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Citation: AIP Conference Proceedings **1960**, 070005 (2018); doi: 10.1063/1.5034901

View online: https://doi.org/10.1063/1.5034901

View Table of Contents: http://aip.scitation.org/toc/apc/1960/1

Published by the American Institute of Physics

2D Simulations of Orthogonal Cutting of CFRP: Effect of Tool Angles on Parameters of Cut and Chip Morphology

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Abstract. Carbon-fiber reinforced composites (CFRP) are attractive materials for lightweight designs in applications needing good mechanical properties. Machining of such materials can be harder than metals due to their anisotropic behavior. In addition, the combination of the fibers and resin mechanical properties must also include the fiber orientation. In the case of orthogonal cutting, the tool inclination, rake angle or cutting angle usually influence the cutting process but such a detailed investigation is currently lacking in a 2D configuration. To address this issue, a model has been developed with Abaqus Explicit including Hashin damage. This model has been validated with experimental results from the literature. The effects of the tool parameters (rake angle, clearance angle) on the tool cutting forces, CFRP chip morphology and surface damage are herewith studied. It is shown that 90° orientation for the CFRP increases the surface damage. The rake angle has a minimal effect on the cutting forces but modifies the chip formation times. The feed forces are increased with increasing rake angle.

INTRODUCTION

Carbon-fiber Reinforced Polymers (CFRPs) are attractive materials combining good mechanical-to-weight ratio [1]. Unfortunately, machining CFRP remains difficult because both matrix and fiber exhibit different behavior under load. Recently, work has been performed to study orthogonal cutting via finite element methods and experiments [2-6]. Xu [2] examined CFRP/Ti stack geometries whereas we only intend on examining CFRP cutting. The first part of the paper consists in validating the model. Then, with this validated model to propose a novel approach of varying the rigid tool geometry and observe the effects on the cutting process in the simulation. Among the different orientations studied in the mentioned work [2], all the common fiber orientations (-45°, 0°, 45 and 90°) will be considered and the rake angles will be varied while maintaining all other parameters constant. The effect of the rake angle variation within the different ply orientations on the cutting forces, chip morphology, complete chip formation time and surface quality will be investigated.

Proceedings of the 21st International ESAFORM Conference on Material Forming
AIP Conf. Proc. 1960, 070005-1–070005-6; https://doi.org/10.1063/1.5034901
Published by AIP Publishing. 978-0-7354-1663-5/$30.00

MODEL

In order to make sure the simulation model depicts what occurs in experiments, a validation is mandatory. Herewith, results were compared to available experimental data from the literature [2]. Based on the description of Xu [2], an orthogonal cutting configuration was set up in Abaqus/Explicit with a Lagrangian scheme.

The CFRP mimicking a T300/914 composite material piece was chosen as a 1 mm long sample oriented in 4 unidirectional configurations, and the tool was modelled as a rigid body. The tool tip radius was set to 2 µm which is the same value as that of reference [2]. A constant clearance angle of 7° was used throughout and the rake angles were varied from 5, 10, 15 and 20°. A run for 45° ply orientation with -5° was also performed. The boundary conditions (BC) were chosen as "encastre" for the bottom part. The tool was restrained within the normal direction of the cutting direction (Y axis). The left boundary was restricted movement within X, ie, no displacement was allowed in the X direction. These BC mimic the conditions of the paper of Xu [2]. Figure 1 shows the model.

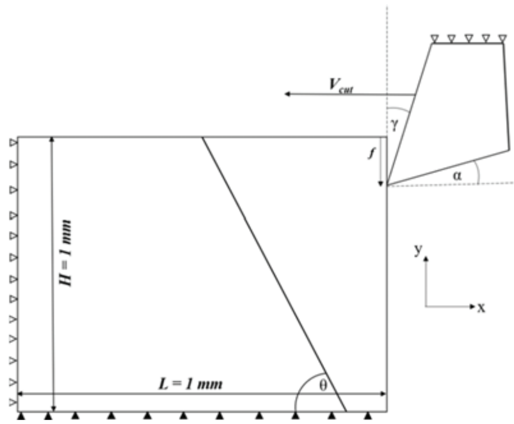


FIGURE 1. 2D orthogonal cutting configuration, triangles show boundary conditions (plain triangles are "Encastre" and empty triangles tips indicate constrained x movement for the left edge and y movement for the tool). f is the feed and V_{cut} is the cutting speed. α and γ are respectively the clearance and rake angles

TABLE 1. Mechanical properties used to model CFRP as an EHM [2, 8]

