

Finite Element Simulation of Compression Molding of Woven Fabric Carbon Fiber/Epoxy Composites: Part I Material Model Development

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ABSTRACT

Woven fabric carbon fiber/epoxy composites made through compression molding are one of the promising choices of material for the vehicle light-weighting strategy. Previous studies have shown that the processing conditions can have substantial influence on the performance of this type of the material. Therefore the optimization of the compression molding process is of great importance to the manufacturing practice. An efficient way to achieve the optimized design of this process would be through conducting finite element (FE) simulations of compression molding for woven fabric carbon fiber/epoxy composites. However, performing such simulation remains a challenging task for FE as multiple types of physics are involved during the compression molding process, including the epoxy resin curing and the complex mechanical behavior of woven fabric structure. In the present study, the FE simulation of the compression molding process of resin based woven fabric composites at continuum level is conducted, which is enabled by the implementation of an integrated material modeling methodology in LS-Dyna. Specifically, the chemo-thermo-mechanical problem of compression molding is solved through the coupling of three material models, *i.e.*, one thermal model for temperature history in the resin, one mechanical model to update the curing-dependent properties of the resin and another mechanical model to simulate the behavior of the woven fabric composites. Preliminary simulations of the carbon fiber/epoxy woven fabric composites in LS-Dyna are presented as a demonstration, while validations and models with real part geometry are planned in the future work.

CITATION: Li, Y., Zhao, Q., Mirdamadi, M., Zeng, D. et al., "Finite Element Simulation of Compression Molding of Woven Fabric Carbon Fiber/Epoxy Composites: Part I Material Model Development," *SAE Int. J. Mater. Manf.* 9(3):2016, doi:10.4271/2016-01-0498.

1. INTRODUCTION

Among the candidates of light weighting materials for automobile uses, woven fabric carbon fiber/epoxy composites are widely considered to be one of the most promising options because of their superior stiffness-to-density ratio. Previous studies on the performance of the woven fabric carbon fiber/epoxy composites made through different procedures have shown that the properties of such material system highly depend on the processing conditions [1, 2, 3]. Delicate design of the processing procedure can not only produce parts with few defects and higher quality, but also lead to a significantly reduced cycle time. Both of these outcomes are highly valued during the mass production in automobile industry which

stimulates the advancements and innovations in the processing technology in recent years. However, traditional trial-and-error procedures can hardly fit into the current research and development scheme due to their low efficiency and high cost. Alternatively, modeling and simulation techniques are paid more attention to in the studies of how the processing conditions can affect the final performance of the material.

Multiple types of processing techniques for woven fabric carbon fiber/epoxy composites are currently being intensively studied by the automobile OEMs and academia, including resin transfer molding (RTM), resin infusion molding (RIM) and compression molding. While pros and cons of these technologies have been discussed

elsewhere [4], compression molding remains appealing due to the following advantages: shorter cycle time, higher limit on the fiber weight fraction and better stiffness and strength. A typical compression molding process is composed of two stages: 1) preforming of the woven fabric prepreg and 2) resin curing while being pressed. Simple and straightforward as it may seem, simulation of the compression molding is a challenging problem as multiple types of physics are involved, *i.e.*, woven fabric micromechanics, resin property changing during curing and viscoelastic deformation mechanism of the resin. Previous studies have been focused on exploration of these physics on separated base and providing isolated solutions for each perspective of the problem. For example, there are extensive discussions over the micromechanics of the woven fabric structure. Different models have been established by Ishikawa and Chou [5], Naik and Shembakar [6], Chung and Tamma [7], Witcomb [8], Peng and Cao [9], Tabiei and Jiang [10], and Ivanov and Tabiei [11]. On the other hand, the curing kinetics of the epoxy resin have been studied by Kamal and Sourour [12], while the models that aims at predicting the change of viscoelastic properties of the resin have been provided in DiBenedetto [13], Pascault and Williams [14], Hale *et al.* [15], which considers the T_g change. There are also works to forecast the influence of the curing degree to the polymer modulus in the framework of generalized Maxwell models, including O'Brien *et al.* [16], Menzel [17], Eom *et al.* [18], and Patham [19]. Despite the fact that insight has been obtained towards the physics involved, there is little effort on utilizing and integrating these models to provide a complete solution to the simulation and modeling of the compression molding on woven fabric carbon fiber/epoxy composites to the best knowledge of the authors of this paper, which creates difficulties for the researchers to achieve a modeling toolset with which the process design can be tested and optimized using simulation methods. Integrated computer aided engineering (CAE) solution for chopped carbon fiber sheet molding compound is provided by a number of the suppliers, including Moldflow by Autodesk and Moldex3D by CoreTech System, in which the resin is regarded as flow with viscosity changing with curing reaction. Yet for the compression molding of woven fabric composites with continuous carbon fiber, the material flow is rather constrained which deviates from the assumption in Moldflow and Moldex3D. An integrated software suite for molding of different types of continuous fiber composites is also available in PAM-FORM and PAM-DISTORTION developed by ESI. However, the integration of the multidisciplinary physics only occurs after the simulation of an individual forming stage is fully completed. For example the curing prediction must use the final output of the preforming stage to as geometric and historical input. The interplay between different types of physics is not considered at a single time increment, which limits the effectiveness of the multiphysics solution.

