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CUTTING MODELS IN DRILLING: DUALITY BETWEEN EXPERIMENTAL AND THEORETICAL MODELS

Philippe DARNIS, Olivier CAHUC

Abstract: *Drilling constitutes a strategic operation in aeronautics. It is involved during assembly operations for which hundreds of thousands of holes are drilled on planes. The modeling of this operation is necessary in order to determine the thermomechanical parameters related to the machining conditions. It is also necessary to predict the behavior of the drills and to link the geometrical and kinematics parameters to the quality of the drilled holes. In this article the juxtaposition of two approaches of the process is presented: experimental and theoretical approach. These two approaches are complementary. Experimental approach allows linking the geometrical and kinematics parameters to the qualitative parameters of the hole. Theoretical approach integrates the thermal and mechanical laws to model the cutting process.*

Key words: *drilling, model, experimental, analytical, geometrical description, cutting forces.*

1. INTRODUCTION

Among the cutting processes, drilling is a strategic operation for aeronautic manufacturers. It is used in machining of parts and mainly during assembly of parts. An airplane such as A380 consists of several hundreds of thousands holes. This is why the industrial and economic stakes related to this operation are very important. The modeling of this operation is thus necessary in order to predict not only the cutting forces but also the behavior of the drill and the quality of drillings.

Two ways of modeling can be used:

i) Experimental modeling allows connecting the entry parameters such as the kinematics and geometrical parameters of the drill to the 6 mechanical actions or central axis by "black box" approach with mathematical functions independent of the physical problem. The same step allows to connect the parameters to the holes quality [8].

ii) Theoretical, analytical or numerical modelings are driven by the phenomenology of the process and the laws of mechanics and physics. It is based on the mechanics of high strains through behavior laws, the tribology of the contact and on assumptions related to the flow of matter. The resolution of the problem by energy minimization allows obtaining the thermomechanical parameters such as the cutting pressures and the temperatures of cut [1].

For these two forms of modeling, a fine geometrical description is necessary. For drilling, the complex shape of the tool is related to the parameters of achievements dependent on the shape of the grinding wheel for finishing and its orientation compared to the drill axis.

The first paragraph is dedicated to the geometrical definition of the drill and to the calculus of the cutting angles. The following paragraphs illustrate the two parallel steps concerning experimental modeling and theoretical modeling. We will show, in this paper that the two forms of models are necessary and complementary.

2. GEOMETRICAL DESCRIPTION

Several methods of description of the tool geometry are proposed [6, 7, 17]. All these methods are linking the tool shape and parameters of the finishing operations of the drill. The forms of a cast solid drill are obtained through a rough form (the body of the drill) by removing matter during the various phases of machining. Various surfaces constituting the drill are the result of the finishing operations. Only these operations are important to determine the geometrical model of the drill.

The geometrical model of a drill can be carried out with CAD system or analytically. The analytical solution makes it possible to define by mathematical equations the various constitutive surfaces of a drill. This mathematical definition being invertible, it is then possible to define the shape, the position and the orientation of the finishing grinding wheel with a known geometric description of the drill [1] The modeling of the drill consists in defining the grooves mathematically and to model the tip of the tool. These two steps allow determining cutting angles.

2.1. Grooves model

The groove surface corresponds to the envelope surface of the movement of the finishing grinding wheel. This envelope surface can be defined starting from shape and the trajectory of finishing grinding wheel [6, 7, 11, 17]. In order to define the envelope surface, it is necessary to make a mathematical description of the grinding wheel and of its trajectory (Fig. 1).

The groove can also be described with its section in a reference plan and an extrusion trajectory. The groove section [16] will be then the envelope of the various intersections of the finishing tool with the reference plan.

The extrusion trajectory that allows generating the surface is corresponding to the movement of the finishing tool.