Mechanical Property	"T300/914" CFRP
Longitudinal modulus, E_1 (GPa)	136.6
Transverse modulus, E_2 (GPa)	9.6
In-Plane shear modulus, G_{12} (GPa)	5.2
Longitudinal tensile strength, X_T (MPa)	1500
Longitudinal compressive strength, X_C (MPa)	900
Transverse tensile strength, Y_T (MPa)	27
Transverse compressive strength Y_C (MPa)	200
Shear strength, S (MPa)	80
Longitudinal Tensile Fracture Energy (N/mm)	89.8
Longitudinal Comp. Fracture Energy (N/mm)	78.3
Transverse Tensile Fracture Energy (N/mm)	0.23
Transverse Comp. Fracture Energy (N/mm)	0.76

The meshing of the CFRP consisted of 4-node plane-stress linearly interpolated elements (CPS4R) with squared 5µm divisions for all elements in contact with the rigid tool. The Stiffness Hourglass algorithm was used as it yielded the lowest artificial error output (as low as 8% Artificial energy/Internal energy ratio compared to ≥50% with the default values) and was critical to make sure the simulation had minimal artifacts. All the hourglass models in Abaqus were tested preliminarily in order to yield the lowest artificial energy output. Distortion control was tested and a fixed value of 0.2 was found to be the best setting. The CFRP material was defined as an Equivalent Homogeneous Material

(EHM) and parameterized as the reference [2]. Hashin damage initiation, available in Abaqus was considered with the parameters from table 1.

In order to consider element deletion, it is possible to modify the degradation parameter to a value slightly different than unity. It simply means that an element will be considered "failed" under Hashin [7] definitions and the damage evolution law will completely remove the failed element past the degradation parameter value. Damage evolution was treated as linear with the values from reference [8]. Coulomb friction between the tool and piece was considered with a constant value of 0.4 [2]. The authors the Coulomb friction model as to remain within the reference's definitions.

The cutting parameters from Xu et al were used in feed (0.2 mm/rev) and cutting speed (40 m/min). Although these authors did explore a range of cutting speeds, we used the same setting as the one where cutting force is presented and compared to experiments in their paper [2]. The so-called Hourglass, distortion control and degradation parameters of Xu were not described so we have assumed that default settings were employed. It was realized that default settings yielded unrealistic behavior in either artificial energy or chip formation so it was decided to perform an additional analysis toward the determination of optimal settings. The Stresses reported by Xu are in the 800MPa range at the crack initiation which is what we obtain according to Fig. 2 in the results section. Table 2 presents the cutting parameters. Experimental cutting forces are also reported in Xu's paper in the range of 30-80 N/mm for the cutting force and 7-27 N/mm for the feed forces [2].

TABLE 2. Simulation parameters employed in simulations

Simulation parameter	Value
Feed, f (mm/rev)	0.2
Cutting speed, V_{Cut} (m/min)	40
Rake angles, γ (°)	5, 10, 15, 20
Clearance angle, α (°)	7
Fiber orientations, θ (°)	-45, 0, 45, 90
Distortion control (%)	20

RESULTS AND DISCUSSION

Cutting forces

Rake angles of 5, 10, 15 and 20° were tested with a constant 7° clearance angle. According to the RMS (Root Mean Square which is the square root of the average squared values) values of cutting and feed forces, the rake angle increased the feed forces values while cutting forces did not vary significantly within the range of studied parameters (tables 3-6). Taking root mean square values allow for an overall average of the cutting forces across the simulation window used of 1 ms.

The feed force over cutting force ratios exhibited small variations across the same fiber orientation. Visually, better contact is kept with the tool rake face, friction coefficients being held constant throughout (0.4) according to [2]. The tool wear was not taken into account here, but it is definitely a factor that ought to be considered on experimental testing. 0° orientation fibers exhibited the smoother surfaces regardless of tool rake angles, whereas at the opposite side of the spectrum, 90° orientations showed the most damage. According to Sheikh-Ahmad [1], optimal rake angle for multidirectional CFRP cutting is roughly 6-7° whereas from 0° to 5°, the cutting forces decrease and increase after 7°, all with a constant 17° clearance angle. These values are experimental but according to our simulations, the same trend on RMS cutting forces values was not confirmed for the unidirectional CFRP model. The feed force increased with increasing rake (within the studied range) regardless of the fiber orientations (tables 3, 4, 5 and 6). Moreover, 90° fiber orientation exhibited the highest cutting force and feed force values (table 5) but the cutting force values remain constant as confirmed in experiments of Glass-Fiber Reinforced Polymers (GFRPs) [1].

