

Process Integration and Optimization of ICME Carbon Fiber Composites for Vehicle Lightweighting: A Preliminary Development

Hongyi Xu, Yang Li, and Danielle Zeng
 Ford Motor Company

ABSTRACT

Process integration and optimization is the key enabler of the Integrated Computational Materials Engineering (ICME) of carbon fiber composites. In this work, automated workflows are developed for two types of composites: Sheet Molding Compounds (SMC) short fiber composites, and multi-layer unidirectional (UD) composites. For SMC, the proposed workflow integrates material processing simulation, microstructure representation volume element (RVE) models, material property prediction and structure preformation simulation to enable multiscale, multidisciplinary analysis and design. Processing parameters, microstructure parameters and vehicle subframe geometry parameters are defined as the design variables; the stiffness and weight of the structure are defined as the responses. For multi-layer UD structure, this work focuses on the discussion of different design representation methods and their impacts on the optimization performance. Challenges in ICME process integration and optimization are also summarized and highlighted. Two case studies are conducted to demonstrate the integrated process and its application in optimization.

Keywords: Integrated Computational Materials Engineering, process integration, optimization, carbon fiber composites

CITATION: Xu, H., Li, Y., and Zeng, D., "Process Integration and Optimization of ICME Carbon Fiber Composites for Vehicle Lightweighting: A Preliminary Development," *SAE Int. J. Mater. Manf.* 10(3):2017, doi:10.4271/2017-01-0229.

1. INTRODUCTION

Firstly introduced in 1997, the concept of "computational design of materials" [1] lays the foundation for the computational design of materials, which follows the chain rule of Process-microStructure-Properties-Performance (P-S-P-P) (Figure 1). The concept of Integrated Computational Materials Engineering (ICME) is introduced in a series of articles [2, 3, 4, 5] in between 2006 and 2008. ICME continues to grow as a multidisciplinary research field, with increased emphasis after the 2011 announcement of the Materials Genome Initiative by US government. ICME is defined as "the integration of materials information, represented in computational tools, with engineering product performance analysis and manufacturing-process simulation". A typical ICME analysis process starts from the material processing/manufacturing models, which predict the influence of processing conditions on the material microstructure features. The second step is to construct microstructure models based on the outputs from the processing simulations. In the third step, the microstructure model is utilized to predict the material properties. Finally, the material properties are taken as inputs of the structure system performance analysis. The advancements in material science, mechanics and high performance computing techniques are the key enabler of the advanced simulations in ICME. However, there still exist two major challenges in ICME: (1) the development of high fidelity simulation models; and (2) the integration of all the validated models and computational tools into one automated workflow, so that the material processing, microstructure and component structure can be optimized simultaneously.

ICME has been successfully employed in the design of metals. In the Ford Virtual Aluminum Casting project [3], a Computer-aided Engineering (CAE) tool is developed for the P-S-P-P prediction. The thermal history of casting process is used to predict the resultant microstructure features (microporosity, eutectic phases, and precipitate phase); the microstructure information is used in the prediction of mechanical property (yield strength, fatigue, etc.); the material properties are finally input into the analysis of the cast aluminum cylinder heads and blocks to predict the residual stresses and durability. In the General Motors Virtual Casting Component Development project [6], the aluminum casting process of an engine block is analyzed and optimized using the ICME methodology. The microstructure and defects (porosity, crack, etc.) of the casted aluminum component are predicted based on the casting process simulation to support product performance analysis, such as durability and reliability. Advanced computational methods are also developed for the prediction of the P-S-P relations of aluminum, such as the solute strengthening and warm formability [7, 8]. Similar developments have also been done on magnesium to provide the computational modules for the ICME development, such as the P-P (process-property) modeling of magnesium to understand the solid-solution strengthening behavior [9]. However, an automatic process integration and optimization workflow for P-S-P-P has not been developed in the existing ICME projects due to the limitations in high performance computing capability, simulation tools and optimization tools when those projects were done.

