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University POLITEHNICA of Bucharest, Machine and Manufacturing Systems Department
Bucharest, Romania

EXPERIMENTAL APPROACH TO DEVELOP A SIX COMPONENTS MILLING CUTTING MODEL

Gaëtan ALBERT, Philippe DARNIS, Raynald LAHEURTE, Olivier CAHUC

Abstract: *To optimize cutting conditions during the milling process, the control of cutting energy parameters must be identified and controlled in order to verify their influence on the cutting mechanical actions. This study is a first step whose final objective is to develop an energetic criterion characterizing all the cutting actions. Thus, this indicator allows the cutting parameter optimization and the result transposition towards another operation. An experimental cutting force model using this criterion and based on an original calculation of the undeformed chip section is presented. As our previous works [3, 7] have shown the existence of the six cutting mechanical actions, an approach based on this study is suggested to develop a six cutting actions experimental model.*

Key words: *milling, energy assessment, cutting actions, real undeformed chip section, cutting coefficient.*

1. INTRODUCTION

The optimization of the energy quantities is controlled by the milling cutting conditions. During the cutting process and considering the variations of the geometric and kinematic parameters, the influence of theses parameters on the six mechanical cutting actions (or the mechanical power) must be identified and controlled.

In a complete cutting energy balance, the six components of mechanical actions of the tool on the workpiece are involved. This assertion has been confirmed by studies conducted previously [3, 7]. Metrological device developed in LMP and LGM²B laboratories [4] has shown the existence and importance of moments in the cutting energy balance. This experimental approach has led to develop predictive semi-analytical cutting models for turning [10] and drilling [6, 11] processes.

Today, our knowledge and equipment can be used to extend earlier approaches (in turning and drilling) to the more complex cases of milling.

The aim is to highlight the most influential parameters (cutting conditions, machining configuration …) on energy quantities (the six cutting actions and therefore the power consumed by the cut). Recent tests have confirmed milling energy balance with the six cutting actions is more influenced by the moments than when the tool rotation is higher (high-speed machining) [5].

During this work, a new experimental approach, using a specific protocol, is developed to establish a six cutting actions experimental model, comparable to force models of [2, 9, 12, 13]. An energetic criterion (force density) is proposed in order to optimize machining operations and also to transpose and adapt cutting parameters to any type of operation or/and process.

Finally, based on earlier work in turning [10] and drilling [6, 11] processes, a predictive semi analytical high speed milling model based on energy criterion will be developed.

A methodology to establish an experimental model of the three cutting force components is presented. This approach will be applied to the cutting moments and cutting power in order to establish a global energetic criterion, in future work.

In the first part of this paper, the procedure used is presented. In a second part, results and their analysis are presented and discussed.

2. EXPERIMENTAL APPROACH

In this section, the experimental approach is detailed to determine, depending on cutting conditions and geometric tool parameters, a cutting mechanical action model comparable to the force models as [2, 9, 12;13].

2.1. Experimental devices

Tests were carried out on a 4 axis CNC machine which can supply a maximum power of 15 kW, can reach a rotation speed of 6000 rpm and a work speed feed of 4 m $\times$ min^{-1}. A special device has been installed on the milling CNC machine in order to recover the three linear axis positions and the spindle angular position through encoders. Thus, the position of the cutting edge is continuously known.

The workpiece is made of 42CrMo4 steel (close to AISI 4142 steel). Its thermo-mechanical characteristics are resumed in Table 1.

