

Development and experimental validation of a macroscopic analytical model aiming to generate metal-FRP stacks drilling cutting force and torque

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Abstract. Composites materials and especially FRP are increasingly employed in many fields of applications (transport, aerospace, ...) due to the current trend of improving global energy performances of new designs notably by mass saving. However the use of metallic materials such as aluminum and titanium alloys is still necessary in many cases and a lot of structures are made of a dual technology called stacks (panels composed of different layers of FRP and metal bounded together). Combining the different properties of these materials offers many advantages regarding the mechanical and structural aspects. This is nevertheless for the same reason that machining and especially drilling stacks is a laborious task: the tools and cutting conditions are way too divergent to avoid vibrations, problems of dimensional tolerances and delamination of the composite. The knowledge and characterization of the drilling cutting forces is a first step to solve these issues. The purpose of this article is to provide an accurate macroscopic analytical model fitted for stacks and compare it quantitatively with experimental tests. The given model is divided in two parts (i.e. respectively adapted for the two materials) and is based on the discretization of the cutting edge. The proposed algorithm is able to predict accurately drilling force and torque along time in function of the cutting conditions, the tool and material configurations. A reverse least squared method is used to obtain the empirical input parameters, allowing to minimize the number of experimental drilling tests to obtain the empirical input parameters.

Keywords. Drilling, Macroscopic, Model, Cutting Force, Stacks, Fiber Reinforced Plastics, Metal

1 Introduction

Stacked metals-FRP materials are increasingly employed in many industries such as automotive, railways and aerospace due to the dual properties offered by these materials: lightweight and mechanical resistance. In addition machining process and especially drilling, which is the more common machining operation used for these kind of net-shaped material, can cause a large range of issues: delamination of the composite part by peel up or push up [1], burrs and tearing especially at the exit [2], vibrations [3] and large tool wear [4] due to the changing machining properties between composite and metal [5]. The knowledge of the cutting force and torque is a key point to avoid all these previous problems. It allows comparing it with a critical thrust force and torque for delamination and crack or to establish limit parameters to prevent tool wear and vibrations.

Since 1950s a lot of research works has been carried out to model cutting force for the basic metal machining operations. The Merchant's [6] model of the orthogonal cutting forces by shear plane modeling is the basis for many other models specific to each machining operation. Firsts drilling force models for metals were introduced in 1970s and can be divided into two categories [7]: some using an iterative theoretical energetical pattern based on the shear plane zone theory by assuming that the mechanical properties are known, while some others prefer to use experimental approaches thanks to empirical parameters giving more accurate results. Most of them are based on a

3D spatial discretization combined with oblique cutting or simplified quasi-orthogonal cutting theory and are tool and material specific.

This paper present a new drilling cutting force and torque algorithm developed for stacks metal-FRP by using Chandrasekharan and al.'s [8,9] and Langella and al.'s [10] theories which is able to predict with a reduced number of drilling tests accurate non-tool dependent values of the empirical input parameters thanks to a reverse least squared minimisation method.