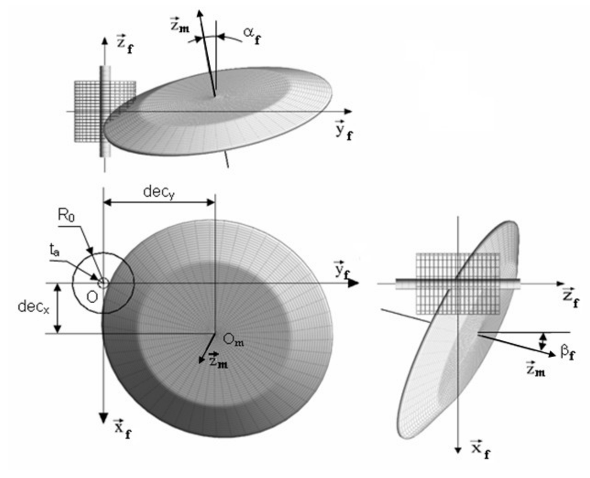

Fig. 1. Position definition of the finishing grinding wheel in the reference mark related to the drill.

The surface of the grinding wheel can be described by the parametric function:

$$\overline{F(u,v)}_{(\overline{x_m},\overline{y_m},\overline{z_m})} = \begin{cases} g(u)\cdot\cos(v) \\ g(u)\cdot\sin(v) \\ f(u) \end{cases} \quad (1)$$

where *u* et *v* are parametric coordinates and *f(u), g(u)* are parametric functions of the profile of the grinding wheel.

The orientation of the reference mark related to finishing tool in the reference mark related to the drill can be defined by two successive rotations: a rotation of angle α around the vector $\overrightarrow{x_f}$ and a rotation of angle β around the vector $\overrightarrow{y_f}$. The vectorial equation of the surface of the finishing tool is :

$$\begin{aligned} &\overline{OM}_{(O,x_f,y_f,z_f)} = \overline{G(u,v)} = \\ &[M_p]\cdot([M_p]\cdot\overline{F(u,v)}) + dec_x\cdot\overline{x_f} + dec_y\cdot\overline{y_f} \end{aligned} \quad (2)$$

$[M_\alpha]$ and $[M_\beta]$ are transformation matrices. dec_x and dec_y are shifts of the grinding wheel respectively along $\overrightarrow{x_f}$ and $\overrightarrow{y_f}$ (Fig. 1).

Starting from the definition of the surface of the finishing grinding wheel its reference position, the trajectory of the finishing grinding wheel allows creating a bundle of surfaces. The movement of the finishing tool is constituted of a helicoid trajectory.

The surface of the groove is the envelope surface of this bundle of surfaces. This one being helicoid, its envelope is a helicoid surface too, defined by a curve and the trajectory of helicoid extrusion corresponding to the trajectory of the grinding wheel. Equations of the movement of completion being known, only the section remains to be determined [1]. This one is defined starting from the envelope curve of trajectories of the grinding wheel and a cross-section of the drill.

Let us consider a point M of the envelope curve: this point also belongs to the intersection of a position of the finishing tool with the plan of the cross-section. The tangents with the envelope curve and with the intersection curve will be collinear. Their vector product will be thus null. This condition can be written:

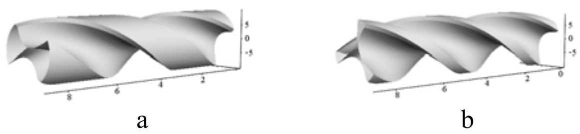

Fig. 2. Body of a drill with two grooves (a) and three grooves (b).

$$\frac{d\overrightarrow{F_{Env}(\Theta_z)}}{d\Theta_z} \wedge \frac{d\overrightarrow{F_{Int}(u,\Theta_z)}}{du} = \vec{0}, \quad (3)$$

where $\overrightarrow{F_{\text{int}}(u,\Theta_z)}$ and $\overrightarrow{F_{env}(\Theta_z)}$ are respectively the function of the intersections of the grinding wheel in the drill reference mark and the parametric function of the envelope curve in the drill reference plan.