TABLE 3. Compilation of reaction forces and forces ratio for 45° fiber orientation. RMS values are shown

Rake Angle (°)	Cutting Force (N/mm)	Feed Force (N/mm)	Feed/Cutting Force Ratio
5	22.319	2.521	0.113
10	21.236	2.427	0.114
15	19.577	3.565	0.182
20	20.333	3.775	0.186

TABLE 4. Compilation of reaction forces and forces ratio for 0° fiber orientation. RMS values are shown

Rake Angle (°)	Cutting Force (N/mm)	Feed Force (N/mm)	Feed/Cutting Force Ratio
5	15.481	0.682	0.044
10	17.874	0.922	0.052
15	26.737	1.490	0.056
20	25.757	2.072	0.080

TABLE 5. Compilation of reaction forces and forces ratio for -45° fiber orientation. RMS values are shown

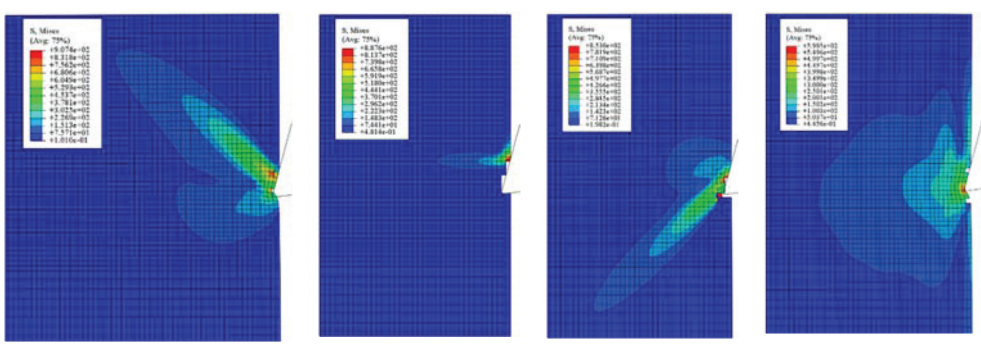
Rake Angle (°)	Cutting Force (N/mm)	Feed Force (N/mm)	Feed/Cutting Force Ratio
5	25.851	4.450	0.172
10	25.493	3.242	0.127
15	27.146	3.326	0.123
20	22.199	5.994	0.270

TABLE 6. Compilation of reaction forces and forces ratio for 90° fiber orientation. RMS values are shown

Rake Angle (°)	Cutting Force (N/mm)	Feed Force (N/mm)	Feed/Cutting Force Ratio
5	55.355	2.394	0.043
10	43.483	3.921	0.090
15	53.038	5.516	0.104
20	43.607	5.367	0.123

These results clearly suggest that the rake angle has only a mild influence on cutting forces. More fiber angles should be tested to explore the influence especially in the case of multi-plies which are preferred in the industry. Regarding chip morphologies versus fiber and rake angles individually, better physical contact between the formed chip and the rake face of the tool was achieved with increasing rake but the fiber angle seems to be dominant in the chip morphology.

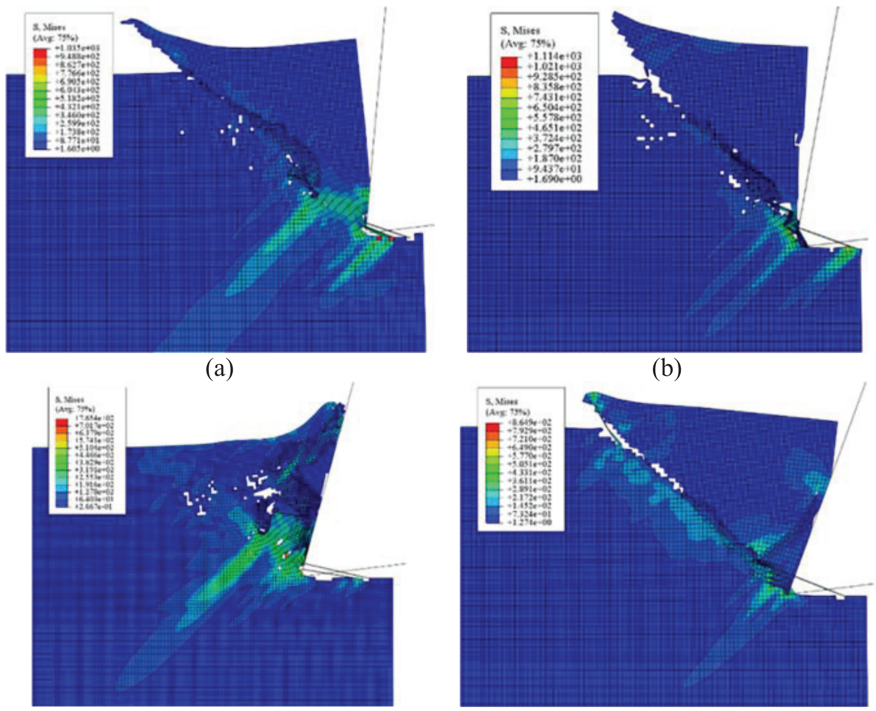
Crack initiation and Chip formation times