Nomenclature

α_n	Normal rake angle [°]	F_{ind}, T_{ind}	Indentation cutting force and torque [N],[Nmm]
η_c	Chip flow angle [°]	F_z, T	Drilling thrust force and torque [N],[Nmm]
$\rho(r)$	Radial coordinate parameter $\rho(r) = \frac{r}{R}$	k	Half point angle [°]
ρ_t, ρ_f	Weighting torque and force parameter for reverse model	K_n, K_f, K_v, K_h	Normal, tangential, vertical and horizontal specific pressure [N/mm ²]
θ	Helix angle [°]	K_s	Yield stress [N/mm ²]
θ_c	Drill chisel edge angle [°]	L_{chisel}	Half chisel edge length [mm]
A, B, C, e	Empirical parameters of Langella's [26] cutting force model	n	Rotation speed [RPM]
A_c	Chip section [mm ²]	N_d	Number of spatial discretized elements
$a_c, a_f, b_n, b_f, c_n, c_f, C_n, C_f$	Empirical parameters of Chandrasekharan's [17] model	P_{chisel}	Point angle of chisel edge [°]
dt	Time discretization period [s]	R	Twist drill's radius [mm]
dy	Length of a discretized spatial element [mm]	r	Radius of a cutting edge element [mm]
f	Feed [mm/turn]	t_c	Uncut chip thickness, $t_c = \frac{f}{2} \cdot \sin(k)$ [mm]
$F(N_i, 1), T(N_i, 1)$	Drilling cutting force and torque matrices [N],[Nmm]	T_t	Total drilling time [s]
F_n, F_f	Tangential and normal cutting force [N]	w	Half of the drill web thickness [mm]
$F_{exp}(N_i, 1), C_{exp}(N_i, 1)$	Experimental cutting force and torque matrices [N], [Nmm]	x, y, z	Global coordinates system
		Z	Vertical coordinate of the twist drill [mm]

2 Stack cutting force and torque modelling

Common architecture for metals and composites

The suggested model is based on a dual discretization in order to highlight the thrust force and torque value:

- A spatial discretization of the cutting edge is set up as shown in figure 1 inspired from Chandrasekharan and al.'s model [8]. Twist drill cutting edges are decomposed in two main parts: chisel edge (central part) and cutting lips (peripheral part) where the cutting phenomena and parameters differ according to the material type and location (described below). The concerned edges are divided into N_d elements of length dy (mm) in which the infinitesimal force $d\vec{F}_z$ and torque $d\vec{C}$ are computed, the total drilling thrust force \vec{F}_z and \vec{C} are then given by the following sums (1) and (2) multiplied by x , the number of cutting lips (2 in this work):

$$\vec{F}_z = x \sum_0^{N_d} d\vec{F}_z \quad (1)$$

$$\vec{C} = x \sum_0^{N_d} d\vec{C} \quad (2)$$

The radial coordinate $\rho(r)=r/R$ of each spatial element n_d is previously necessary to determine the location of the elements (chisel edge of cutting lips) and thus calculate the drilling force by an appropriate equation.

- A time discretization is also required to obtain the drilling cutting force value in function of the time through the different materials crossing phases (figure 2) contained in a drill test. The total drilling time T_t (s) of an operation is divided into N_t steps of a time length dt which gives total cutting force matrices $F^*(N_t)$ and $C^*(N_t)$. The vertical position $Z_{Rp}(t)$ of a reference point R_p placed on the center of the twist drill is computed at each time steps and allows to obtain the position $Z_{elem}(\rho, t)$ of a spatial element located in the chisel edge or in the cutting lips by geometric knowledge of the twist drill. Knowing the vertical position of each cutting edge element then makes it possible to determine the material in which it is located and set the appropriate theoretical cutting force model for the element thanks to the positioning of boundary z_1, z_2, z_3 at the border of each material.