In recent years, the regulations on fuel efficiency and low carbon emission play a major role in raising demand for lightweight components to replace metal in automotive structure building. The carbon fiber composites are identified as one of the most promising candidates for automotive lightweighting, because this type of material has competitive mechanical properties, non-toxic, fast cycle times and part consolidation potential [10, 11, 12]. Different from the metal system, the carbon fiber composites have the unique features of anisotropic properties, heterogeneous multiscale microstructure, and large variations in the material properties induced by the injecting/compression molding process. There are three types of fiber composites: short fiber composites (e.g. Sheet Molding Compound, SMC), unidirectional (UD) long fiber composites, and woven fiber composites. Currently there exists no ICME tool for the development of carbon fiber composites. This work aims to provide a process integration and optimization tool to enable the ICME design of SMC and UD structure system. Processing, microstructure and component structure parameters are considered as the design variables (Figure 1). The end goal is to optimize the processing technique, microstructure features and vehicle component structure simultaneously to achieve the optimum system performances. Based on the simulation modules developed in each disciplinary, the integrated workflows are established to automate the computational process-structure-properties-performance analysis. These workflows provide the infrastructure for the design optimization and uncertainty quantification study of the carbon fiber composites. The remainder of this paper is organized as follows: in Section 2, the overview of ICME process integration and optimization workflow is presented. In Section 3, the process integration of SMC is introduced. In Section 4, optimization of multi-layer UD composites is discussed. In Section 5, the current development and the future works are summarized.

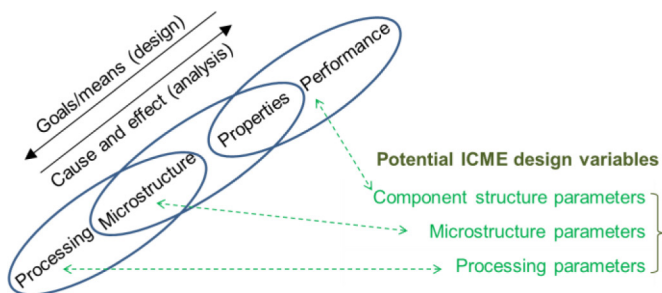


Figure 1. Chain rule of computational design of materials: Process-microStructure-Properties-Performance. Bottom-up: analysis process; top-down: design process.

2. OVERVIEW OF ICME PROCESS INTEGRATION AND OPTIMIZATION WORKFLOW

The general process integration and optimization workflow for ICME carbon fiber composites is proposed in Figure 2. Both computational research and experimental research play a critical role in ICME. The computational modules and tools are presented in blocks. The input-output relations between different modules are indicated using arrows. All the modules are integrated by the “Process Integration & Design Optimization tool”, which has three major functions: (1) it is a platform for controlling the simulations and transferring the data/

models between different simulation modules; (2) it is the control panel that enables the users to create, operate and revise the Design-of-Experiment (DOE) or multidisciplinary optimization (MDO) jobs; (3) control the process of High Performance Computing, such as parallel computing. The software ESTECO modeFRONTIER is selected to this end. Three functions of modeFRONTIER are utilized to support ICME optimization: process integration, optimization and data visualization.

On the platform of modeFRONTIER, the simulation modules are “inserted” into the ICME workflow. The first module is the material processing simulation. In this work, compression molding simulation tools are developed in Autodesk Moldflow (SMC chopped fiber composites) and LS-DYNA (UD and woven composites). The macroscale compression molding simulation is conducted on the component level. The input of the process simulation is the mesh of the component, the raw material information (fiber choice, resin choice, fiber volume fraction, fiber tow volume fraction), processing parameters (temperature, compression force profile, etc.). The output is the fiber orientation tensor (microstructure information), which is the reduced form of fiber orientation distribution at different locations of the component.

The second module is to extract the fiber orientation tensor of each element in the meshed components from the compression molding simulation results. As the mesh used in the component performance analysis is different from the mesh used in compression molding simulation, a mapping script is developed in MATLAB to interpolate the orientation tensor of each element in the new mesh. This step provides the statistical microstructure information for the next step: microstructure representative volume element (RVE) simulation.

The third module is microstructure RVE reconstruction and modeling, the fiber orientation tensor of each element is used to predict the material properties of that element. For example, one way of material property prediction is to generate statistical microstructure RVE reconstructions for each element based on its fiber orientation tensor. Then the material properties of the RVE model are simulated using ABAQUS (Finite Element Analysis, FEA software). In order to capture the spatial variations of the material properties in the component, RVE reconstruction and FEA is conducted for each element in the component mesh. The simulated material properties of each element are written into the simulation input deck of the macroscale performance simulation (component level).

The last simulation module is the component level performance analysis. Stiffness, durability, Noise Vibration and Harshness (NVH) are the major responses that are considered in vehicle component design. Crash response is obtained by LS-DYNA, durability response is obtained by nCode, and NVH and stiffness responses are obtained by Nastran. The multidisciplinary simulations can be operated in parallel to minimize the turnaround time.

In addition to the computational models, the experiments also play a critical role in the ICME. The computational models need be validated by experiments; some of the simulation inputs are obtained from the experiments, such as the material properties of fiber and pure resin; furthermore, the development of certain computational models is inspired by the experimental observations.