(a) (b) (c) (d)

FIGURE 2. Crack initiations after the tool tip for the 4 orientations tested (45° (a), 0° (b), -45°(c) and 90° (d)). The images are all taken at 1.5 10^{-5} s. Stresses are in MPa. Rake angle is 15° in all cases

For a given fiber orientation, as seen on Fig. 3, increasing the rake angle delayed the chip formation time except at 15°. At this point, the authors would like to emphasize that this behavior is surprising and additional simulations are needed to explain the phenomenon.



(c) (d)

FIGURE 3. Chip morphologies for -45° fiber orientation at 5° (a) at 1.12 10^{-4}s, 10° (b) at 1.17 10^{-4}s, 15° (c) at 2.81 10^{-4}s and 20° (d) rake angle at 1.39 10^{-4}s. Von-Mises stresses in MPa

Surface Damage

The surface damage is more important in the 90° fiber orientation runs compared to the 0° and +45° and - 45°. This is shown on Fig. 4. This behavior has been observed in Xu's simulations [2] and is confirmed by Wang's experiments [9]. It is possible to quantify delamination damage by estimating the maximum distance between the ideal surface to the origin of the crack tip which is usually the tool tip and our result indeed suggest that during machining processes of CFRP, care needs to be taken regarding fiber orientation depending on the application but also the machining in itself.

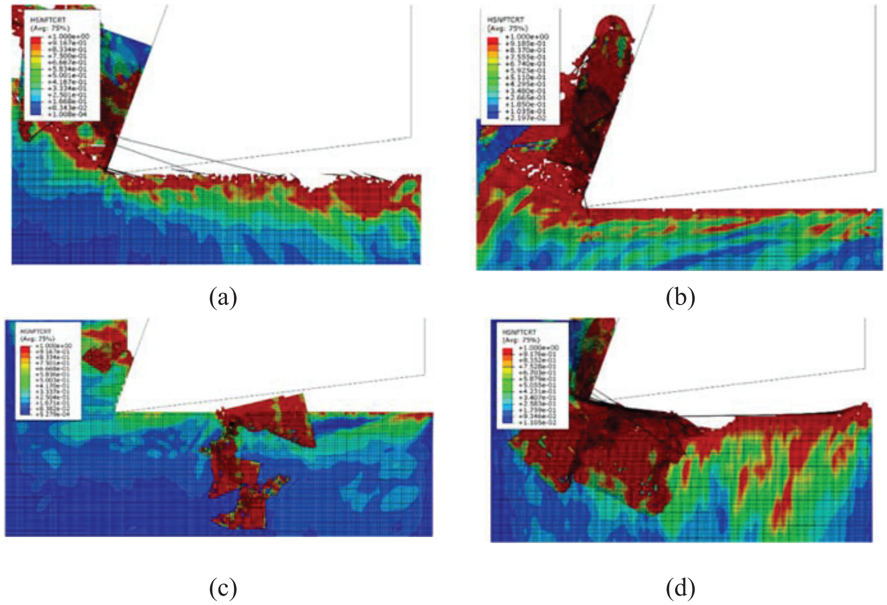


FIGURE 4. Surface damage after tool cut, for 20° rake angle. Hashin Fiber Traction failure parameter is displayed (red = failed). Clockwise from top left is 45° (a), -45° (b), 90° (c) and 0° (d) fiber orientations

CONCLUSIONS

In the present article, 2D orthogonal cutting of a “T300/914” EHM model CFRP was studied with Abaqus/Explicit for 4 different fiber orientations. It was shown that for each orientation, the feed force increased with increasing rake angle from 5 to 20°. The cutting force were shown not to be influenced significantly by the rake angle but more data is needed for a more thorough interpretation. Composite surface damage was very important at 90° which indicates that when machining CFRP care must be taken toward the relative angles between the composites and the tools. Chip morphology and complete chip formation times were shown to be very dependent on the rake angle. An optimum may exist but the range studied only permits to show a qualitative trend. 90° orientation should thus be avoided when machining CFRP and 0° should be privileged (this does not take tool wear into account). More studies with more rake and clearance angles with experimental testing will be performed in a future contribution.

ACKNOWLEDGMENTS

Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11. The authors also acknowledge the Région Wallonne for funding under Convention N° 1610039.

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