The final stage consists in carrying out a helicoid extrusion to define completely the groove. The equation of the drill body with the grooves can be written :

$$\overline{OM}\Big|_{(\vec{x}_f,\vec{y}_f,\vec{z}_f)} = \begin{vmatrix} f_x(s)\cdot\cos(\Theta_z) - f_y(s)\cdot\sin(\Theta_z) \\ f_x(s)\cdot\sin(\Theta_z) + f_y(s)\cdot\cos(\Theta_z) \\ R_0\cdot\cot(\delta_0)\cdot\Theta_z \end{vmatrix} \quad (4)$$

where f_x and f_y are the envelope curve coordinates respectively along $\vec{x}_f$ and $\vec{y}_f$. δ_0 is the drill flute angle and Θ_z is a parameter of rotation in the helicoid trajectory.

To define the whole body of the drill, the section of the groove has just to be copied (Fig. 2).

The groove being defined, the machining of the tip of the drill makes allows defining the cutting edges.

2.2. Tip model

There is several types of tip of drill (2 sides, 4 sides, spiral-bevel, standard Hertel, standard Sandvik, Bickford geometry …) [12]. Nevertheless, the geometries usually used to define the tip of drill are of revolution shapes (cylinder, cone, hyperboloid, ellipsoid) [14] and helicoid forms [5]. In both cases, the surface of the tip is described with a generating curve planes and a trajectory curve (circle or ellipse).

For a biconical machining of the tip, surfaces generating the tip of the drill can be expressed in the reference mark related to the point of the drill by:

The biconical machining is defined by a translation and two rotations respectively around $\vec{y}_f$ axis and around the cutting edge (Fig. 3).

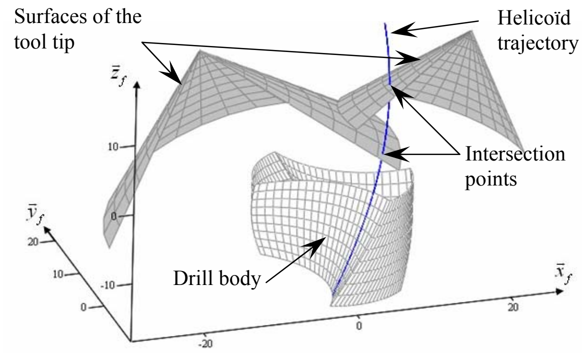

Fig. 3. Biconical machining– construction of the intersection between the tip and the body of the drill.

$$\overrightarrow{O_pM}\Big|_{(\vec{x}_c,\vec{y}_c,\vec{z}_c)} = \overrightarrow{F_p\left(s,\Theta_p\right)} = \left| \begin{array}{c} f_p(s)\cdot\cos(\Theta_p) \\ f_p(s)\cdot\sin(\Theta_p) \\ g_p(s)+R_p\cdot\cot\left(\delta_p\right)\cdot\Theta_p \end{array} \right. \quad (5)$$

These two rotations allow defining the tip angle; angle and the principal clearance angle [1].

2.3. Cutting angles

With the mathematical description of the drill surfaces, tangent and normal vectors can be easily calculated. Then, tool angles can be calculated in a specific plane by the projecting the vector orthogonal in the chosen plane. Vectors used for calculation of cutting angle (γ) and clearance angle (α) are presented on Fig. 4: $\vec{N}_d$ for the rake face and $\vec{N}_c$ for the cutting face. Therefore, the vector normal to the surface is needed and is given by the equations of the surface [2].

The variation of the cutting angles for a HSS 16 mm diameter drill is presented on figure (Fig. 5). Cutting angle (γ), rake angle (α) and inclination angle (λ) varies respectively from 35 deg to −55 deg, from 6 deg to 36.0 deg and from −5 deg to −5' deg along the main and the secondary edge. On the chisel edge, two zones can be separated: the first one at the centre of the drill where the rake angle is negative and the second one where the rake angle is positive. On the chisel, cutting angle and rake angle varies respectively from −55 deg to 30 deg and from 24.0 deg to −56 deg.

The three tool angles present great variations along the main edge with a highly negative cutting angle at the limit between cutting edge (secondary edge) and chisel edge.

