# CHALLENGES IN MODELING MACHINING OF MULTILAYER MATERIALS

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## ABSTRACT

Multilayer structural members are used extensively in aerospace applications and there is a critical need for accurately modeling their machining, especially drilling. Modeling the machining of multilayer materials is complex as it's a 3D dynamic process with multiple interacting material domains. These models can be used to minimize edge imprecisions and increase workpiece accuracy in machining by optimizing the process and geometric parameters. This report discusses the challenges in modeling the machining of aerospace multilayered materials, which include metal-metal stackups and metal-composite stackups. The challenges composite materials specifically pose from a modeling perspective are also discussed. A brief review of existing work in composite machining and finite element modeling is also presented. Finally, a framework for solving this problem is suggested and a roadmap based on the framework is presented.

## INTRODUCTION

Advances in numerical techniques have given engineers and researchers tools to create predictive numerical models for manufacturing processes. These numerical models further the basic understanding of manufacturing processes and are a suitable replacement for analytic formulations. Analytical models involve the tedious application of boundary conditions which makes obtaining results from them very complicated (Klocke, 2002). The finite element method is a numerical method that has been very popular in this respect, and the last two decades have seen significant work in applying the finite element method to further understand metal cutting.

This report discusses the challenges in modeling (specifically, finite element modeling) the machining of multilayered materials. Multilayered materials are being used increasingly for engineering applications, especially in the aerospace industry. To keep costs down and minimize workpiece imprecisions such as burrs, it is essential to understand the behavior of these materials during machining. Accurate FE simulations (using these models) can be used to facilitate efficient tool and process design, as well as increase part reliability.

This report argues that the modeling of machining of multilayered materials is different from that of the machining of single-layered materials. Specifically challenges in modeling the drilling of aerospace multilayered materials, which include metal-metal stackups and metal-composite stackups, are investigated.

The use of multilayer materials in the aerospace industry and the need for controlling burr formation in their machining are first presented. Next, existing work in the finite element modeling of metal cutting is reviewed, specifically looking at burr formation and drilling models. The differences between machining single-layer workpiece materials and multilayer workpiece materials are then discussed. After this, specific challenges in modeling the machining of composite materials are presented along with a review of previous work in modeling composite machining. Finally, a framework for further research in this field is suggested.

## MULTILAYER MATERIALS IN THE AEROSPACE INDUSTRY

Multilayer materials (or stackups) are used extensively in the construction of aerospace structural members. They provide increased strength-weight ratios compared to traditional structural material. Also, the different layers provide a wide range of functionality that increases the utility of the structural member. Composite materials are being used increasingly as constituents of these stackups.

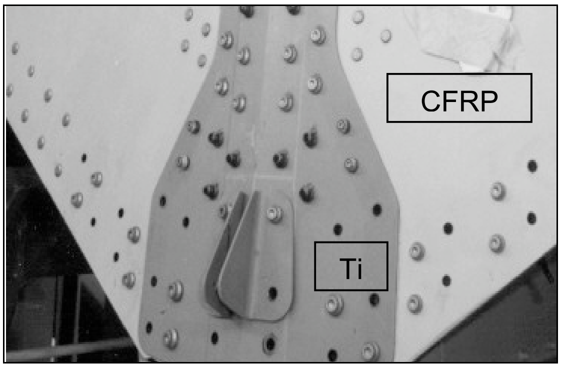


FIGURE 1. PORTION OF A HORIZONTAL STABILIZER OF A COMMERCIAL AIRCRAFT MADE OF A METAL (Ti) – COMPOSITE (CFRP – CARBON FIBER REINFORCED POLYMER) – METAL (Ti – UNSEEN) STACKUP (FFIELD, 2004).

The principal machining operation performed on these structures is drilling. These structures are usually assembled and drilled during this operation interface burrs are formed. The aim is to control these interface burrs and other debris from occurring. The need in industry is to be able to drill through these layers in one operation, without need for any rework (i.e. without having to disassemble and clean the parts before fastening). Currently, deburring operations account for about 30% of the total manufacturing cost. Examples of aerospace panel stackups are CFRP/CFRP (CFRP –Carbon Fiber Reinforced Polymers), CFRP/Titanium, CFRP/Titanium/CFRP, and CFRP/Aluminum.