Table 1

42CrMo4 steel thermo-mechanical characteristics

Density: 7800 kg/m^3	**Melting temperature: 600 °C**
Heat diffusity : K = 4.6.10^{-5} m^2.s^{-1}	Specific heat : Cp = 379 J/kg°K
Limit stress : σ_r = 900 MPa	Young modulus : E = 210 GPa
Hardness : 260 Hv	

Johnson-Cook material law coefficients	
Viscosity parameter : m = 5.5.10^{-3}	Hardening parameter : n = 0.0563
B = –7.9.10-4	A = 1.288

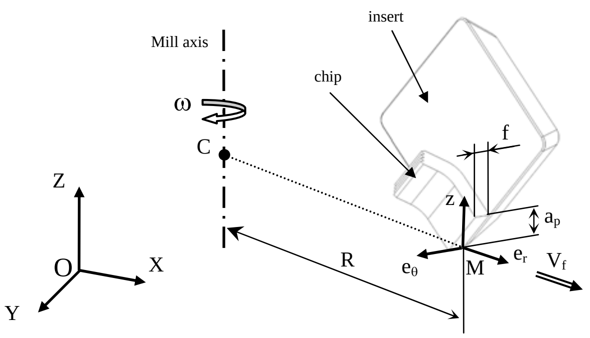


Fig. 1. Two different reference points.

The six components of the cutting actions of the tool on the workpiece (3 forces and 3 moments) and kinematic parameters (rotation and linear displacement of the tool) are measured. They are directly involved in the evaluation of cutting power consumed. These quantities are measured and analyzed in two points of reference. The first is fixed and named reference of measures (point *O*), and the second is a local turning reference linked to the tooth tip (point *M*).

The dynamometer measurement accuracy, in the fixed reference, are ± 50 N on forces (*Fx*, *Fy*, *Fz*) and ± 4 Nm on moments (*Mx*, *My*, *Mz*).

Tools used in our tests have a single insert. This approach has been adopted to simplify studies and to analyze phenomena occurred from a single cutting edge rather than the interaction of several. Moreover, the insert (without coating, chip break ….) was chosen with a simple geometry in order to be able to focus on primary phenomena related to the cut and to compare these results with the future semi-analytical milling model.

Two test designs have been achieved and allowed to test two different milling operations. Thus, the most influential parameters have been found on chosen output parameters (the six cutting mechanical actions).

2.2. Results of a the first experimental approach [1]

A 63 mm diameter mill tool with positive cut geometry, a 45° κ_r angle with a SEMN 120308T insert was used.

The cutting configuration is defined in Fig. 2.

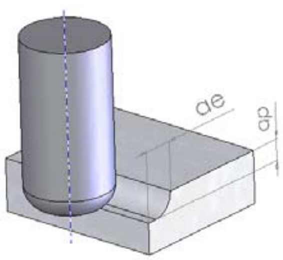


Fig. 2. Tool and machining configuration of first test series.

Table 2

Parameter level variations of first test series

Parameters / Level	Radial width of cut, a_e (mm)	Machining configuration	Depth of cut, a_p (mm)	Feed rate, *f* (mm.tooth^{-1})	Cutting speed, *Vc* (m.mn^{-1})
Low (-1)	15	opposition	1	0.1	50
High (1)	30	concordance	2	0.2	150

According to the complete test design with 5 factors (with input parameters: a_p, a_e, *f*, *Vc*, strategy machining), 32 tests have been achieved.

After the plan linearity verification, the presence of six components (3 forces and 3 moments) of cutting mechanical actions is confirmed, like the previous works [3, 7]. Moreover, the experiments have highlighted a linear evolution of force cutting, which confirms empirical cutting models [2, 9, 12, 13], but also a non-linear evolution of the moment Mz, power consumer, according to the machining parameters chosen.

Thus, cutting forces can be modeled with a linear relationship using the experimental coefficients. For moments, linear relations as forces could not be used.

2.3. New experimental approaches

The previous study does not demonstrate a relationship between cutting parameters and moments, so in order to model all of the six cutting mechanical actions, and especially the three moments, a new study is necessary.

To conduct this study, a specific tool was developed to obtain different geometric configurations of the cutting edge. It's sized 50 mm diameter with 3 interchangeable insert holders. All of these insert holders have a single square insert (SEHHW 1204) and allows choosing the *cutting angle* γ_0 (one value per insert holder) whereas turning angle edge λs, and cutting edge angle κ_r, are respectively fixed to 0 and 90 degrees.