Recently a collaborative effort between Ford Motor Company, LSTC, The Dow Chemical Company and other partners has been casted in order to provide a systematic solution for the simulation of carbon fiber/epoxy composites made with compression molding technique within the framework of integrated computational materials engineering (ICME). As part of the project, we develop an integrated material model capable of handling the multiphysics problem in the compression molding of woven fabric carbon fiber/epoxy composites. This model targets at consideration of multidisciplinary integrated physics taking place during compression molding in the meantime,

including the curing degree, chemical shrinkage, thermal expansion and the stiffening of the resin during curing process, and the mechanical behavior of the woven fabric carbon fiber. As a continuum material model, the homogenization between the resin matrix and the woven fabric fibers is performed when overall stiffness matrix of each element is assembled. While this model keeps the capability of modeling the whole compression molding problem, *i.e.*, both the preforming stage and resin curing stage, the development work and the initial testing runs of the model are specifically focused on the latter one for now.

In the following sections, the framework of this material model will be introduced in details. Some initial testing results will then be presented, followed by discussions and future work to further refine the material model.

2. MODEL DESCRIPTIONS

While in most of the previous studies, researchers tend to follow a divide-and-conquer strategy, providing solutions for individual physics in the compression molding, it may probably lead to an incomplete consideration of the process and thus the tools developed can hardly be utilized directly by the engineers while designing and optimizing the processing parameters. A set of the processing parameters that is identified as the optimal solution for one type of the physics may not lead to the best overall performance for the whole process. To address such issues and provide tools for the multidisciplinary optimization to achieve the globally optimal solution, an integrated model is favored with the capability of solving the multiphysics problem and updating the variables of different physics at every time increment. The schematic of the material model is shown in Figure 1, which has been implemented in LS-Dyna. The chemo-thermo-mechanical problem of compression molding is solved through the coupling of three material models, *i.e.*, one thermal model for temperature history in the resin, one mechanical model to update the curing-dependent properties of the resin and another mechanical model to simulate the elastic behavior of the woven fabric composites. The presented modeling framework put emphasis on encountering the multiple types of physics and capturing the major changes of the properties of both woven fabric and resin to provide more reliable and complete solutions.

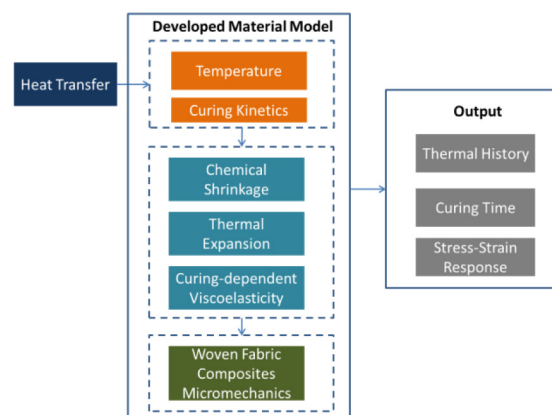


Figure 1. Schematic of the presented material model in LS-Dyna.