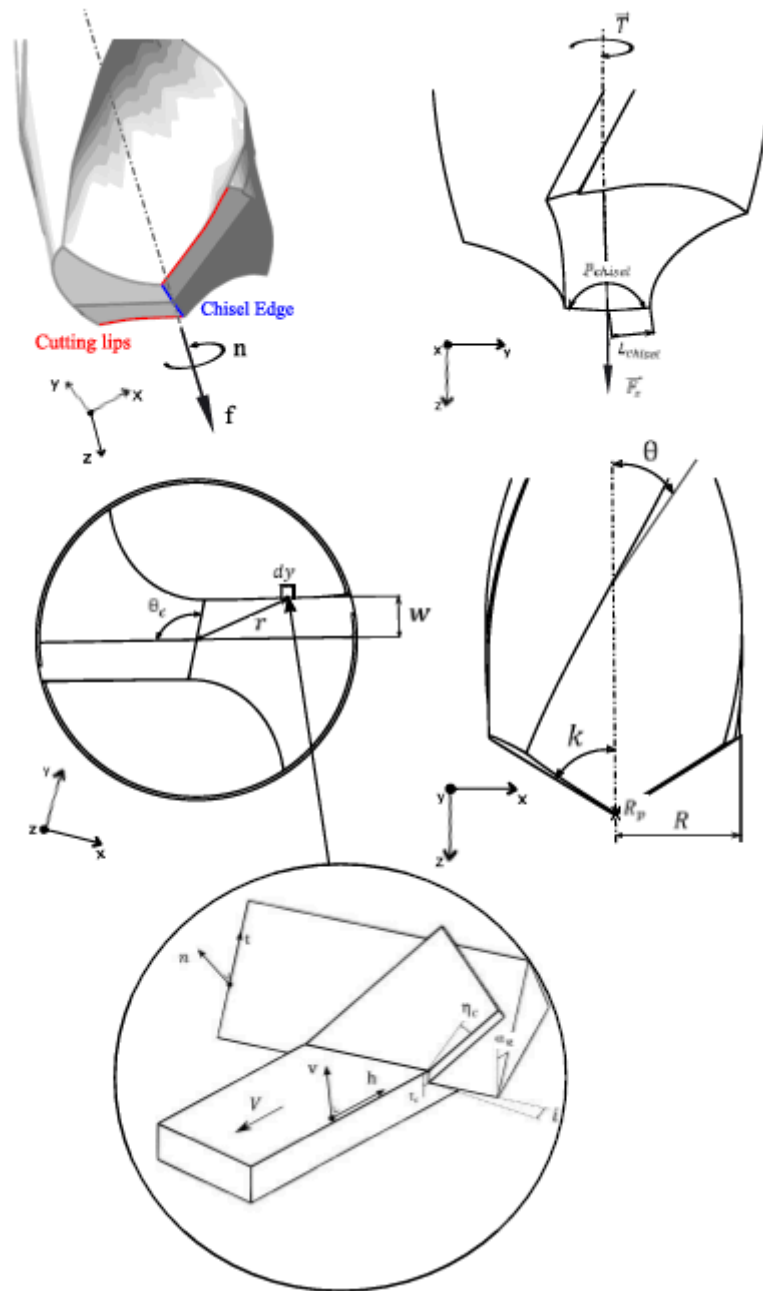


Fig. 1. Geometrical parameters and spatial discretization of a twist drill

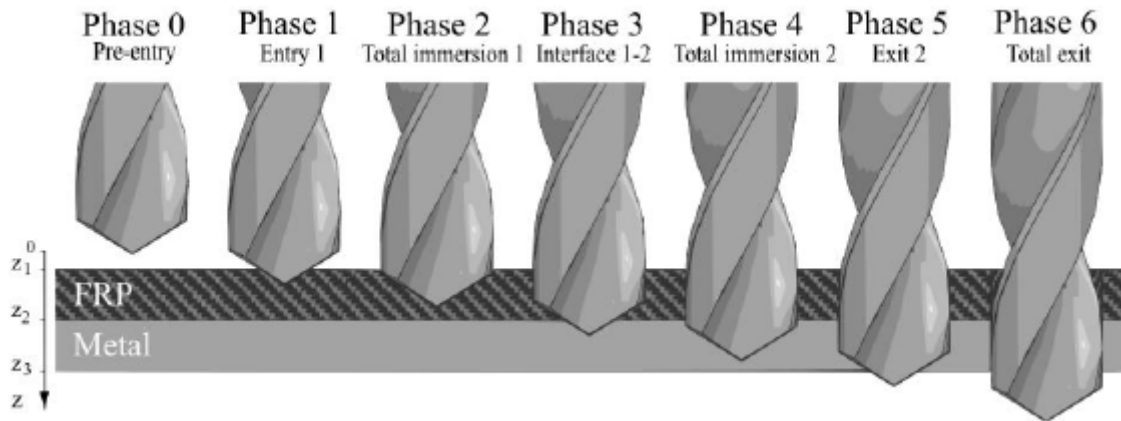


Fig. 2. Temporal steps of a standard drilling operation for a FRP-metal stacks

As previously mentioned the cutting mechanisms (as well as its mathematical descriptions) taking place in the cutting lips and in the chisel edge are different. This distinction can be explained by the geometric difference and the orientations of the two types of cutting edges:

- The orthogonal cutting theory is used for chisel edge (with a large negative rake angle) thanks to its radial orientation (which induces that the cutting speed of each discretized edge element will always be orthogonal to its edge direction).
- Cutting lips are not radial and the cutting speed of each discretized edge element is not orthogonal to the cutting edge, this explains why oblique cutting theory (more complex three dimensional problem) is used for this geometric part (this induces the introduction of an inclination angle i between the normal direction to cutting speed and the cutting edge).

Cutting forces are then specifically given according to the material, cutting conditions, the tool parameters and cutting zone by Chandrasekharan and al.'s [8] equations (3) and (4) for metals and by Langella and al.'s [10] equations (5) and (6) for UD (unidirectional) FRP:

$$dF_n = K_n \cdot dA_c \quad (3)$$

$$dF_t = K_t \cdot dA_c \quad (4)$$

$$dF_v = K_v \cdot (dA_c)^{0.5} \quad (5)$$

$$dF_h = K_h \cdot dA_c \quad (6)$$

With K_n , K_t , K_v , K_h called respectively the normal, tangential, vertical and horizontal specific pressure given by equations (7), (8), (9), (10), themselves depending on 8 empirical parameters a_n , a_t , b_n , b_t , c_n , c_t , C_n , C_t for metals and 4 parameters A , B , C , c for UD FRP.

$$K_n = C_n \cdot t_c^{a_n} \cdot V^{b_n} (1 - \sin(\alpha_n))^{c_n} \quad (7)$$

$$K_t = C_t \cdot t_c^{a_t} \cdot V^{b_t} (1 - \sin(\alpha_n))^{c_t} \quad (8)$$

$$K_v = B \cdot 10^{-1.089 \cdot \alpha_n} \quad (9)$$

$$K_h = A + B \cdot 10^{-1.089 \cdot \alpha_n} \quad (10)$$

These assumptions lead to a global algorithmic structure developed on MATLAB, which can, from the different parameters of the standard tool ($\theta, \theta_c, k, R, P_{chisel}, w$), of the cutting operation (feed f , rotation speed n), of the discretization (number of time N_t and spatial increment N_d) and of the stacks configuration (thickness of each layer, order of drilled materials and empirical parameters linked to the specific pressure), return plots and analytical results of the total thrust force and torque induced through time.

3 Reverse model

Finding the associated material parameters can be a hard and specific task especially with energetical and shear plane methods. The choice of the two previous macroscopic cutting force models using empirical parameters has been made consequently taking into account the efficiency and the facility to obtain reliable results. Furthermore many methods can be used to find these parameters: for instance Chandrasekharan and al. [8,9] use experimental turning tests (orthogonal cutting) while Langella and al. [10] apply experimental drilling tests by approximation using an average constant rake angle $\alpha_{n,m}$. The most common problem of using these drilling tests methods is the large tool dependency of the results and the number of experimental tests to be performed to ensure reliability on a large range of cutting parameters. On the other hand applying the turning tests or orthogonal cutting methods for unidirectional FRP is difficult to implement in practise and will not provide efficient results due to the dependence on the fibre's orientation while this drilling method does not take it into account.

