

Modeling and Simulation of Compression Molding Process for Sheet Molding Compound (SMC) of Chopped Carbon Fiber Composites

Yang Li
Ford Motor Company

Zhangxing Chen
Chongqing University

Hongyi Xu, Jeffrey Dahl, and Danielle Zeng
Ford Motor Company

Mansour Mirdamadi
Dow Chemical Company

Xuming Su
Ford Motor Company

ABSTRACT

Compression molded SMC composed of chopped carbon fiber and resin polymer which balances the mechanical performance and manufacturing cost presents a promising solution for vehicle lightweight strategy. However, the performance of the SMC molded parts highly depends on the compression molding process and local microstructure, which greatly increases the cost for the part level performance testing and elongates the design cycle. ICME (Integrated Computational Material Engineering) approaches are thus necessary tools to reduce the number of experiments required during part design and speed up the deployment of the SMC materials. As the fundamental stage of the ICME workflow, commercial software packages for SMC compression molding exist yet remain not fully validated especially for chopped fiber systems. In the present study, SMC plaques are prepared through compression molding process. The corresponding simulation models are built in Autodesk Moldflow with the same part geometry and processing conditions as in the molding tests. The output variables of the compression molding simulations, including press force history and fiber orientation of the part, are compared with experimental data. Influence of the processing conditions to the fiber orientation of the SMC plaque is also discussed. It is found that generally Autodesk Moldflow can achieve a good simulation of the compression molding process for chopped carbon fiber SMC, yet quantitative discrepancies still remain between predicted variables and experimental results.

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INTRODUCTION

Recent development of lightweight vehicle favors materials with high stiffness-to-mass ratio, among which carbon fiber composites are one of the intuitive options. While polymer reinforced with continuous carbon fiber shows great performance as has been reported widely, significant material cost and limited formability hesitates their application in automobile industry. Alternatively, chopped carbon fiber composites produced via SMC compression molding approach present a more balanced solution with lower cost and better formability and thusly gain increasing focus in recent years. However, due to the random fiber distribution in the SMC chopped carbon fiber composites, remarkable inhomogeneity and anisotropy are commonly observed which pose challenges to the design of parts

using such type of material. Moreover, these material behaviors are closely related to the processing conditions during compression molding process and thus also sensitive to variations during molding, which amplifies the difficulty in predicting the material properties in the molded parts. Traditional trial-and-error practices during part design are therefore inevitably accompanied with large testing matrix to consider all the factors that can lead to the various part performance, which is obviously cost inefficient. ICME approaches, aiming at replacing unnecessary tests with simulations to reach an optimal design, are therefore favored during the development of the SMC chopped carbon fiber composites.

As an essential part of the ICME approach, modeling and simulation of the manufacturing process are utilized to provide microstructure information which is required to determine the local material properties in the macroscopic performance simulations. Although the application of chopped carbon fiber composites are relatively new in automobile industry, studies of the SMC compression molding can actually date back to several decades ago. [1, 2, 3, 4, 5] Among one of the pioneering efforts, Barone and Caulk [1, 2] conducted the compression molding tests on SMC made with resin as matrix and chopped glass fiber and calcium carbonate as filler phase. Deformation of the initial charge was also modeled by considering the resistance of the material against extensional deformation during the compression molding which was determined by temperature distribution in the cavity. [2] To simulate the flow pattern during SMC compression molding process, different models based on finite element method were developed by a number of researchers, including Lee and Tucker [6], Osswald and Tucker [7], Lee et al. [8], Liang and Tucker [9], Lin and Weng [10], Youn and Lee [11], Dumont et al. [12], to name a few. Apart from filling simulation, prediction of press force during SMC compression molding was also discussed by Kau and Hagerman [4], Castro and Tomlinson [13], Abrams and Castro [14] and Dumont et al. [12]. As the material properties of the molded SMC parts were significantly influenced by the fiber orientation distribution throughout the parts, fiber orientation models were also developed and coupled with flow field predictions, as seen in Jackson et al. [15]. Later on Advani and Tucker [16, 17] proposed orientation tensor based formulation to describe the distribution of fiber directions within the composites, which bridged the random nature of the fiber directions and the deterministic flow field prediction. Soon enough, this formulation was widely accepted as one of the most popular methods to describe the fiber orientations. Researches were conducted to further improve the numerical details of the orientation tensor formulation [18, 19] as well as the governing equations in the proposed orientation model. [20, 21, 22] Despite the fact most of these works were performed in the scenario of injection molding problems, they usually remained applicable in the compression molding simulations with reasonable accuracy. Commercial software packages have also been developed to provide integrated solution to simulate the compression molding process for SMC composites, for example, Autodesk Moldflow and Moldex3D, which are greatly helpful for the manufacturing engineers to design the process in details without the need of running through trial-and-error approaches.

In the traditional SMC material, however, usually is the case that glass fiber or glass fiber bundles are selected as the filler phase. Carbon fiber in the form of thin chips chopped from continuous fiber tows is rarely seen as the reinforcing material in the composites in the previous studies. To the best knowledge of the authors, as for the SMC made with chopped carbon fiber chips, the validation on the major outputs from the compression modeling and simulation, i.e., filling pattern, press force/displacement of the molding machine and the fiber orientation in the composites, has not been adequately discussed in the literature. With the decreased fiber diameters and stronger anisotropic material behavior brought by the carbon fiber fillers, whether or not the previous models can directly fit into the scheme remains to be examined. As a preliminary study to understand the SMC molding process and examine the validity of models used in

simulation of SMC compression molding, the authors performed trial molding experiments to produce plaques parts for testing use. The press force data collected from the molding machine is then compared with the predictions via a model built in Autodesk Moldflow. Furthermore, to evaluate the anisotropy of the elastic properties of the material, tensile tests were performed on the coupons cut from selected locations of the plaques along different directions. A procedure to combine the fiber orientation prediction with a structural finite element analysis (FEA) was developed to perform virtual DIC tensile test on the parts, similar to the methodology we present previously for injection molded parts. [23] Comparison between results of the DIC tensile test and the simulated test in FEA was then used as an indirect measure of the effectiveness of fiber orientation prediction.

In the following sections, the experimental information of was first introduced, followed by the configuration of SMC compression molding simulation in our Moldflow models. The results from the experiments and simulations are then compared to evaluate the capability and limitation of the current models. Discussion on the results and future works are then summarized.

EXPERIMENTS

Material

SMC initial charges were made with uncured resin, curing agent and chopped carbon fiber chips, all provided by Dow Chemical Company. The average cross section of the chips in the initial charge is approximately 3mm x 0.1mm and the average length of the chips is 1.0in. To form the initial charge, chips were chopped from carbon fiber tows with resin and cured agent already dipped on, and then randomly spread to the uncured resin mat and compressed to plaques with planar dimension of 12in x 12 in and thickness of roughly 2mm covered with plastic film. The initial charges were stored in refrigerator to prevent curing before molding.

Compression Molding of SMC Plaques

The compression molding of the SMC plaques was carried out in lab scale molding facility at Ford Motor Company. The maximum press force of the machine is 2500kN. Press speed profiles, press force, in-mold temperature and switch criteria from speed to force control can all be programmed in the user interface of the molding machine. Different press speed and force conditions were tested while molding temperature was kept as 150°C for all the samples. Zero point of molding time, t , was defined as the moment when press contacts the initial charge. The processing parameters are listed in Table 1 while the press speed profiles used in the experiments are listed in Table 2. Force values were set in the machine for $t = 0s$ and $t > 1s$. During each experiment, press speed increased continuously with press position, following the preset values interpolated from Table 2. Once the force required for maintaining the press speed went beyond the force curve interpolated from Table 1, the machine automatically switched from speed control to force control till the end of curing stage. The plaques were then taken out of the cavity and cooled on a steel plate. The actual press force history was recorded from the machine, and later extracted to compare with prediction results.

Table 1. Processing parameters tested in the compression molding experiments. t is the molding time which is defined as 0s when press contacted the top surface of the initial charge.

Experiment #	Press Speed Profile	Press Force at $t=0s$ (kN)	Press Force at $t>1s$ (kN)
1	I	0	0
2	II	0	0
3	II	0	0
4	II	0	250
5	II	0	125
6	II	0	500
7	II	0	1000
8	II	250	1000
9	II	250	500
10	II	0	1500
11	II	0	1500
12	II	0	1500

Table 2. Press displacement profile I and II used in the compression molding test.

Step	Press Speed Profile I		Press Speed Profile II	
	Press-Cavity distance (mm)	Press Speed (mm/s)	Press-Cavity distance (mm)	Press Speed (mm/s)
1	200	75	100	50
2	50	25	50	25
3	25	15	10	10
4	15	5	5	5
5	0	1	0	1

The setup of the initial charges in the cavity is shown in Figure 1. The initial charges were cut from 12in x 12in plaques into 6 in x 6 in quadrants. 4 pieces of such quadrants were piled up together and placed at the center location of the 12in x 18in cavity. If fully filled, the expected plaque thickness is 1.2mm. To ensure the fiber orientations in the initial charge piles were as close to 2D random as possible, the 4 quadrants were cut from the same larger plaque and rotated by 0/90/180/270° when placed into the mold.

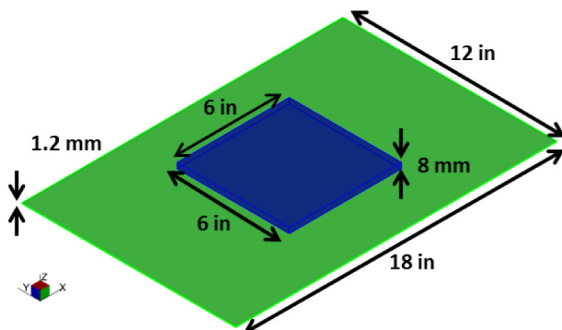


Figure 1. Dimension of the part (green) and initial charge (blue) which is located in the center position of the part.

With the mold temperature set as 150°C, the crosslinking of the resin happened quickly during the compression molding. Consequently the viscosity built up which provided resistance for the initial charge to fill in the cavity. If the press speed profile was not fast enough or the press force was not high enough, the initial charge could not fill in the whole cavity and produced the unfilled pattern when curing stage was over. For experiments #1~5, we observed the unfilled plaques, while for experiments #6~12, the plaques were all fully filled. The unfilled patterns and an example of fully filled plaque are shown in Figure 2.

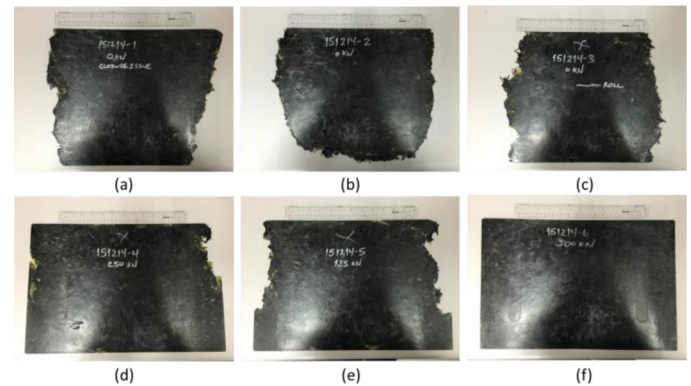


Figure 2. Examples of plaques obtained from the compression molding experiments. The patterns from experiment #1~6 are shown in (a)~(f) respectively.

DIC Tensile Test

In order to examine the mechanical properties of the SMC composites and check the fiber orientation distribution, the tensile tests were performed on the fully filled plaques. As the processing conditions could largely vary the material properties, plaques molded in experiment #10~12 were selected to provide tensile test coupons as they shared the same processing conditions. The schematic of coupons cut from the plaques is shown in Figure 3. The in-plane dimension of the tensile test coupons was chosen as 8in x 1in following an ASTM-D3039 testing standard. 5 locations, A~E, as shown in Figure 3, were chosen as the center locations of the coupons. On each of the selected center locations, coupons aligning along 0°, 45° and 90° directions were cut. Due to the limited plaque dimension, only the coupons aligned in the same direction could be obtained from the same plaque and 2 of the coupons, i.e. C-0 and B-0, were with decreased length (6 in). The 0°, 45° and 90° coupons were on plaque #10, #12 and #11, respectively. The tensile tests of the coupons were done on MTS tensile test frames, with the strain captured by DIC (Digital Image Correlation) system from GOM. The tests were conducted under displacement control with the loading speed as 5mm/min.

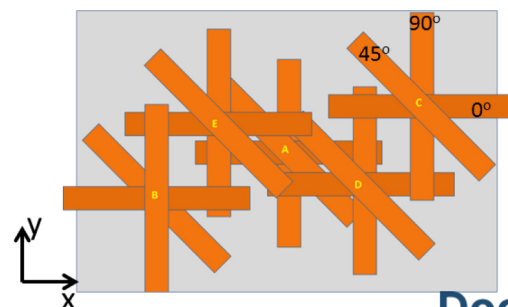


Figure 3. Schematic of the tensile coupon positions in plaque #10~12.