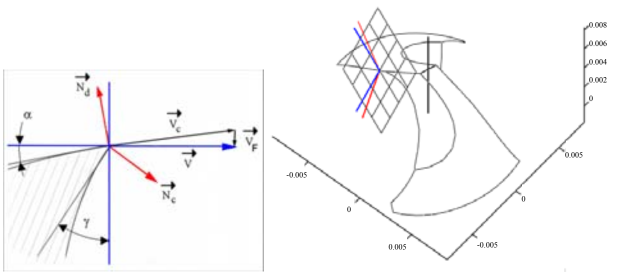

Fig. 4. Cutting and rake angles in the calculation plane.

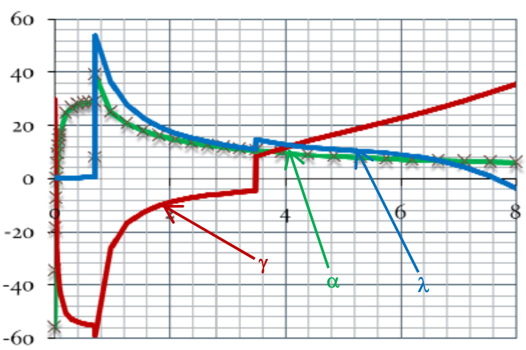

Fig. 5. Working cutting angle (γ), rake angle (α) and inclination angle (λ) for a 16 mm drill with thinning chisel (Fig. 4) - 2.κ_r= 120°, N = 994 tr/mn, V_f = 160 mm/mn.

On chisel edge, two zones can be defined: the first one at the centre of the drill where the rake angle is negative and the second one where the rake angle is positive, but with a highly negative cutting angle. In the first one, one can suppose that the cutting phenomenon is replaced by an indentation phenomenon.

3. THEORETICAL MODEL

The aim of the thermomecanical model is to represent what occurs during a drilling operation in order to estimate the mechanical actions, temperatures and stresses on tool surfaces and in the work material. The complex geometry of a drill implies great variations in tool angles and so a global approach of drilling is almost impossible. As a consequence, in other drilling models [3, 4, 18] the tool edges are decomposed into slices. For each slice of the cutting edge, forces and temperature are calculated with the use of an oblique cutting model. For chisel edge, Elhachimi et al. assume that the cutting only occurs on a part of the chisel and they neglect the influence of the centre part of the chisel. However, Yang et al. use an empirical model to represent the indentation phenomenon occurring at the centre of the chisel. The developed model is an oblique cutting model based on Oxley's work [13] for cutting edges and an analytical indentation model for the chisel edge [1].

3.1. General description of the model

During a machining operation, the work material coming in front of the tool will be divided into two parts. The part near the surface flows along the cutting face and becomes the chip (zone 1 on Fig. 6) and the other part (zone 2 on Fig. 6) moves below the cutting edge on the clearance face. As most of tools have a rounded edge, the second part of the work material is deformed when flowing under the cutting edge and along the clearance face, causing mechanical actions and heat flux on the tool.

For the first part of the material, an oblique cutting model, derived from Oxley's model [13] and from Toulouse work [15] is used. For the second part which is neglected in most previous studies, an analytical plastic deformation model has been developed [2].

Unlike for main cutting edge, we assume that there is no cutting on the chisel edge. As shown with the geometrical model, the cutting angle is highly negative in this part of the tool. Moreover, the cutting speed has decreased to less than one tenth of the outer cutting speed.

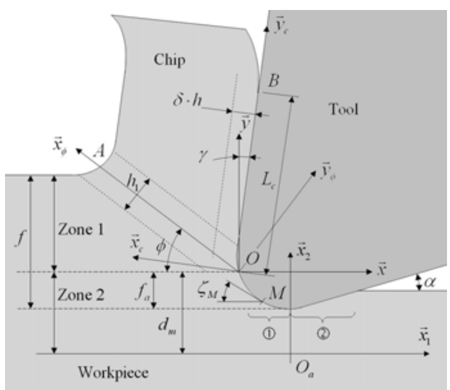

Fig. 6. Calculation zones and parameters.

