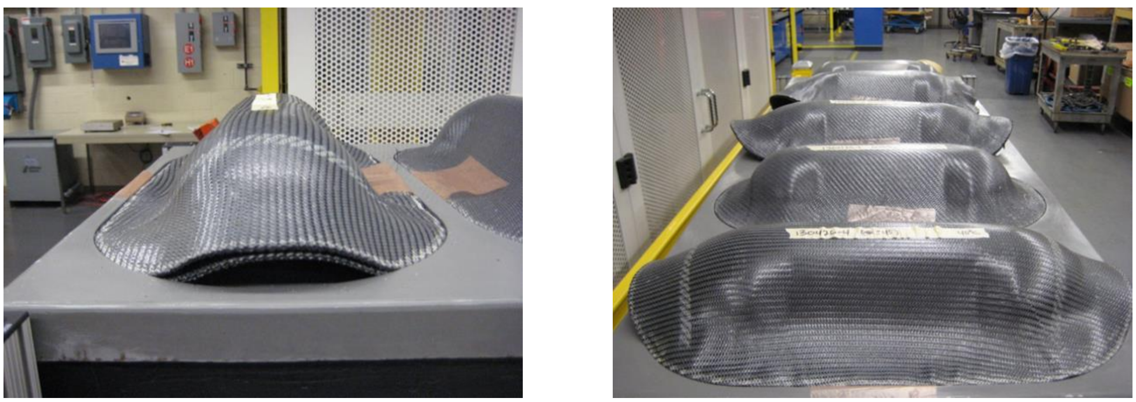
Prepreg materials utilized in these experiments exhibit an uncured glass transition temperature (T_g) above room temperature. This is required to minimize material tack for other aspects of processing. This also necessitates preheating of the material prior to forming in order for the material to be preformed and maintain shape following forming. Figure 2 shows a preheated two dimensional ply layup placed on the draw ring of the double dome preforming tool. The press is then closed and the cavity half forms the two dimensional blank over the core half and subsequently trims the part to net shape. Upon opening of the press, the formed part along with the trim offal is ready for removal (Figure 3).

As the particular resin formulation in the hot melt prepreg had not yet been tested, preliminary forming trials were conducted. Resultant post-forming shape dimensional instability necessitated experimental preforming trials using a designed experiment to determine the critical processing parameters.

Figures 1,2,3: Double dome preforming tool (1), with two dimensional ply layup (2) and following forming and trimming (3)

Preforming Process Experiments: Hot Melt Prepreg System

Double dome preforming trials using the Dow P6300 prepreg material (670 g/m^2 2x2 twill fabric) were unsuccessful when using processing parameters previously developed for a similar resin system. The preforms would not maintain shape while fully constrained in the holding fixture immediately following forming. Additionally, an extended post-forming dimensional instability occurred following several days in the fixture (Figures 4 and 5).



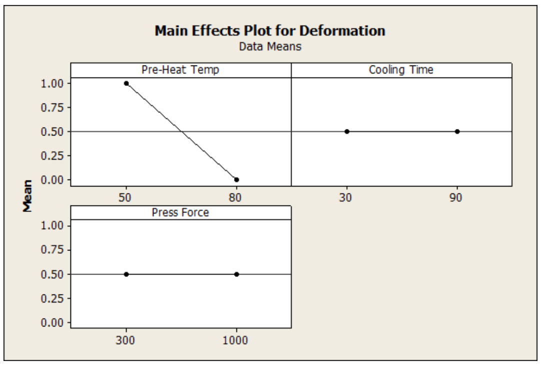
Figures 4,5: Double dome preforms exhibiting post-forming dimensional instability while in holding fixture

A designed experiment was performed to determine the preforming factors which affect post-forming dimensional instability (Table 1). The ply layup was $[(0/90)]_{2s}$ with the two dimensional blank geometries being previously determined via Siemens Fibersim software. Processing factors were press force, cooling time following forming, and the preheat temperature of the prepreg. The qualitative response was whether post-forming dimensional instability was present immediately following forming and after one day in the holding fixture.