In order to solve these problems a least squares function has been developed which allows to find an approached value of the empirical parameters by minimisation of experimental drilling forces tests carried out on each of the material separately. The least squared function is obtained considering respectively the metal's and FRP's empirical parameters $a_n, a_t, b_n, b_t, c_n, c_t, C_n, C_t$ and A, B, C, c as variables to optimize into the following expression:

$$f(a_n, a_t, b_n, b_t, c_n, c_t, C_n, C_t \text{ or } A, B, C, c) = \rho_f \cdot \sqrt{\sum_{i=1}^{N_t} \left(\frac{F(i) - F_{exp}(i)}{F_{exp}(max)} \right)^2} + \rho_c \cdot \sqrt{\sum_{i=1}^{N_t} \left(\frac{C(i) - C_{exp}(i)}{C_{exp}(max)} \right)^2} \quad (11)$$

With $F(T_t)$ and $C(T_t)$ respectively the force and torque in function of the empirical parameters obtained thanks to the previous algorithm (section 2), $F_{exp}(T_t)$ and $T_{exp}(T_t)$ the measured force and torque matrices of experimental drilling test, $F_{exp}(max)$ and $T_{exp}(max)$ the measured maximum force and torque (this parameters allows to obtain a dimensionless function), ρ_f and ρ_t the weighting factors which makes possible to give more importance to one test than another, and T_t the total time of the drilling test. By choosing carefully an efficient iterative minimization method (e.g. the MATLAB `fmincon()` constrained minimization function using the interior point algorithm which is able to work with a large number of parameters) this reverse technique can offer many advantages: an efficient, robust and uniform method able to obtain the necessary parameters thanks to a few tests (see section 4 below) without any variables

approximation. The least squared method allows to find accurate results even with large measuring noise and makes it possible to override some experimental disadvantages such as experimental initial time which can also be considered as a minimization variable (i.e. the time delay between the initial measurement and the initial time of drilling which is often an unknown to consider).

4 Validation and experimental tests

In order to validate the different developed algorithms, first theoretical tests using the presented parameters of Chandrasekharan and al.'s [8] and Langella and al.'s [10] models have been performed allowing to compare and set up the direct stacks cutting force model.

Once this first step achieved, experimental drilling tests have been performed on stainless steel AISI 304 and UD CFRP layers (separately) with a standard HSS-E5 4.0 Tivoly twist drill to confirm the efficiency of the reverse model. The cutting forces were measured by means of the Kistler 9257B dynamometer as shown in figure 3.

Table 1 below lists the input parameters used for the tests, it is necessary to stress that both of the metallic and composite reverse models have been performed using 4 cutting tests selected on a large range of feeds as reference with a constant spindle speed (selecting a constant spindle speed does not affect significantly the results).



Fig. 3. Experimental measurement set up used for drilling tests

Table 1. Input parameters for experimental tests

Tool parameters	TIVOLY HSS-E5 4.0			
k [°]	67.5			
P_{chisel} [°]	0			
θ [°]	30			
θ_c [°]	120			
R [mm]	0.4			
w [mm]	0.75			
Experimental and simulation parameters				
Sample frequency [Hz]	500			
dt [s]	0.002			
N_d	200			
Cutting tests parameters				
n [RPM]	1	2	3	4
f [mm/rev]	0.0125	0.025	0.03125	0.0375
Material parameters				
Thickness [mm]	AISI 304		UD CFRP	
	3		3.8	

Figure 4 shows a graphical comparison between the curve obtained for the single test 1 for both AISI 304 and CFRP and the experimental measurement (filtered on Matlab thanks to a lowpass filter set at 10 Hz), and finally table 2 shows then the obtained values of the empirical parameters and the average errors in percentage for phase 2 and 4 (total immersion of the twist drill in CFRP and AISI 304 respectively).