## REVIEW OF METAL CUTTING FEM MODELING

Significant work has been done in the last decade in modeling metal cutting using the finite element (FE) method. Early models used variations of the parting line method for chip separation (Huang, 1996), while more recent models use sophisticated adaptive meshing techniques for chip separation (Marusich, 1995; Klocke, 2001).

The LMA's work in analyzing burr formation using the FE method includes Park's (1996) 2D orthogonal model using the parting line method for analyzing burr formation, Min's (2001) 3D model of drilling burr formation and Choi's (2003) simulation of drilling through two sheets of SS304L to observe the gap formation between the layers.

## MULTILAYER DRILLING

Despite the extensive research in the field, existing results from single-layer machining simulations cannot be applied to multilayer machining cases, especially drilling. The multi-layer problem should be considered as a fundamentally different problem, some of the reasons for this are presented in Table 1.

| Aspect | Single Layer Workpiece | Multilayer Workpiece |
|---|---|---|
| Steady State Assumptions | Taken as a spatial criterion. Criterion is constant though analysis. | Several "steady states" may be present in one operation and depends on geometry of the layers. |
| Burr Morphology | Existing FE simulations have demonstrated the formation of crown and uniform burrs as a function of the drill feed (Min, 2001). | It is unknown if these morphologies are also applicable when multiple materials are present in the workpiece. |
| Temperature Effects | The temperature properties are constant across the workpiece. Only one set of thermo-mechanical relationships have to be considered. | Temperature properties vary across the workpiece and are dependant on the material in each part of the workpiece. |

TABLE 1. DIFFERENCES IN SINGLE-LAYER AND MULTI-LAYER DRILLING.

The multilayer problem also opens up other interesting machining parameters to study which are not pertinent to the single-layer problem. Some of them are:

Clamping Position – Choi (2003) studied the effect of clamping position on gap formation during drilling of two sheets of SS 304L. He concluded that gap formation is due to plastic deformation which depends on the thrust force of the drill and that the clamping position only influences the elastic deformation. When the clamps are located farther from the hole there is more elastic displacement of the material. The effect of clamping position on burr formation has to be studied for more general cases.

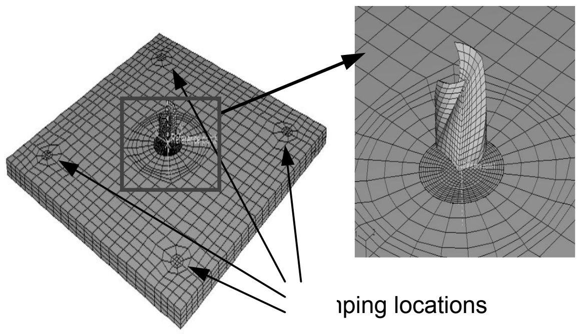


FIGURE 4. A FINITE ELEMENT MESHES OF A CLAMPED TWO-LAYER WORKPIECE AND A DRILL (CHOI, 2003).

Order of placement – If there is some flexibility in changing the order of placement of the material layers in a stackup, then a pertinent question is if there is an optimal configuration such that burr formation is minimized.

Composite materials are of increasing importance in multilayer stackups, especially in the aerospace industry. The next section examines the challenges of constructing accurate finite element models for machining composite materials.

## CHALLENGES OF MODELING COMPOSITE MATERIAL

### Composite Material Composition

A composite material is a multiphase material that has been engineered to consist of more than one material type (Callister, 1999). Composites usually consist of a matrix in which reinforcement is embedded. The two broad kinds of composites are fiber composites which have a fibrous reinforcement and particulate composites which have small dispersed reinforcement particles (Matthews, 2000). The focus here is almost exclusively on fibrous composites, although some of the information pertains to particulate composites too. CFRP is a popular fiber-reinforced composite material which is frequently used in the form of laminates, which are 2-dimensional layers arranged in a specific configuration. CFRP laminates are characterized by the order of orientation of the reinforcing fibers of the individual layers which largely determines the strength and applicability of the composite.

### Composite Modeling

Since machining metals (the metal cutting process) has been extensively modeled, it is instructive to first consider the differences between machining metals and composites. Composite materials are heterogeneous anisotropic which makes their machining quite different from that of metals (which can be usually assumed as isotropic homogeneous). Also, as they have low thermal conductivity, heating effects in composites also have to be observed. Generalized observations on chip formation cannot be made for composite machining as the chip morphology depends on the orientation and properties of both the matrix and the fiber. In order to better model composite materials, it is useful to look at some of their distinct properties which have to be captured in the finite element simulation.

**Failure Modes**. It is significantly harder to predict failures in composites as compared to metals. Failure is often of a random nature, and hence statistical tools are needed for prediction. Also, there are five significant failure modes for FRPs (Fiber Reinforced Polymers) – longitudinal compression, longitudinal tension, transverse compression, transverse tension and shear failure. The failure criterion used to predict failure should take into account the effect of all these models Soden et al. (1998) and Hinton et al. (2002) have prepared a comprehensive comparison of various FRP failure theories.

**Crack Propagation**. Composite materials exhibit crack formation in the form of micro-cracks. Cracks in composites do not cause catastrophic failure as in metals but usually cause local failure. Cracks propagate depending on the strength of the matrix-fiber bond. If the matrix-fiber bond is very strong, then cracks originating in the matrix extend across the fiber. If the bond is weak, the crack may extend in separate paths across the matrix and the fiber (Matthews, 2000).

**Delamination**. Excessive out-of-plane stresses in the composite can also cause delamination of the layers. The onset of delamination can be predicted by using fracture mechanics theories (Hocheng, 1990). The magnitude of the out-of-plane stresses is dependant on the fiber orientations in the laminates.

**Stress Effects.** Stress concentrations are seen in these end planes and may cause failure in the form of cracks and delamination (Matthews, 2000). Also, stress concentrations are seen in the edges of other features when axial loads are applied to laminates. This is especially pertinent in the modeling of drilling through a laminate where another feature (e.g. a hole) is already present on that laminate. Also, it is possible for different regions of a composite laminate to be pre-stressed differently by design (this is common when laminates are used as structural members for aerospace applications (Ffield, 2005). This will require specific regions of the laminate to be modeled explicitly. There may even be the need for modeling each fiber individually.

**Thermal Effects**. Composite materials generally have poorer conductive properties when compared to metals. This leads to increased temperature during machining operations. Also composites have pre-stresses from the thermal contraction of fibers as they get cooled during manufacture.

## REVIEW OF COMPOSITE MATERIAL MACHINING

There has been considerable work in studying the machining of composite materials. The major influencer of the cutting properties of FRPs is the fiber orientation (Komanduri, 1993). For a detailed discussion of different work in cutting of composite materials, the reader is directed to Gordon and Hillery's (2002) review of cutting of composite materials.

Hocheng and Dharan (1990) present a criterion for the delamination of composites during drilling using fracture mechanics theories. The criterion sets delamination to occur when the thrust force is greater than a limit which is calculated based on the material properties and the geometry of the workpiece.

Hocheng and Tsao (2003) also studied the effect of various drill geometries on the delamination of composites. They conclude that drill design to minimize the thrust force is key to decrease delamination.

Arola et al. (1999) used finite element models to simulate chip formation in orthogonal cutting of FRPs using a dual-mode failure method. Failure was simulated as primary fracture, consisting of fiber failure and secondary fracture, consisting of matrix failure. The fiber orientation angle was assumed as the shear plane angle and the primary fracture plane was defined using experimental results. Principal cutting forces predicted using this method agreed with experimental results, though the thrust force predictions did not concur with experimental results. As this method uses a very rudimentary material model, accurate chip and burr morphologies cannot be simulated.

Zhang and Mahdi (2001) modeled the machining of a 3D cell of composite material consisting of a fiber and its surrounding matrix. An adaptive meshing technique based on a shear stress criterion was used to handle excessive distortion and element separation was achieved using a maximum shear stress criterion.

## FRAMEWORK FOR FE MODELING OF MULTILAYER MATERIALS

A basic framework is suggested for developing a finite element model for machining of composite materials. The framework is as follows:

| Facet | Detail |
|---|---|
| Model Type | Lagrangian models have proven very popular in application to machining problems. As much work has been done using Lagrangian formulations, it will be apt to use them in composite models as well. |
| Thermal Effects | A thermo-mechanically coupled model must be employed. The relationship between the thermal and mechanical properties of the material must be evaluated. |

| | |
|---|---|
| Material Modeling | Suitable element types must be used to model the composite material accurately such that the features discussed in the above sections are captured effectively (failure, crack propagation, etc.) |
| Contact Effects | In multilayered drilling contact between the different layers is a critical phenomenon. A suitable contact modeling method must be used so that thermal and mechanical energies transmit across material domains. |
| Element Separation /Fracture Criteria | Using a combination of failure criteria outlined above, material separation should be defined. The criteria should be distinct to different parts of the composite material given the disparate properties under consideration. Based on existing work [Soden 1998; Hinton, 2002] an appropriate failure criterion must be chosen. |
| Adaptive Meshing | As high material distortion is expected, an adaptive meshing algorithm has to be employed. |
| Element Types | The element type used for the model should have both thermal and mechanical properties. Also, it should be able to exhibit stress/strain behavior in-plane and out-of-plane. |
| Crack Propagation | Crack formation is unlike in metals and should not be modeled as occurring only at the tip of the tool edge and propagating from thereon. As illustrated previously, cracks can form in arbitrary locations dynamically and hence the crack formation criteria should be dynamically tracked at multiple locations of the workpiece. |
| Tool Modeling | The tool should be modeled as a dynamic object with both stress and thermal effects. A tool wear model should be incorporated to consider the effect of wear on chip and burr formation |

TABLE 2. COMPOSITE MODELING FRAMEWORK.

**CONCLUSIONS**

Modeling drilling is complex it is a 3D, dynamic cutting problem with multiple cutting edges. The drilling process can be abstracted as a composition of several orthogonal cutting operations. Hence, as a precursor for modeling the drilling of composite materials it is instructive to first study the orthogonal cutting of composite materials. Orthogonal simulations will shed more light on the machining behavior of composite materials and results from these simulations can be used to build more efficient drilling simulations. The complexity of the material models used to describe the composites can also be increased in steps. As a first step, FRPs can be idealized as 2D orthotropic and finally can be modeled as 3D anisotropic. Once these basic steps are completed, the effect of different materials and drill geometries on burr formation can be studied and optimal drill geometries can be realized specific to composite properties.

Based on the outlined approach, the following simulation roadmap is proposed:

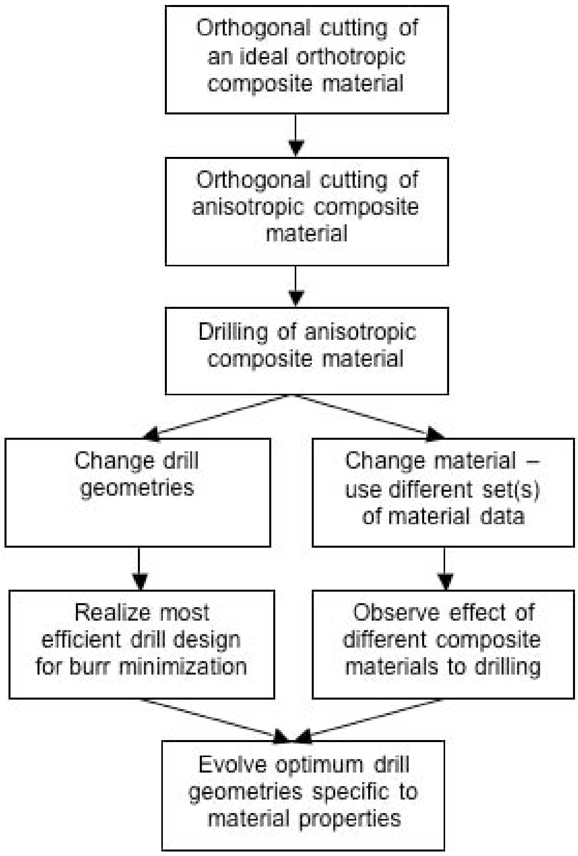


FIGURE 5. SIMULATION ROADMAP.

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