Table 1: Preforming process designed experiment

Designed Experiment		
Factor	-	+
Press Force (kN)	300	1000
Cooling Time (s)	30	60
Preheat Temperature (°C)	50	80

Despite cooling time and press force being insignificant factors with respect to post-forming dimensional instability, this still yields useful processing information. Press force need only be great enough to allow trimming of the material and additional force, within the range examined, is not required to achieve shape retention and eliminate post-forming dimensional instability. As cooling time was also insignificant, the cycle time could potentially be reduced although additional experimentation would be required to verify this limit of the experimental boundary. The preheat temperature of the ply layup was determined to be the only significant factor relative to shape retention and post-forming dimensional instability (Figure 6). The higher preheat temperature of 80°C led to no dimensional instability of the preform. All preforms with a preheat temperature of 50°C exhibited post-forming dimensional instability immediately following forming.



Figures 6, 7: Main effects plot for post-forming dimensional instability (6), double dome preform exhibiting no post-forming dimensional instability from a preheat temperature of 65°C (7)

However, a preheat temperature of 80°C created handling issues due to increased resin tack and reduced blank stiffness. This was deemed potentially problematic for automated robotic handling of the prepreg blanks. Hence, the midpoint preheat temperature of 65°C along with the midpoints of both cooling time and press force were examined. These processing conditions yielded no dimensional instability following forming along with improved prepreg handling characteristics. To be sure, the double dome preform exhibited no post-forming dimensional instability following 12 days in the holding fixture (Figure 7).

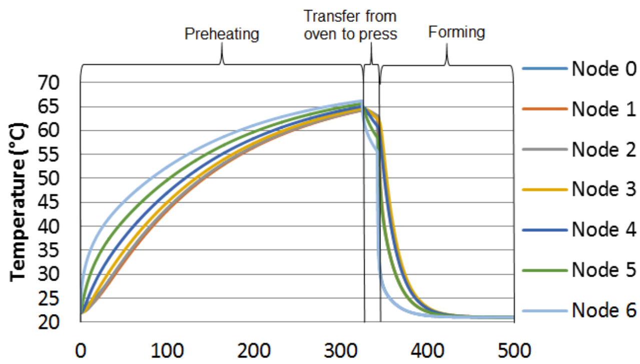
Preforming Transient Heat Transfer Model

Introduction

The previous section concluded that a significant factor for shape retention after preforming was preheating temperature. Knowing this information, it was important to understand how oven temperature and preheat duration changes with varying prepreg systems to achieve optimal forming. Preheat duration was highly variable based on factors such as ply areal density, number of plies, thermal properties, fiber resin ratio, etc. Instrumentation using thermocouples can generate the necessary heating and cooling data for various prepreg systems but a predictive tool was deemed necessary to minimize the required experimentation. The intent was to gain insight into the heating and cooling processes during the following preforming steps: preheating, material transfer to forming tool, and preforming.

Heat Transfer Model Development

During preforming the material experienced transient heating, the temperatures were discretization points in time as well as space (i.e. nodes). Using enough nodes provided a clear understanding of temperature variation through the thickness of the material. The nodal temperatures were calculated using the explicit method.



Figures 8,9: Cross-section view depicting nodal spacing (8), transient heat transfer model output for the preforming process using six nodes (9)

The process included convection and conduction heating. The first portion of the model represented the material preheating phase. The exterior nodes experienced convection heating and the interior nodes experienced conduction heating. The second portion of the model represented the material being transferred from the oven to the preforming tool. This step experienced the same modes of heat transfer as the previous step. The final portion of the model represented the material being formed in a steel tool at ambient temperature. All of the nodes were subjected to conduction heating during this step.

Experimental

Convection Oven Air Velocity

As the preheating process occurred in a convection oven, the exterior nodes of the material were subjected to convection heating. Hence, the air velocity inside the oven was required for the heat transfer model. The oven was configured with a holding fixture consisting of four preform ply racks (Figure 10).