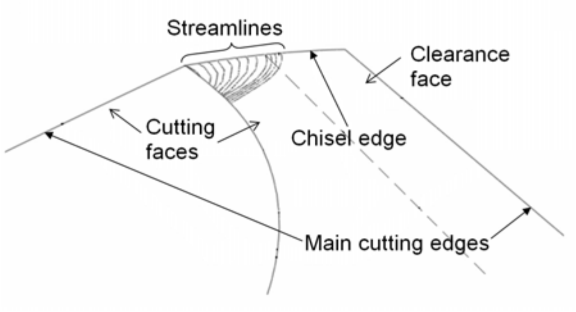

Fig. 7. Streamlines for a material point from the chisel edge to the flute.

Therefore, no chip formation is regarded but phenomenon occurring on the chisel is assumed to be similar to indentation.

On chisel edge, the material is supposed to flow along the drill point surfaces. If the clearance angle is positive, the work material flows along the cutting face. But if the clearance angle is negative, the material is divided into two parts: one goes along the cutting face and the other goes along the clearance face (Fig. 7).

3.2. Results and analysis

In order to validate the model of the main edge of cut, reaming tests were carried out with angles of cut values reached along this edge. The values used are recapitulated in Table 1.

The calculation results for the primary shear angle by minimisation of the mechanical power are in good agreement with the experimental results with a maximum error of 18 % for tool #1 and a mean error of 5 %. This shows the validity of the minimum power comsumption criterion (Fig. 8).

In the part of the model connecting the chisel of the drill with its main edge, Fig. 9 and Fig. 10 illustrate experimental and model results for respectively thrust force produced by the central element and the torque results.

Table 1

Cutting angles used for validation of cutting model

Tool number	1	2	3	4	5	6
Cutting angle γ_c (deg)	-32.5	-21	-11	4	18	29
Clearance α_c angle (deg)	25	19	15	10.5	7	4

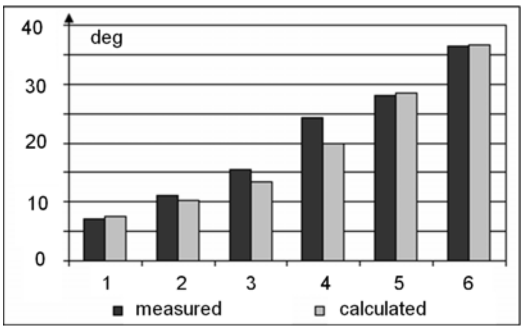

Fig. 8. Comparison of experimental and theoretical results for primary shear angle.

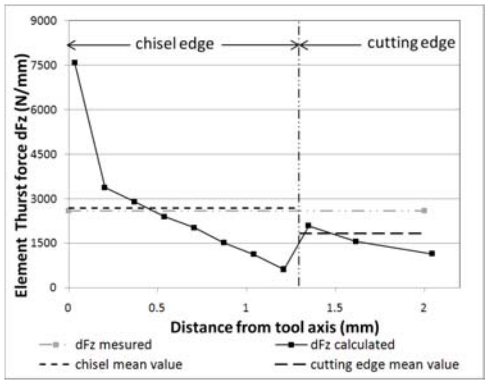

Fig. 9. Example of thrust force results for drilling tests for the central element.

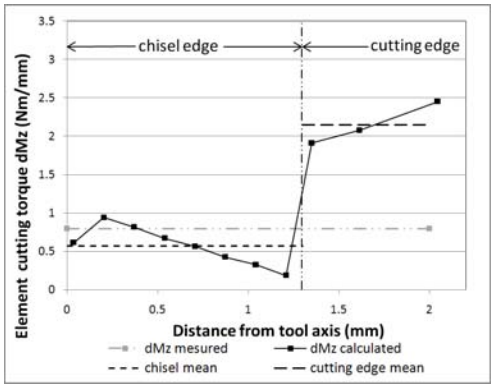

Fig. 10. Example of Cutting torque results for drilling tests for the central element.

As it can be seen on Fig. 9, the calculation mean value of thrust force for the chisel is close to the experimental value (less than 4% error). For cutting torque (Fig. 10), results are over estimated for the cutting part of the element but the chisel model gives better agreement. So it seems that chisel model give acceptable results, with a slight under estimation on cutting torque.