2.1. Thermal Model for Curing Kinetics

As has been widely reported, the crosslinking in the resin curing process alters the molecular structure of the resin polymer and consequently leads to property changes at the macroscopic level [13, 14, 15, 16, 17, 18, 19]. The extent of this chemical reaction is often quantitatively tracked by the curing degree, which reads by definition:

$$\alpha(t) = \frac{H_R}{H} \quad (1)$$

where H_R is the heat released up to time t and H is the heat required to complete the reaction. There are different models to predict the curing degree during the crosslinking reaction. The one used in this model is developed by Kamal and Sourour [12], which is in the form of an n -th order autocatalytic equation:

$$\frac{d\alpha}{dt} = (K_1 + K_2\alpha^m)(1 - \alpha)^n \quad (2)$$

in which m and n are the material parameters obtained from the characterization experiments for the epoxy resin and κ_1 and κ_2 are reaction rates obtained from

$$\kappa_1 = \kappa_{01} \exp\left(-\frac{C_1}{RT}\right) \quad (3)$$

$$\kappa_2 = \kappa_{02} \exp\left(-\frac{C_2}{RT}\right) \quad (4)$$

where T is the temperature, R is the gas constant, and C_1 and C_2 are the activation energy corresponding to reference reaction rate κ_{01} and κ_{02} , respectively. C_1 , C_2 , κ_{01} and κ_{02} are also determined from the resin characterization experiments. The temperature is prescribed the presented model, and will be obtained by coupling the thermal solver and the mechanical solver together in LS-Dyna in the future, in which case an independent thermal material in LS-Dyna will be used along with the developed model to address the heat transfer in the composites.

In addition to the curing degree evolution, the thermal expansion and chemical shrinkage are also calculated based on the temperature input and the curing degree. Linear thermal expansion is considered while the coefficient can change at different curing degree. For the chemical shrinkage, a second order polynomial is used to describe the deformation of epoxy caused by the chemical reaction. The parameters in the LS-Dyna material card need to be obtained from characterization tests.

2.2. Curing-Dependent Properties of the Resin

Prior to this study, the model that can capture the viscoelastic property change of the epoxy resin has been discussed by multiple researchers [16, 17, 18]. It has been demonstrated that the viscoelastic behavior of the resin is alternated by the curing degree. Generally, the increase of the curing degree, which indicates the increasing

crosslinking density in the resin, gives rise to the stiffening of resin. While for thermoplastic polymers in which the viscoelastic behavior can be described using the Prony series in a generalized Maxwell model, for the thermosetting epoxy resin the moduli terms are functions of α , namely,

$$G(t, \alpha) = G_0 - \sum G_i(\alpha)(1 - \exp(-\beta_i t)) \quad (5)$$

In which $G(t, \alpha)$ is the viscoelastic shear modulus, $G_0(\alpha)$ is the instantaneous modulus and $G_i(\alpha)$ is the i^{th} modulus term in the Prony series and β_i is the inverse of corresponding relaxation time. In order to characterize the curing dependency of the Prony series, we choose the similar method as in ref. 18 based on our experimental results on the resin. At different curing degree, the Prony series modulus terms are always proportional to the instantaneous shear modulus, *i.e.*,

$$\frac{G_i(\alpha)}{G_0(\alpha)} = \frac{G_i(\alpha=\alpha_{ref})}{G_0(\alpha=\alpha_{ref})} \quad (6)$$

where α_{ref} is the reference curing degree. In practice, we choose $\alpha_{ref} = 1.0$ and thus

$$\begin{aligned} G(t, \alpha) &= G_0(\alpha) - \sum G_i(\alpha)(1 - \exp(-\beta_i t)) \\ &= G_0(\alpha) \left(1 - \sum \frac{G_i(\alpha)}{G_0(\alpha)} (1 - \exp(-\beta_i t))\right) \\ &= G_0(\alpha) \left(1 - \sum \frac{G_i(\alpha=1.0)}{G_0(\alpha=1.0)} (1 - \exp(-\beta_i t))\right) \end{aligned} \quad (7)$$

It can be seen that after this simplification is applied, the $G(t, \alpha)$ is determined by the instantaneous shear modulus measured at different curing degree and the Prony series of the fully cured resin.

Likewise, the bulk modulus terms are expressed following the same way:

$$K(t, \alpha) = K_0(\alpha) \left(1 - \sum \frac{K_i(\alpha=1.0)}{K_0(\alpha=1.0)} (1 - \exp(-\beta_i t))\right) \quad (8)$$

where $K(t, \alpha)$ is the bulk modulus at a given curing degree and time, and K_0 and K_i are instantaneous bulk modulus and the i^{th} term in Prony series, respectively. The time-temperature superposition of the Prony series stills follow the WLF shifting equation:

$$\ln a_T = -\frac{A(T-T_{ref})}{B+(T-T_{ref})} \quad (9)$$

where a_T is the shifting coefficient and A and B are constants measured from experiments. Note that natural logarithm function is intentionally used here to be consistent with the internal settings in the LS-Dyna.