

Multiscale Modeling Approach for Short Fiber Reinforced Plastic Couplings

Atish Gawale and Abhijit Kulkarni
Eaton Technologies Pvt, Ltd.

Mark Pratley
Eaton Corp.

ABSTRACT

The demand for injection molded reinforced plastic products used in the automotive industry is growing due to the capability of the material for volume production, high strength to weight ratio, and its flexibility of geometry design. On the other hand, the application of fiber filled plastic composites has been challenging and subject of research during past decades due to the inability to accurately predict the mechanical strength and stiffness behavior owing to its anisotropic characteristics. This paper discusses a numerical simulation based technique using multiscale (2 scale Micro-Macro) modeling approach for short fiber reinforced plastic composites. Fiber orientation tensors and knit lines are predicted in microscale analysis using Autodesk Inc.'s Moldflow® software, and structural analysis is performed considering the homogenized structure in macroscale analysis using ANSYS® software tool. This approach accurately captures the stiffness and stress behavior of reinforced plastic materials. Further, a case study is discussed with application of developed approach on reinforced plastic supercharger couplings which are used to connect two coaxial shafts for torque transfer. It is observed that critical locations in couplings are high stress regions with undesirable fiber orientation and presence of knit lines, which further reduced the strength of the coupling. Modification of gate location is recommended to improve fiber orientation and change in location of knit lines, in order to increase the coupling strength which is verified numerically and through testing using this developed approach.

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INTRODUCTION

Short fiber reinforced plastic composites are widely used due to low cost, high strength to weight ratio, and ease of fabrication. A polymer is a thermoplastic or thermoset, while fiber reinforcement can be glass, carbon, or aramid. Function of fibers is to provide strength and stiffness to the composite product where the polymer acts to bond and protect the fibers from chemicals and the environment, allowing load transfer between the fibers. These are commonly manufactured by injection molding, compression molding and extrusion processes. During these processes, fibers orient themselves due to the flow and interactions between neighbouring fibers and/or cavity wall. Fiber orientation is random in general resulting in an anisotropic property of final product having complex mechanics which is difficult to measure experimentally, is expensive and involves a large number of permutations. Thus, the application of fiber-filled thermoplastic materials has been limited in many cases due to the inability to accurately predict strength and stiffness as the behavior. It depends primarily on the fiber length and fiber orientation which has been the subject of considerable amount of research during past decades. There have been necessity of new methodologies that can predict more accurately the life and serviceability conditions of such parts.

Many numerical methods have been developed to help solve complex engineering problems like the ones involving the design of composite parts. Some of the most commons are: Finite Difference Methods, developed in the 1950s; Boundary Element Methods, developed in the 1970s and principally used in linear continuum mechanics problems; Discrete Element Methods, developed in the 1970s and used mainly with granular materials problems; Meshfree Methods, recently propagated and it has its primary uses in fracture and crack propagation analysis; and the Finite Element Method, originated in the 1950s by the necessity for solving complex structural analysis problems.

Recently advanced modeling techniques for composites materials have been developed in which components are analyzed at micromeso-macro scales and known as multiscale modeling. Microscale analysis allows us to have a better understanding of how the materials fail, along with identification of failure initiation locations while macro mechanical analysis determines when the part will fail under a certain set of boundary conditions (loads and supports).

The standard approach to model composite materials is to use the finite element method. If all the micro-structural components to be accounted in a numerical setting is not feasible, numerical

homogenization techniques using classical theories are used to obtain the material properties. This allows to solve large scale problems with minimal computational power. In the next step, multiscale modeling methodology is utilized by including the effects of the fiber-matrix combination. Recently, a multiscale analysis methodology to evaluate short fiber reinforced injection molded composites has been established by successfully interfacing the two commercial codes Moldflow® and ANSYS®. Multiscale analysis methodology demonstrated the influence of the material configuration and fiber orientation over the structural analysis of the composite components with higher accuracy.[1]

This paper deals with interdependency of modeling techniques at two different scales for fiber reinforced composites. Each scale model is addressed independently and proper connection between the two is established. A modeling strategy is proposed for conducting two-scale analyses of composite materials.

MULTISCALE MODELING METHODOLOGY

A multi-scale model is based on continuum mechanics that can be used as a predictive tool for designing injection molded short fiber reinforced plastic composites. In multiscale modeling, the small length scale information enhances the response of the large scale continuum independently or by coupled manner.

Traditional engineering deals with treating matter as continuous with no internal structure. In contrast to engineers, physicists have dealt with matter in its discrete structure at small length scales to understand fundamental behavior of materials. Multiscale modeling is of great scientific and technical importance as it can aid in designing novel complex materials that will enable to tailor properties specific to an application like multi-functional materials.

Materials are inherently multi-scale in nature consisting of distinct characteristics at various length scales from atoms to bulk material as shown in figure 1. There are no widely accepted predictive modeling techniques that span from atomic level to bulk relating the effects of the structure at the nanometer (10⁻⁹ meter) on macro-scale properties. Hence, multiscale modeling techniques have been developed.

Three important factors required for the accurate prediction of properties using multiscale approach are: (i) The assumed continuum mechanics based constitutive relationship, (ii) The selection of the molecular level interatomic potential, and (iii) Molecular modeling procedure. The first factor consists of continuum mechanics discipline which includes numerical methods such as FEM which is usually applied to structures for solving complex structural analysis problems. The second factor consists of quantum mechanics discipline dealing with electrons, protons and neutrons. The third factor consists of material science discipline dealing with micro continuum theory basically known as micromechanics. The cause and effect relationship of the factors are studied to establish an efficient modeling framework.

The developed multiscale modeling methodology can be distinct into the two major steps: (i) Microscale modeling and (ii) Macroscale modeling. Each scale modeling was addressed independently and proper connection between the two is established.

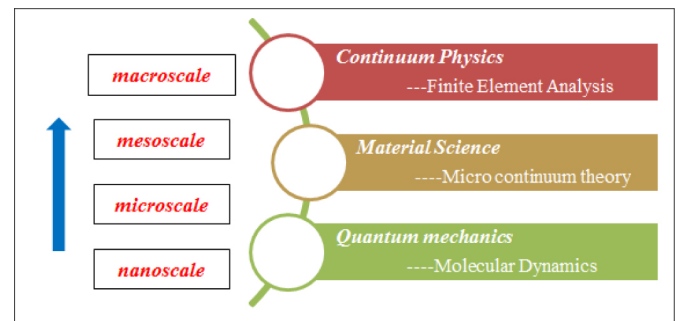


Figure 1. Multi-scale modeling overview

1. Microscale Modeling

Microscale modeling provides an approach to study local physical phenomena in a large structure with microstructural features as relative to traditional meso- or macro-scale modeling approach. In this modeling approach, constitutive relationships are established as a function of the molecular structure for prediction of the bulk mechanical properties for plastic composites.

It considers numerical simulation approach to predict the orientation of molecular structure using injection molding process which is a well-established mass-production method for plastic materials. In this process, the molten plastic composite is injected into a mold cavity. After cooling the plastic material inside the mold, the final product is ejected from the mold and a complex three-dimensional shape can be produced quite easily.

Mold flow analysis is required to predict fiber orientation, meld lines and weld lines in the injected molded short fiber composite materials. Autodesk Moldflow® a commercial modeling software predicts the flow of plastic during all phases of the injection molding process based on a Folgar-Tucker model. This model allows for significantly enhanced orientation prediction accuracy over a range of materials and fiber contents.

Fiber orientation determines the strength and stiffness of structure. A knit line or meld line can cause structural problems or be visibly unacceptable. A knit line or meld line is a weakness or visible flaw created when two or more flow paths meet during the filling process. Weld lines can be caused by material flowing around holes or inserts in the part, multiple injection gates or variable wall thickness where race tracking can occur. If the different flow fronts have cooled before meeting, they don't interfuse well and can cause a weakness in the molded part. A line, notch and/or color change can appear.

In the above figure, the converging flow fronts are shown to be meeting. If the angle is greater than 135° a meld line will form. If it is less than 135° a knit line will form.

A knit line forms, the thin frozen layers at the front of each flow path meet, melt, and then freeze again with the rest of the plastic. The orientation of the plastic at the weld is therefore perpendicular to the flow path. The weld line occurs where two flow fronts meet, and the plastic molecules are misaligned. It is the sharp difference in molecular orientation at the weld which causes the significant decrease in strength at this point.