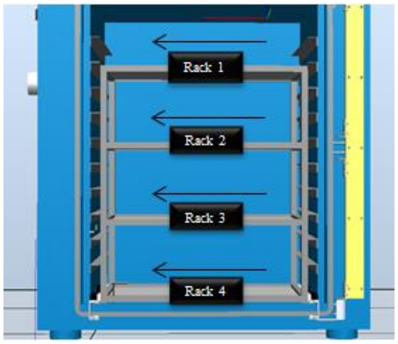


Figure 10: preheating convection oven layout

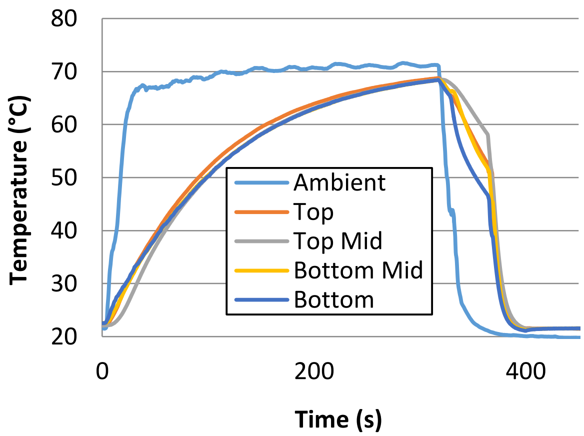
Velocities were measured at three locations on each of the four racks; near the right edge, the center, and near the left edge. Air velocity was measured at the preheating temperature of 70°C using a one inch vane anemometer. The air velocity was found to be approximately 3 m/s throughout the oven (Table 2). Based upon the low range of the data, this was deemed suitable for use in the heat transfer model.

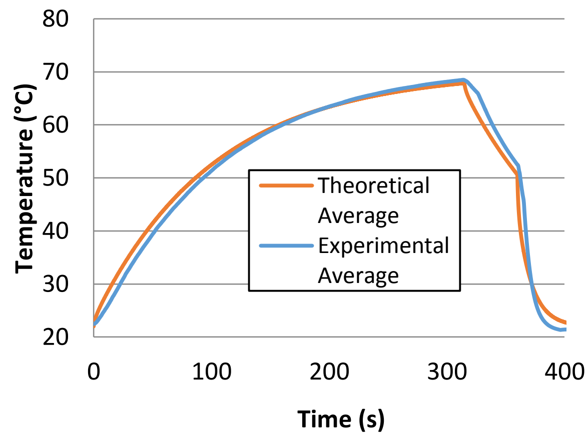
Table 2: Convection oven air velocity (m/s)

Air Velocity				
	Rack 1	Rack 2	Rack 3	Rack 4
Left	3.06	2.89	2.92	2.90
Center	3.05	2.96	2.90	2.87
Right	3.03	2.90	2.99	2.86

Ply Layup Heating and Cooling Trials

The temperature of a three ply layup was experimentally determined for model validation. The material used was a 670 g/m^2 twill carbon fiber epoxy prepreg with a fiber volume fraction of 53%. Four thermocouples were placed within the ply layup dispersed between the plies and on the exterior surfaces. An additional thermocouple was used to collect ambient temperature. The data was collected via a NI-DAQ™ system using Labview™ software. The part was placed in the convection oven set to 70°C and was heated until the midplane temperature reached 67°C. The material was then removed from the oven and transferred to the preforming tool. A 30 second preforming cycle was performed with a tooling surface temperature of 22°C. The press did not apply the typical forming/trimming force due to the thermocouples within the ply layup. The preforming tool contains a shear trimming edge that would have damaged all of the thermocouples. The experimental temperature data can be found in Figure 11.





Figures 11, 12: Thermocouple trace of a three ply carbon fiber epoxy prepreg preforming cycle (11) and a preforming cycle comparison of a four nodal average between theoretical temperature and experimental temperature (12)

Model Validation

The heat transfer model compared to the experimental thermocouple data can be seen in Figure 12. The data represents the heating and cooling of the prepreg layup used in the previous section. For clarity, the graph shows an average of four nodes from each of the outputs. Good correlation can be observed between experimental data and predicted results (Table 3).

Nodal temperature data from the heat transfer model was compared to the experimental data at given times during the process. The time examined was at the end of each process stage. Since a three ply layup was used, four nodes were chosen for comparison with the experimental thermocouple data (Table 3).

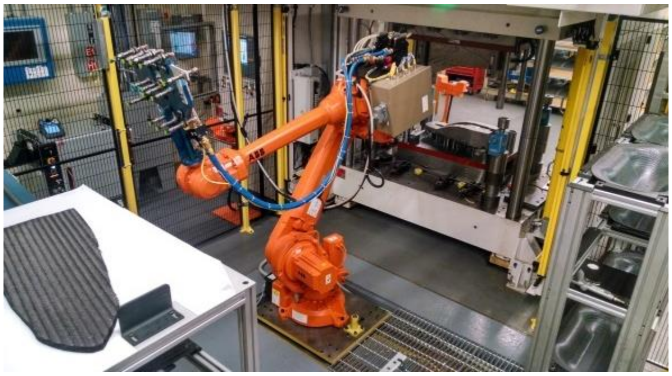
Table 3: Preform temperature comparison between experimental and theoretical data

Heating data: theoretical versus experimental					
Node	**Process Stage**	**Time (s)**	**Nodal Temperature (°C)**		**Difference (°C)**
			Heat Transfer Model	**Experimental**	
0	Preheating	315	67.8	68.7	0.9
	Transfer	360	53.6	53.0	0.6
	Forming	400	22.4	21.6	0.8
1	Preheating	315	67.2	68.5	1.3
	Transfer	360	53.3	58.3	5.0
	Forming	400	23.2	21.5	1.7
2	Preheating	315	67.9	68.4	0.5
	Transfer	360	50.1	51.8	1.7
	Forming	400	23.2	21.3	1.9
3	Preheating	315	68.3	68.4	0.1
	Transfer	360	45.5	46.7	1.2
	Forming	400	22.4	21.2	1.2

As the data suggests, good agreement was obtained when comparing the transient heat transfer model output to the experimental data. One outlier is seen at Node 1 during the transfer stage, the maximum difference between the model prediction and the experimental data was 5.0°C. At Node 1 the experimental study yielded good correlation during the preheating and forming stages (1.3°C and 1.7°C, respectively). It is believed that during the manual transfer process from the oven to the preforming tool the thermocouple was disrupted and then repositioned when forming force was applied.

B-Pillar Reinforcement: Automated Manufacturing

The prepreg preforming and compression molding process was performed within an automated robotic cell (Figure 13). The preforming process started with ultrasonically stitched layups stacked on a nesting fixture. At the designated time the robot moved a layup from the nesting fixture into the preheating oven. The preheating oven consisted of four potential locations having an automated door that opened and closed as the robot was entering and exiting the oven. Timing was optimized to achieve the highest throughput rates such that when a layup reached the designated preheating time the robot moved the part to the preforming tool. Once the robot cleared the light curtain the press initiated the forming process. When forming was completed the press opened and the robot moved both the preformed part and the trimmed offal to a conveyer that exited the system. The preformed parts were stored on a holding fixture awaiting the molding process (Figure 14).

Figures 13, 14: Automated manufacturing cell for B-pillar fabrication (13), B-pillar preform holding fixture (14)

The molding process had a holding rack for the preformed parts within the automated cell. The robot pick and place system transferred a preformed part into the molding tool. Once the robot cleared the light curtain the press initiated the molding process. If the part utilized discontinuous reinforcements, the robot would pick the discontinuous material with the preformed part for a co-molding process. Once the molding cycle was completed the robot moved the molded part onto a conveyer that exited the cell and the part was ready to be deflashed.

B-Pillar Reinforcement: Two Dimensional Blank

The preforming process started with a two dimensional geometry that was formed and trimmed into a three dimensional net shape preform. For initial forming trials, two dimensional blanks were cut oversized to ensure sufficient material was present to form and trim the part. This can lead to increased material deformation and wrinkling of plies. A preliminary blank geometry was determined using Siemens Fibersim. The analysis output allows for a kinematic view of forming and produces a two dimensional blank geometry for the three dimensional part. The material database did not include triaxial material so three different unidirectional studies were performed; 0º, 60 º, -60 º. The results were combined by overlapping the three blank geometries and combining the outermost portions to form one part producing an estimated two dimensional blank geometry. The blank geometry was extended to allow material to be constrained during preforming by the draw ring and trimmed. The blank geometry was further optimized by digitizing a flattened non-crimp fabric (NCF) and braid preform.

B-Pillar Reinforcement: Preforming

The B-pillar preforming process used tooling similar to that of the double dome preforming tool (see Preforming Shape Retention Study: Double Dome Geometry). During the preforming process the blanks were formed and trimmed in situ resulting in a net shape preform ready for the molding process. The B-pillar preforming studies focused on two different fiber architectures: a triaxial NCF (590 g/m^2) and a triaxial braided fabric (733 g/m^2). The ply layup for the NCF and braid were $[(0/\pm60)_s]_3$ and $[0/\pm60]_5$, respectively.

Figures 15,16,17: B-pillar preform tool with braided material prior to forming (15), post-forming (16), and a preformed NCF B-pillar with offal (17)

Table 4: B-pillar fiber architectures

Materials		
Sample		
Reinforcement	Triaxial braid (0/-60/60) (50%/25%/25%)	Triaxial NCF (0/-60/60) (50%/25%/25%)

Based on the transient heating model, discussed in the previous section, preheating and preforming times were calculated for the layups based on an oven temperature of 80°C and a preform tool temperature of 22°C. The timing was based on the ply layup's midplane temperature of 65°C. The model assumes an 18 second transfer time from the preheating oven to the forming tool. The NCF layup preheating and forming times were found to be 415 seconds and 52 seconds, respectively. The braid layup preheating and forming times were found to be 495 seconds and 77 seconds, respectively. The preforming tool was not plumbed for cooling resulting in an increase in tool surface temperature as more cycles were run. The preforming time was set at 120 seconds to ensure the desired part temperatures would be reached as tool temperature increased.

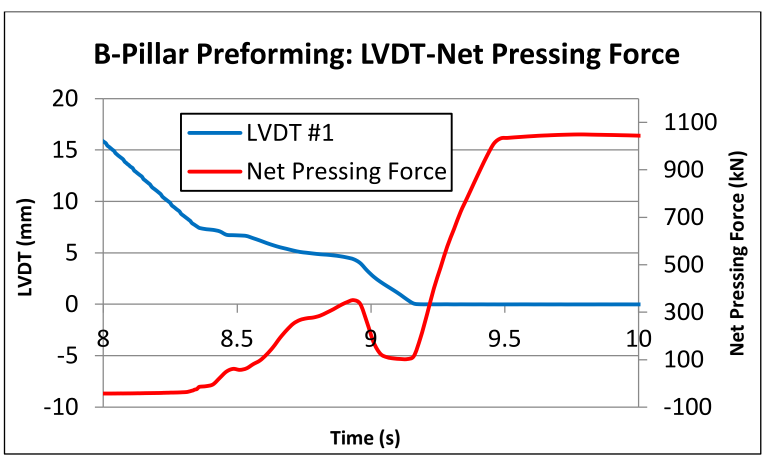


Figure 18: The trimming portion of a B-pillar preform cycle

When preforming was initiated the press was controlled by a velocity profile. As the tooling came into contact with the material, constant velocity could not be maintained and the press switched to the force profile. Figure 18 shows tool positioning and press force. At ~8.3 seconds the switch from velocity to force profile can be observed. The initial force profile builds irregularly due to material forming and trimming. At ~9 seconds the material is trimmed and the force builds to the set point of 1000kN.

B-Pillar Reinforcement: Molding Process Parameters

After the part is preformed it is ready for the compression molding process. The molding tool was set at 150ºC to achieve a 180 second cure time. The molding process begins with a 250kN holding force to allow the resin viscosity to increase. Once the designated time has been reached the force increases to 1000kN for the remainder of the cycle. The tool contains molding sensors that include a pressure transducer, dielectric sensor, and a thermocouple. Figure 19 shows pressure and dielectric histories during molding. The dielectric data shows material impedance during molding, an indicator for the rate of cure.

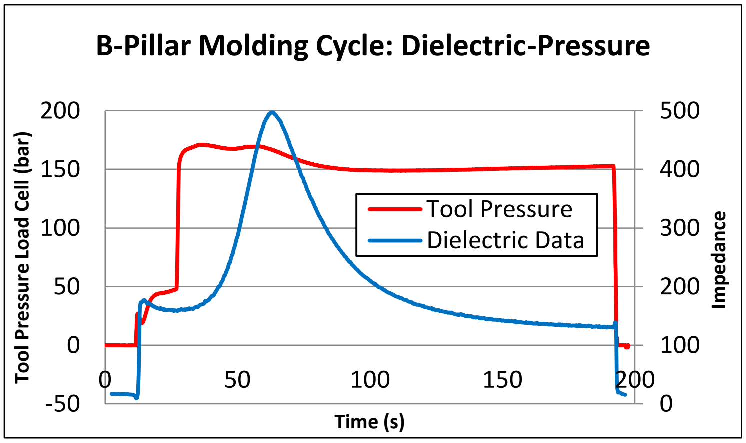


Figure 19: A B-pillar molding cycle showing molding pressure and dielectric data

Summary

Preforming of carbon fiber prepreg material is a critical and often overlooked processing step. It is vital the preforms maintain dimensional stability, without post-forming deformation, to allow for the subsequent compression molding step of the final component. To ensure dimensional stability, a designed experiment was performed and material preheat temperature was found to be a key processing consideration. To support this development, a transient heat transfer model was developed and experimental verification was presented. An overview of the automated preforming cell was described. The two dimensional blank geometry used for preforming was investigated to increase material utilization. Once the blank geometry and preheating were understood, the B-pillar reinforcement underwent the preforming process where a two minute cycle time was demonstrated. The preformed part was then molded, where a three minute cycle time was demonstrated.

References

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