University of Victoria | Graduate Studies

Notice of the Final Oral Examination
for the Degree of Master of Science

of

AMIR SALAR SALEHI

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"3D Finite Element Model for Predicting Cutting Forces in Machining Unidirectional Carbon Fiber Reinforced Polymer (CFRP) Composites"

Department of Mechanical Engineering

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Engineering and Computer Science Building
Room 468

Supervisory Committee:
Dr. Martin Byung-Guk Jun, Department of Mechanical Engineering,
University of Victoria (Co-Supervisor)
Dr. Keivan Ahmadi, Department of Mechanical Engineering, UVic (Co-Supervisor)

External Examiner:
Dr. Phalguni Mukhopadhyaya, Department of Civil Engineering, UVic

Chair of Oral Examination:
Dr. Craig Brown, Division of Medical Sciences, UVic

Dr. David Capson, Dean, Faculty of Graduate Studies

Abstract

Excellent properties of Carbon Fiber Reinforced Polymer (CFRP) composites are usually obtained in the direction at which carbon fibers are embedded in the polymeric matrix material. The outstanding properties of this material such as high strength to weight ratio, high stiffness and high resistance to corrosion can be tailored to meet specific design applications. Despite their excellent mechanical properties, application of CFRPs has been limited to more lucrative sectors such as aerospace and automotive industries. This is mainly due to the high costs involved in manufacturing of this material. Machining, milling and drilling, is a critical part of finishing stage of manufacturing process. Milling and drilling of CFRP is complicated due to the inhomogeneous nature of the material and extreme abrasiveness of carbon fibers. This is why CFRP parts are usually made near net shape. However, no matter how close they are produced to the final shape, there still is an inevitable need for some post machining to obtain dimensional accuracies and tolerances. Problems such as fiber-matrix debonding, subsurface damage, rapid tool wear, matrix cracking, fiber pull-out, and delamination are usually expected to occur in machining CFRPs. These problems can affect the dimensional accuracy and performance of the CFRP part in its future application.

To improve the efficiency of the machining processes, i.e. to reduce the costs and increase the surface quality, researchers began studying machining Fiber Reinforced Polymer (FRP) composites. Studies into FRPs can be divided in three realms; analytical, experimental and numerical. Analytical models are only good for a limited range [0°–75°] of Fiber Orientations[1], to be found from now on as “FO” in this thesis. Experimental studies are expensive and time consuming. Also, a wide variety of controlling parameters exist in an experimental machining study; including cutting parameters such as depth of cut, cutting speed, FO, spindle speed, feed rate as well as tool geometry parameters such as rake angle, clearance angle, and tool edge/nose radius. Furthermore, the powdery dust created during machining is known to cause serious health hazards for the operator. Numerical models, on the other hand, offer the unique capability of studying the complex interaction between the tool and workpiece as well as chip formation mechanisms during the cut. Large number of contributing parameters can be included in the numerical model without wasting material. Three main objectives of numerical models are to predict principal cutting force, thrust force and post-machining

[1] Fiber orientation is the clockwise angle between the cutting direction and fiber axis.

subsurface damage. Knowing these, one can work on optimization of machining process by tool geometry and path design.

Previous numerical studies mainly focus on the orthogonal cutting of FRP composites. Thus, the existing models in the literature are two-dimensional (2D) for the most part. The 2D finite element models assume plain stress or strain condition. Accordingly, the reported results cannot be reliable and extendable to real cutting situations such as drilling and milling, where oblique cutting of the material occurs. Most of the numerical studies to date claim to predict the principle cutting forces fairly acceptable, yet not for the whole range of fiber orientations. Predicted thrust forces, on the other hand, are generally not in good agreement with experimental results at all. Subsurface damage is reported by some experimental studies and again only for a limited FO range. To address the lack of reliable force and subsurface damage prediction model for the whole FO range, this thesis aims to develop a 3D finite element model, in hope of capturing out-ofplane displacements during stress formation in different material phases (Fiber, Matrix and the Interface bonding). ABAQUS software was chosen as the most commonly used finite element simulation tool in the literature.

The present work is completed in three phases. The focus of phase I is to develop a VUMAT program to simulate behavior of carbon fibers during the cut. Carbon fibers are assumed to behave transversely isotropic with brittle (perfectly elastic) fracture. In phase II, elasto-plastic behavior of Epoxy matrix is simulated. Ductile and shear damage models are also incorporated for the matrix. The last phase is to combine the carbon fiber and epoxy matrix phases along with the interface bonding between them. Surface-based cohesive zone technique in ABAQUS is used to simulate the behavior of the zerothickness bonding layer. The tool is modeled as a rigid body. Mechanical properties were extracted from the literature. The obtained numerical results are compared to the experimental and numerical data in literature. The model is capable of capturing principal forces very well. Cutting force increases with FO from zero to 45° and then decreases up to 135°. The simulated thrust forces are still underestimated mainly due to the fiber elastic recovery effect. Also, the developed 3D model is shown to capture the subsurface damage generally by means of a predefined dimensionless state variable called, Contact Damage (CSDMG). This variable varies between zero and one. It is stored at each time step and can be called out at the end of the analysis. It was shown that depth of fibermatrix debonding increases with increase in FO.