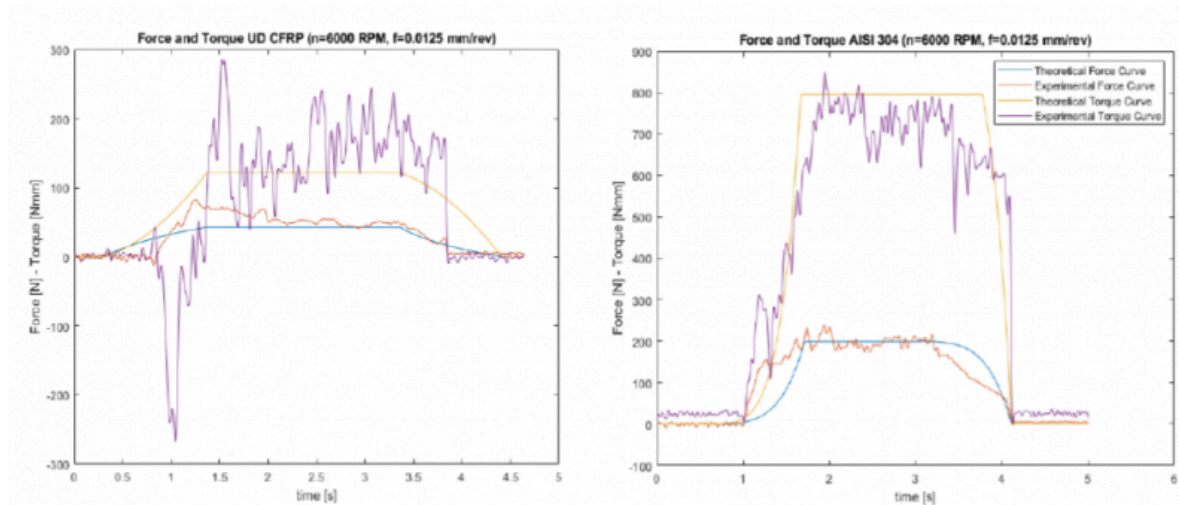


Fig. 4. Comparison between experimental measurements and the established reverse model

Table 2. Obtained parameters and results

UD CFRP parameters		A		B		C		c	
		362.951		60.763		1.998		1.452	
AISI 304 parameters		a_n	a_t	b_n	b_t	c_n	c_t	C_n	C_t
		-0.385	-0.895	3.779	4.085	0.207	-1.618	0.026	0.779
Av. Error [%]		1		2		3		4	
UD CFRP	Force	19.7		9.8		9.0		2.2	
	Torque	13.3		1.3		0.2		8	
AISI 304	Force	3.9		5.5		9.8		14.5	
	Torque	16.6		21.1		15.5		19.1	
Standard deviations		1		2		3		4	
UD CFRP	Force [N]	10.8		11.4		17.8		30.4	
	Torque [Nmm]	51.0		39.6		76.6		106.5	
AISI 304	Force [N]	16.9		22.7		34.7		67.0	
	Torque [Nmm]	54.3		61.7		197.9		500	

Comparison with the first experimental measurements of drilling thrust force and torque and theoretical value obtained thanks to the empirical parameters shown in table 2, average errors of 5 to 20% have been obtained. These first results confirm the reliability of the developed reverse mode despite large measurement noise shown in table 2 by the standard deviations of the experimental acquisitions for all the tests.

5 Conclusion

A new cutting force and torque model for stack metal-FRP has been developed and then experimentally validated with drilling cutting forces measurement on AISI 304 and UD CFRP. The use of Chandrasekharan and al.'s [8] and Langella and al.'s [10] empirical material parameters coupled with the developed reverse least squared minimization function allows to find easily non tool dependent parameters, giving first accurate results that will be further developed in the future (on different materials and tools). This type of algorithm allows to find reliable values and temporal evolution of thrust force and torque for stacks metal-FRP (or each of the materials specifically) on a large range of cutting parameters and thanks to a few tests, despite large measurement noise. This will then make it easier to solve problems such as premature wear of cutting tools or vibrations causing bad dimensional tolerances in drilling parts.

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