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Procedia CIRP 28 (2015) 52 – 57

www.elsevier.com/locate/procedia

3rd CIRP Global Web Conference

Modelling of cutting fibrous composite materials: current practice

F. Kahwash[a], I. Shyha[a,b]*, A. Maheri[a]

[a]*Faculty of Engineering and Environment, Northumbria University, Ellison Place, Newcastle upon Tyne, NE1 8ST, UK.*
[b] *Production Engineering Department, Faculty of Engineering, Alexandria University, 21544 Alexandria, Egypt*
* Corresponding author. Tel.: +44-191-243-7834; fax: +44-191-227-3598 .*E-mail address:* islam.shyha@northumbria.ac.uk

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

doi:10.1016/j.procir.2015.04.010

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.

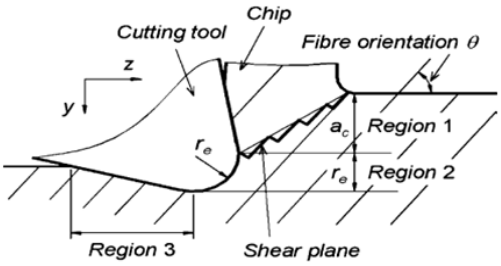

Fig. 1. Deformation zones in orthogonal cutting of FRPs [6]

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].

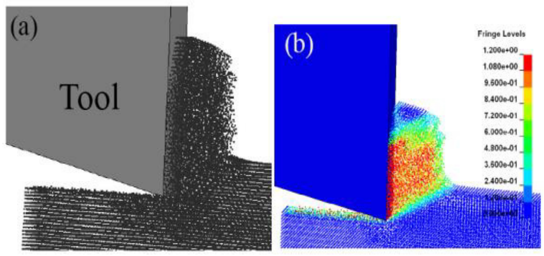

Fig. 2. Orthogonal cutting simulation using smoothed particle hydrodynamics: (a) 3D view and (b) effective plastic strain [18]

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, it results mainly from thrust force pushing the last uncut lamina via the chisel edge causing interlaminate failure as seen in Figure 3. Delamination is initiated when the thrust force exceeds a critical value also called critical thrust force (CTF) and most of the modelling efforts were directed towards calculating this value. The earliest CTF model was developed by Hocheng and Dharan [34] then, seminal contribution was made in the work of Hocheng and Tsao [30, 35-39]. Based on linear elastic fracture mechanics approach, they developed several models for special drill bits such as candle stick drill, saw drill and core drill that are designed to reduce delamination by distributing the thrust force away from the chisel edge onto the periphery of the tool. Their other work includes critical thrust force models taking the effect of tool eccentricity, using pilot holes and drilling with backup plate. More recently Rahmé et al. [40] studied the effect of loading assumption on the critical thrust force model as a function of the number of delaminated plies. Thrust force was modelled as concentrated, uniformly distributed, triangular, disc and concentrated with uniform distribution; the latter assumption was found to be closest to experiments.

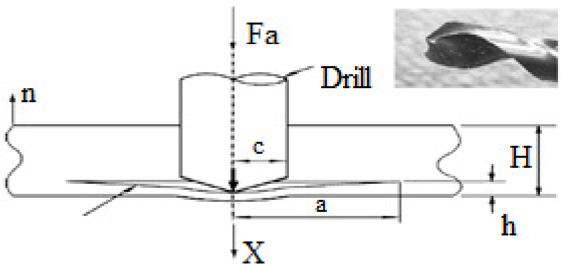

Fig. 3. Delamination onset while drilling with twist drill [39]

FEM studies of drilling were conducted to study the effect of cutting parameters on the thrust force, v torque [41] and to study delamination [42] where the numerical model was compared with the existing analytical models. It was found that both approaches do not capture the effect of parameters variation on delamination onset which necessitates further development of both modelling approaches.

The only mechanistic model for drilling was developed by Zhang et al. [43] to predict average thrust force and torque in vibration drilling of FRPs. The model required one test to determine the shear flow stress as an input. The results showed acceptable agreement between model predictions and experiments. Delamination was also investigated experimentally by Davim and Reis [44] as a function of tool geometry and cutting parameters. The study showed positive correlation between cutting parameters and delamination and that cutting speed is more statistically significant. However, this result contradicted the findings of Tsao and Ho-cheng [45, 46] who developed empirical CTF models for step drill and candle stick drill using Taguchi design and artificial neural networks. They found that feed rate and drill diameter were the most statistically significant factors. Furthermore, delamination-free step-drilling was achieved using low feed rates and high spindle speeds.

2.3. Milling

Milling is usually used in cutting FRP as corrective end machining operation or to give the required dimensional accuracy and produce high quality surfaces [47]. Delamination is also a concern during milling operations, it was studied by Hintze and Hartmann [48] during contour milling of CFRP. An analytical model for predicting delamination at the top layer was proposed by taking into account the geometric and mechanical properties of the laminate. The cutting force was found to cause the fibres to bend rather than fracture causing delamination. Mechanistic force model was developed by Karpat et al. [49, 50] who started by conducting milling tests with constant cutting speed. Cutting speed was deemed less significant compared with feed rate, which agreed with the findings in [51, 52]. A dynamic force model was then developed with force coefficients approximated to Sine function of fibre orientation and was found to have reasonable agreement with results. Karpat et al. also investigated the quality of the machined surfaces and found the locations of maximum cutting forces coincided with locations of largest delamination. Mechanistic model for helical milling was developed by Kalla et al. [53] for predicting cutting forces of uni/multi-directional CFRP for fibre orientation between 0-180^{o}. The cutting force coefficients required in such models were obtained from artificial neural network (ANN) database. The relationship between the cutting parameters with the cutting forces and surface roughness [51, 52] was studied empirically and found that cutting forces increased with feed rate and decreased with cutting velocity. Sreenivasulu [54] conducted experimental study on the effect of cutting parameters on the delamination and surface roughness of GFRP during end milling using Taguchi design and neural networks. The cutting speed and depth of cut were found to be statistically significant parameters affecting delamination and surface roughness.