4. EXPERIMENTAL MODEL

Experimental modeling allows establishing mathematical relations between the geometrical and kinematics parameters, and the exit variables such as the six components of the mechanical actions or the quality parameters of drillings.

4.1. General description of the model

The model developed by LMP and LGM²B laboratories of Bordeaux 1 University is made of three elementary models (Fig. 11):

a) a geometrical model presented in the first part of this article [2],

b) a cutting model linking the geometrical parameters (cutting angles) to the six components of forces and moments [10],

c) a phenomenological model linking the six components of forces and moments to the quality off drillings [9].

This model is based on cutting parameters (cutting speed, feed) and a material fixed. The coefficients of the multilinear relations used in this model come from experimental tests carried out with a specific tool allowing

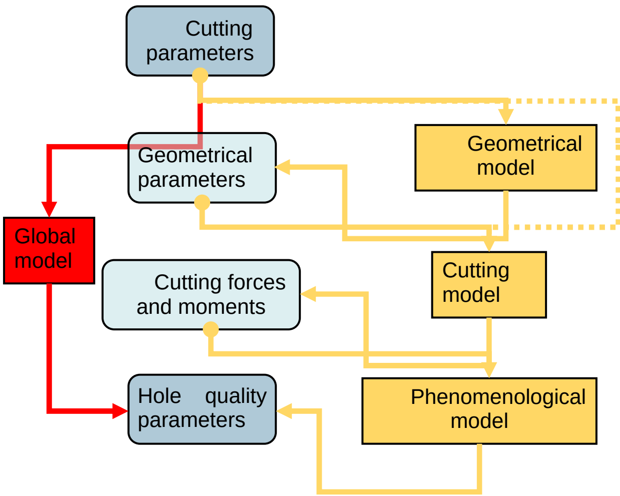

Fig. 11. Principle of the global experimental model.

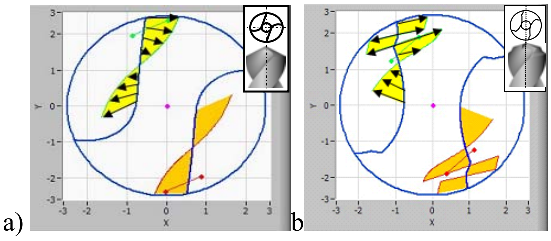

Fig. 12. Radial force repartition for: a) standard drill, b) step drill.

simulating the main edge of a drill and variations of the cutting angles along this one.

4.2. Results and analysis

For a better understanding of results from the model, a display of the forces allocation along the cutting edge has been carried out on LabVIEW ©.

In Fig. 12, a variation in radial force direction can be observed. A positive moment is generated near the web due to the great negative rake angle and low cutting speeds. This phenomenon is not described in "orthogonal cutting models" or "oblique cutting models" because the influence of the ship coiling around two axes is not taken into account. Indeed, for these classical models, each part of the cutting edge is considered independent form the others.

Experimentally, the iterated segmentation of the edge allows determining the contribution of the chip coiling on mechanical actions.

Practically, drill points are often split nearby the web which generates a chisel edge. As a consequence, influence of the chip coiling (that mainly occurs in this zone) is less observable. Note that invertion of the force direction nearby the web is all the more observable as forces from the chisel edge (70 to 80 % of the global force) are not modelized. Indeed, thanks to the chisel edge "cutting" forces, the global force and cutting speed are in opposite direction.

This model allows us to involve the tool geometry by tuning tool's cutting angles and predicting the repartition of forces and moments along the tool edge. In particular for step drills (industrial issue), the existence of a remaining breakage in the middle of the cutting edge has been

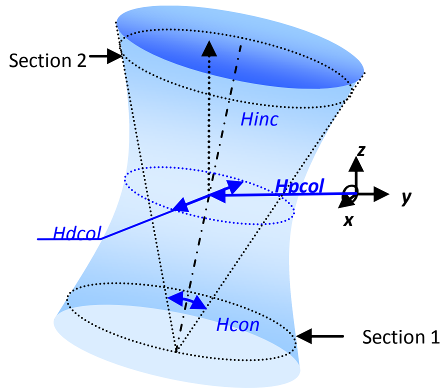

Fig. 13. Hyperboloid of revolution diagram of the distribution of central axis, for one revolution.