Moreover, grooving tests were conducted with a known workpiece thickness where only the middle of the cutting edge works (Fig. 3). The cutting process is likened to orthogonal cut.

Influential cinematic and geometrical parameters cutting energy quantities on milling model have been confirmed in our previous works [1] like researches carried out by [2, 8, 9, 12, 13].

Thus, a complete test design with 4 parameters has been achieved (Table 3). The *workpiece thickness* a_p*, the feed rate f, the cutting speed* V_c *and the cutting angle* γ_0, have been selected as factors.

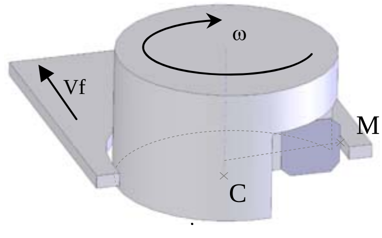


Fig. 3. Tool and machining configuration for second test series.

Table 3

Parameter level variations of second test series

Parameters / Level	Cutting angle γ_0 (°)	Workpiece thickness a_p (mm)	Feed rate, *f* (mm.tooth^{-1})	Cutting speed *Vc* (m.mn^{-1})
Low (-1)	-6	2	0.08	80
High (1)	6	4	0.24	240

The aim of these tests is to analyze cutting phenomena during a milling operation. Then, through a sensitivity analysis, the most influential parameters are introduced into an experimental model.

2.4. Cutting force densities

Force densities are defined by the ratio between forces and the chip section.

$$\mathcal{D}_{forces}(t) = \frac{Cutting\ force(t)}{S_{chip}(t)} \quad (1)$$

Three criteria can be obtained depending on three cutting force components

Under feed direction, $\vec{e_r}$:

$$\mathcal{D}F_r(t) = \frac{F_r(t)}{S_{chip}(t)} \quad (2)$$

Under the cutting speed direction, $\vec{e_\theta}$:

$$\mathcal{D}F_\theta(t) = \frac{F_\theta(t)}{S_{chip}(t)} \quad (3)$$

Under the direction of the mill rotation axis, $\vec{z}$:

$$\mathcal{D}F_z(t) = \frac{F_z(t)}{S_{chip}(t)} \quad (4)$$

Thus, force densities are similar than cutting specific pressure [2, 9, 12, 13]. However, as the real undeformed chip section is not approximated through a sinusoidal relationship, these criteria are specific and more precise than empirical coefficients. Moreover, this concept is being implemented to establish a coherent approach to characterize the six cutting actions and not only the three forces.

2.5. Real instantaneous undeformed chip section, $S_{chip}(t)$

2.5.1. Real instantaneous radial feed, $\Delta er(t)$

The position of the point C (x_C (t), y_C (t), z_C (t)) located at tip and on the axis of the mill (Fig. 3) in the reference $\Re_0$ (O, x, y, z) (fixed-reference point liked to the six components dynamometer) is given by the position encoders information of linear axis. In addition, the spindle angular position is known thanks to the spindle encoder. Thus, after controlling carefully the initial angular position of the cutting edge into $\Re_0(O, x, y, z)$, the instantaneous cutting edge position represented by the point M can be calculated:

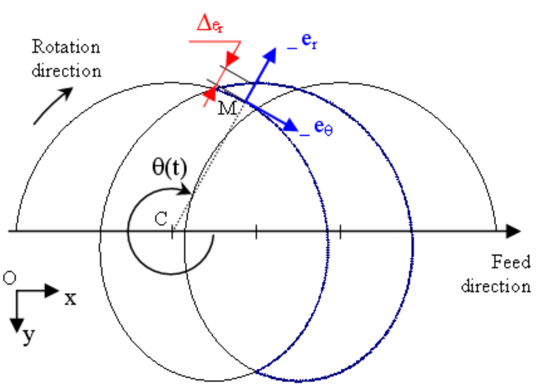


Fig. 4. Path of a peripherical point of the mill.