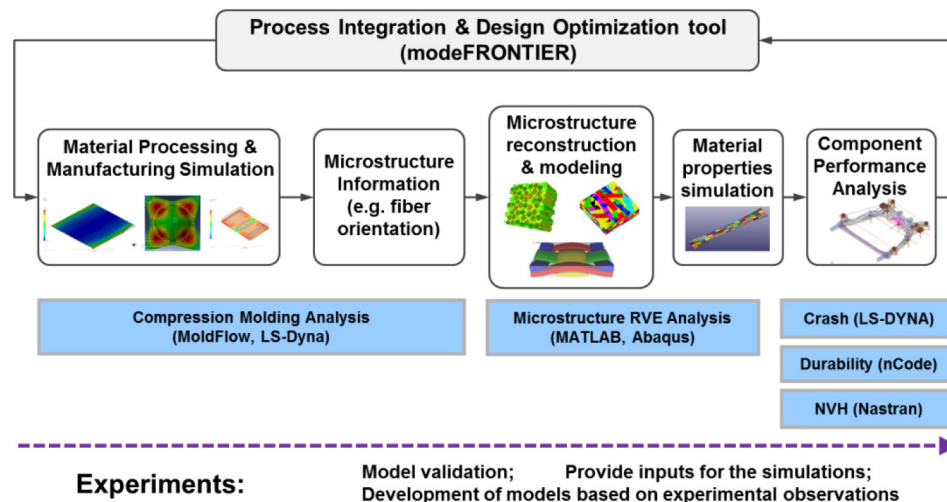


Figure 2. Overview of the ICME process integration and optimization workflow. Above the dashed line: integration of computational modules; below the dashed line: usage of experimental data in ICME

3. IMPLEMENTATION OF ICME PROCESS INTEGRATION ON SMC SHORT FIBER COMPOSITES STRUCTURE ANALYSIS

In this section, an integrated workflow is developed to demonstrate the ICME analysis of the SMC chopped fiber composites. This case study provides a detailed description of the implementation of the proposed ICME workflow on a real engineering problem. Summary of the learnings and challenges is provided after the case study.

3.1. Problem Description

The performance of the structure component is simulated considering the impact of the material processing conditions and the microstructure features. The T-shape SMC components is produced by compression molding. The microstructure of SMC consists of chopped carbon fiber tows, which are approximately 25 mm in length. Each fiber tow is formed by a bundle of fibers. The diameter of a single fiber is in the range of 10–14 μm . All the fibers inside a fiber tow has the same orientation, so each fiber tow is assumed to have the same material property as the UD composites of the same fiber/resin type and the same fiber volume fraction. The statistical distribution of the fiber orientation in SMC can be described by orientation tensor, which is a reduced representation of the fiber orientation's probability distribution function. In the compression molding process, the material flow rate and direction vary at different locations, so that the correspondent fiber orientation tensor also varies spatially. It induces the variations in the anisotropic material properties at different locations on the part. The stiffness of the T-shape is defined as the structure performance. The vertical arm of the structure is clamped, and a force is applied on the tip of the horizontal arm. The displacement on the horizontal arm's tip is used as the quantification of the structure stiffness.

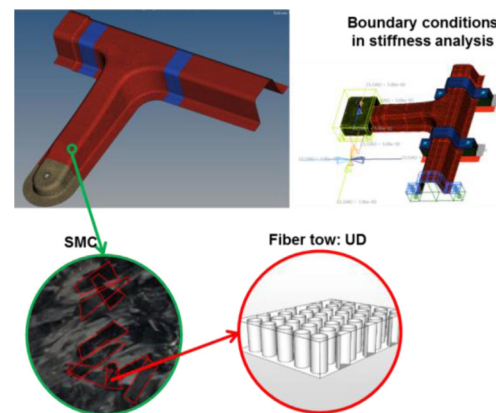


Figure 3. The microstructure features of SMC

3.2. Implementation of the ICME Process Integration

Before constructing the integrated process, five computational models/tools are prepared in advance. First, a compression molding simulation model is developed in Moldflow to predict the fiber orientation tensor on each element of the T-shape mesh. Second, a mapping script in MATLAB is prepared to map the fiber orientation results from the compression molding simulation mesh to the structure stiffness simulation mesh. Third, a simulation package of UD composites RVE is developed, which provide the material properties for each fiber tow in the SMC microstructure. Forth, a code package is developed for the prediction of SMC's elastic modulus based on the resin properties, microstructure information (orientation) and the fiber tow properties of each element. The last model is the stiffness analysis of the T-shape structure in NASTRAN.

The five computational modules are integrated as the flowchart shown in Figure 4. Any input parameters of each module can be defined as the design variables. In this work, the following five parameters are considered as design variables for demonstrative purpose: