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Modelling of cutting fibrous composite materials: current practice

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Abstract

Using fibre reinforced polymers (FRP) is increasing across many industries. Although FRP are laid-up in the near-net shape, several cutting operations are necessary to meet quality and dimensional requirements. Modelling of cutting is essential to understand the physics of the cutting phenomena and to predict quality and cost of products. This paper aims at reviewing the current practice in modelling of cutting FRP including analytical, numerical, mechanistic and empirical approaches, with emphasis on analytical models of cutting forces and delamination. Processes detailed include orthogonal cutting, drilling, milling and turning. Finally, advances in machining of metal-composite stacks are presented.

Keywords: Fibre reinforced plastics; Analytical modelling; Cutting forces; Meshfree methods; Metal-composite stacks

1. Introduction

The use of composite materials is increasing in many industries such as aerospace, automotive and sports equipment due to their superior properties to metallic materials. Fibre reinforced polymers (FRP) are the most widely used composites with carbon or glass as reinforcement constituent. Machining operations are required to obtain the necessary shape, dimensions and surface quality of the composites parts. Modelling of cutting is important for predicting the quality and cost of manufacturing processes by calculating fundamental process outputs such as cutting forces, stresses and strains and/or industry relevant outputs such as tool wear and surface quality. Modelling of cutting can be done using one of four main approaches namely, analytical, numerical, mechanistic and empirical. Selecting one approach over others depends on the type of input data, available computation resources, the desired output variables and the required level of accuracy. Modelling of cutting composites is challenging task due to (i) the composites’ anisotropic and heterogeneous nature (ii) the inherent complexity of the cutting process.

This paper therefore, discusses the applications of the different modelling approaches to conventional cutting processes of composites with emphasis on analytical modelling of cutting forces and delamination.

2. Modelling of FRP Cutting

Most of the research on cutting composites has adopted the empirical approach, which is very useful in observing the process variables and their relative importance however, theoretical studies are needed to understand the physics of FRP cutting [1].

2.1. Orthogonal cutting

Orthogonal cutting is the most studied process theoretically and experimentally because it is 2D problem [2] thereby, it is easier to study. Majority of the analytical studies focused on calculating cutting forces. Takeyama and Iijima [3] proposed a model based on the minimum energy principle to predict the cutting and thrust forces. The model agreed fairly well with experiments, despite being criticised because it does not account for the effect of machining direction and for the lack of transparency in obtaining the shear angle values [4]. Subsequently, it was observed by Bhatnagar et al. [5] that crack propagation happens along the fibre

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direction in the range 90° to 180°, thus they developed a cutting force model based on Merchant's principle of minimum energy by substituting the shear plane angle with the fibre orientation angle. The study confirmed the significance of fibre orientation and cutting direction on cutting forces values and on tool-chip friction on the rake face. Later, Zhang [6, 7] proposed new analytical model by dividing the cutting domain into three regions (i) chipping region (region 1) in front of the rake face of the tool, (ii) pressing region (region 2) under the nose of the tool and (iii) bouncing region (region 3) below the relief face of the tool as shown in Fig. 1. Cutting and feed forces were calculated in each region and then superimposed to calculate the total cutting forces. The model was built for fibre orientation less than 90° since beyond that; additional damage mechanisms exist that are not captured by the model.

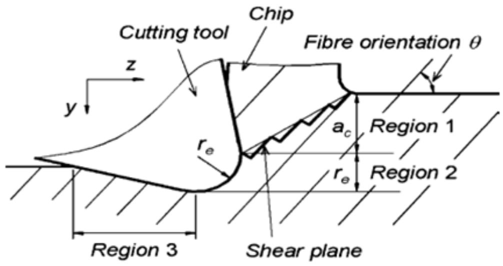

Fig. 1. Deformation zones in orthogonal cutting of FRPs [6]

Later, Sahraie-Jahromi and Bahr [8] extended Zhang's model to the range 90° to 180° by proposing additional damage mechanisms for that region. They identified three main damage mechanisms namely; fibre micro-buckling, fibre-matrix de-bonding and fibre bending then calculated the cutting and thrust forces accordingly and compared it with experiments. The accuracy of predictions was limited due to the mismatch in materials properties and boundary conditions between the model and experiments and due to non-uniform distribution of fibres among the matrix.

Subsurface stresses were studied analytically by Gururaja and Ramulu [1] who proposed a model to calculate stress fields in the subsurface area after orthogonal cutting of FRPs by modelling the effect of the cutting tool as line load profile inclined with an angle. The effect of anisotropy on stress fields varied with changes in volume fraction and fibre orientation.

Numerical methods can have more predictive power than analytical because it is possible to include more variables in the study and to account for more failure mechanisms [9]. Finite element methods (FEM) have been applied extensively to study composites machining; refer to Dandekar and Shin's review [9]. FEM models require defining material model, element failure criteria for chip formation and tool-chip contact models. Moreover, using FEM in machining requires remeshing because of the large deformations and severe element distortion. Remeshing is time consuming, can be complicated for 3D problems and for every iteration, studied quantities should be projected on the new mesh leading to gradual accumulation of error [10]. Moreover, FEM is not well suited for modelling discontinuities if they do not coincide with elements' boundaries [11].

Meshfree methods are group of numerical methods for solving partial differential equations in which the studied domain is discretised through non-connected nodes rather than connected elements. This eliminates part or whole of the meshing process [12]. Some advantages in using meshfree methods in machining problems are (i) the ability to simulate large deformations and discontinuities without the need for remeshing, (ii) the flexibility in adding or removing nodes without worry about their relation to neighbouring nodes [12], (iii) better integration with CAD/CAE/CAM software [10], (iv) elimination of separation criteria and arbitrary contact conditions [13]. Meshfree methods include: smoothed particle hydrodynamics, finite pointset method, element-free Galerkin, reproducing kernel particle, moving least square interpolations and constrained natural element method. These methods have been applied to solid mechanics problems [10, 12, 14, 15], machining of metals [16-24], as seen in Fig. 2 and to fracture of composite materials [11, 25, 26].

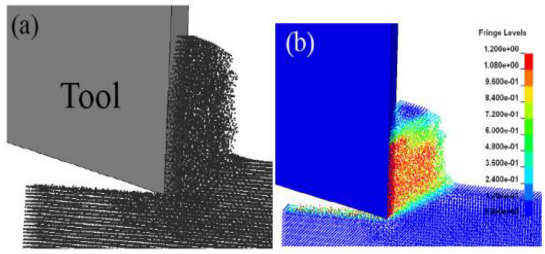

Fig. 2. Orthogonal cutting simulation using smoothed particle hydrodynamics: (a) 3D view and (b) effective plastic strain [18]

Few empirical models have also been developed for orthogonal cutting of FRPs, one to calculate cutting forces [27], another to evaluate the effect of tool wear on cutting forces [28] where it was found that tool wear has significant effect on cutting force values. In addition, cutting mechanisms identification study was conducted in [29] by analysing frequency of measured force signals. The study showed that signal characteristics differ for different cutting mechanisms.

2.2. Drilling

Drilling is the most widely used cutting operation for composite materials because of the need for joining structures [30], therefore considerable amount of literature exists with comprehensive review papers [31-33]. Delamination is the major concern in drilling FRPs,