2.4. Turning

Very limited work was done on modelling of turning composite materials with majority of the studies using the experimental approach. Chang [55] developed force model for turning GFRP using chamfered tool. The model was experimentally verified. Cutting forces and temperatures were investigated as a function to cutting tool material and geometry. Tool material was found to be statistically significant factor affecting cutting forces (K carbide tools yielded lower cutting forces than P carbide tools). Palanikumar [56-58] developed empirical models to predict surface roughness and tool wear when turning GFRP. Higher surface roughness values were observed with increasing feed rate, fibre orientation angle, while it decreased with higher cutting speed and depth of cut. With regards to tool wear, cutting speed was found to be the most significant factor followed by the feed rate. Hanfi et al. [59] developed a fuzzy rule-based model and response surface method-based model to predict cutting forces and power using control variables including cutting speed, feed and depth of cut. Gill et al. [60] also developed an empirical model to study the effect of cutting conditions and tool geometry on the cutting forces during turning of unidirectional GFRP lamina. Depth of cut had the most statistical significance on cutting forces.

3. Cutting metal-composite stacks

The usage of multi-layer materials is increasing in aerospace industry [61] especially in parts with high mechanical loads [62]. This is due to their high strength to weight ratio, superior fatigue performance and the wide range of functionality that every layer contribute to the overall properties of the stack [63, 64]. Different layers are joined by riveting or bolting, which necessitates generating holes into the different layers to the required dimensional tolerances. This is done mostly by drilling, but also by helical milling [65] and rotary ultrasonic machining [66]. There are three popular material combinations namely, CFRP/Al [67-69], CFRP/Ti [65, 66, 70-73] and Ti/CFRP/Al [61, 62, 67].

Limited theoretical modelling attempts were made when cutting metal-composite stacks. Roudgé et al. [74] introduced stacking order indicator which quantified the effect of stacking order on the machinability of the stack and quality indicator by aggregating all relevant quality measures with different weighting factors. Qi et al. [69] formulated CTF model when drilling CFRP/Al stack. The stacking order was changed and models developed for both cases. When CFRP was drilled last, the CTF was function of proportional coefficient of concentrated force, the critical energy release rate and the material coefficient of the uncut laminates. When Al was drilled last, CTF was affected by the assumed edge conditions, furthermore, a critical thickness of Al plate was calculated after which delamination did not occur. Vijayaraghavan and Dornfeld [64] presented a framework for FEM modelling of multi-layer materials that can be used to develop an accurate and practical drilling simulation tool. Matsumura and Tamura [75] developed a mechanistic model to predict cutting forces and chip flow in drilling multi-layer stacks by assuming that the oblique cutting process is a series of orthogonal cutting processes with different tool geometries. Material properties coefficients were experimentally obtained and model was verified as shown in Fig. 4.

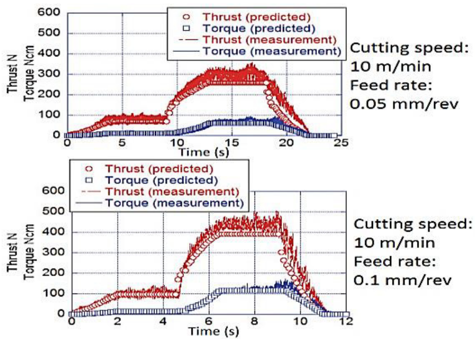

Fig. 4. Predicted vs. measured torque and thrust force values [75]

4. Conclusions

Current practices in modelling conventional cutting of FRP were presented in this paper. It is noted that orthogonal cutting has the most coverage in the literature due to its relative simplicity. Analytical models for orthogonal cutting are simple and discard much of the cutting phenomena, whereas more sophisticated models have been constructed using numerical approach. Drilling is investigated extensively, with concentration on delamination, especially using analytical models. Several critical thrust force models have been developed for special drill bits and delamination-free assistive techniques such as pilot holes and drilling with backup plate. Cutting forces, delamination and surface roughness are examined as function of cutting parameters for contour, helical and end milling of FRPs using the four modelling approaches. Modelling research on turning was found scarce and focused on cutting forces and surface quality. Metal composite stacks are becoming popular in aerospace industry and there is a need for generating holes through the different layers in a single shot for joining purposes. This is mainly achieved by drilling, but also by helical milling and rotary ultrasonic machining. Most of the research is experimental with recent and few attempts in analytical force modelling.

Despite the noticeable progress documented above, more modelling research is still needed. In analytical modelling, 3D models and models that include thermo-mechanical effects are absent. In numerical modelling, accurate representation of multi-scale failure mechanisms, large deformations and discontinuities are still challenging tasks, in addition to the high computational cost. Improvements on mechanistic models can be achieved by reducing the number of required tests to obtain the coefficients.

Authors believe that current literature metal cutting modelling might give useful insights into the development of more accurate analytical models of composites cutting. Emerging applications of multi-scale modelling and meshfree methods into machining and fracture problems provide a good opportunity to improve the accuracy of the numerical approach.

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