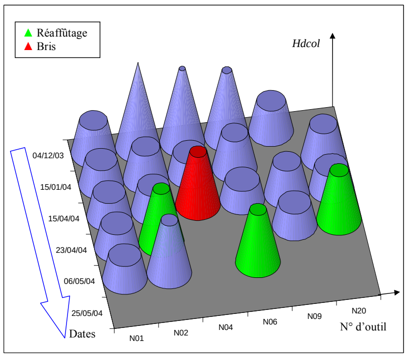

Fig. 14. Evolutions of the parameter Hdcol according to the tool wear.

explained by the model that predicts this particular location matches with a shearing zone. Effects of shearing in this zone most often entail a pilling of the cutting edge.

The good marker for the drilling operation in term of efforts is not each but every component of the wrench (the entire wrench itself). Therefore, the wrench central axis (which is calculated using the 6 components) [4, 7] concretely represents the cutting phenomenon. In a second approach, wrench parameters are:

- Mean central axis inclination,
- Mean central axis deflection,
- Dispersion of central axis reduction points.

Indeed, during a revolution, the wrench central axis does not keep a frozen position but moves according to a conic like shape [9, 10].

In order to establish the correlations between the quality parameters of the hole (Ra, Rt, Φm, δΦ, rect) and the mechanical actions parameters (Hinc, Hcon, Hdcol, Hpcol) (Fig. 13), a straight regression line based on a least squares method is calculated for each couple of parameters [8]. It is thus possible, thanks to the use of the parameters defining the central axis, to study the evolution of geometrical and roughness of the bored holes (Fig. 14).

5. DISCUSSION

On a particular case the experimental model makes it possible to avoid the use of physical laws but cannot thus be generalized. Indeed, in our study, the cutting parameters as well as machined material are fixed. Its field of validity remains restricted and tests to be realized are heavy and numerous. The theoretical model, based on physical laws, allows a microscopic approach and a fine discretization of the cutting edge. The development of the orthogonal cutting model for the great cutting angles makes it possible to make evolve other cutting processes models. It is dependent on the sometimes constraining initial assumptions necessary to its construction. It is also dependent on the behavior laws of materials which are often very difficult to obtain for strain speeds and temperatures reached into the cutting zone.

The results of these two models can be analyzed simultaneously. Indeed, the experimental model reveals a discontinuity of the forces on the cutting edge related to the great cutting angles and the low cutting speed. This phenomenon is not taken into account with the theoretical modeling. It means that the experimental model is complementary to theoretical model and it allows defining new assumptions.

The measurement of the six components of forces and moments allows defining the central axis which is a very important marker of the drill behavior into the two models.

6. CONCLUSIONS

Two types of modeling of the drilling process were presented. These two approaches use a same geometrical description of the tool. This description is necessary to determine the cutting angles along the cutting edge. This geometrical modeling showed that the cutting angles in drilling vary a lot along the cutting edges. These great variations required to develop a cutting model resulting from Oxley's work which field of validity was widened [1]. An experimental model based on multilinear relations was also developed [8]. This model had shown that the mechanical loading on the main cutting edge is complex and that the assumptions taken in for the theoretical model were to be improved. Thus, this article demonstrates that the two models are complementary.

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Authors:

PhD, Philippe. DARNIS, Assoc. Prof., University of Bordeaux, EA 496, Laboratoire de Génie Mécanique et Matériaux de Bordeaux, Bordeaux, F33000, France

E-mail: `philippe.darnis@u-bordeaux1.fr`

PhD, Olivier CAHUC, Assoc, Prof. HDR, Université Bordeaux 1, Laboratoire de Mécanique Physique UMR CNRS 5469,

E-mail: `olivier.cahuc@u-bordeaux1.fr`