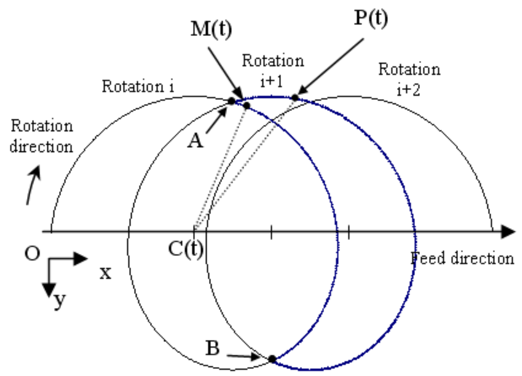


Fig. 5. Parameters for undeformed chip section calculus.

$$\begin{cases} x_M(t) = x_C(t) + R\cos(\theta(t)) \\ y_M(t) = y_C(t) + R\cos(\theta(t)) \\ z_M(t) = z_C(t) \end{cases} \quad (5)$$

Therefore, the instantaneous position of the point C, located on the axis and at the mill tip representing the cutting edge, is known. P represents the cutting edge at the next rotation and can be found in order to align P with C and M, minimizing the following relation:

$$\frac{\left\| \overline{C_iM_i} \wedge \overline{C_iP_{i+1}} \right\|}{\left\| \overline{C_iM_i} \right\| \cdot \left\| \overline{C_iP_{i+1}} \right\|} \quad (6)$$

Thus, knowing $P(t)$, the distance $\left\| \overline{M_iP_{i+1}} \right\|$, called "instantaneous radial feed" $\Delta er(t)$, can be calculated for each point M between points A and B, which are intersection points between rotation i and rotation $i + 1$.

2.5.2. Real instantaneous undeformed chip section, $S_{chip}(t)$

The undeformed chip section calculus is given by the machining configuration, instantaneous radial feed, $\Delta er(t)$, and the insert geometry. In this basic case of these tests (Fig. 6):

$$S_{chip}(t) = \Delta er(t) \cdot a_p \quad (7)$$

with a_p – workpiece thickness.

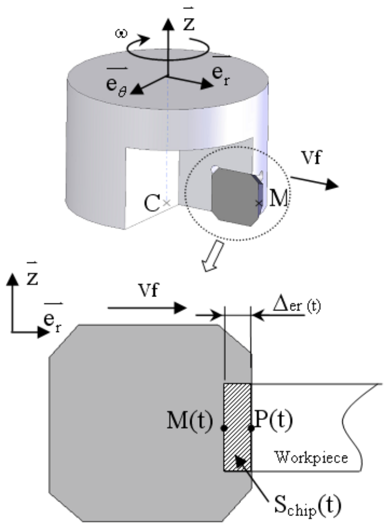


Fig. 6. Real instantaneous undeformed chip section.

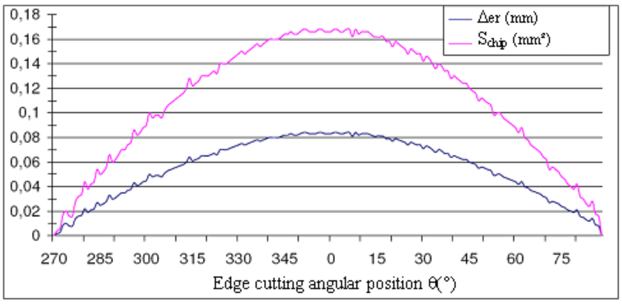
3 ANALYSIS AND RESULTS

3.1. Real instantaneous undeformed chip section, $S_{chip}(t)$

The real instantaneous undeformed chip section, $S_{chip}(t)$ can be calculated with the above approach and with information encoders acquisition of the tool machine.

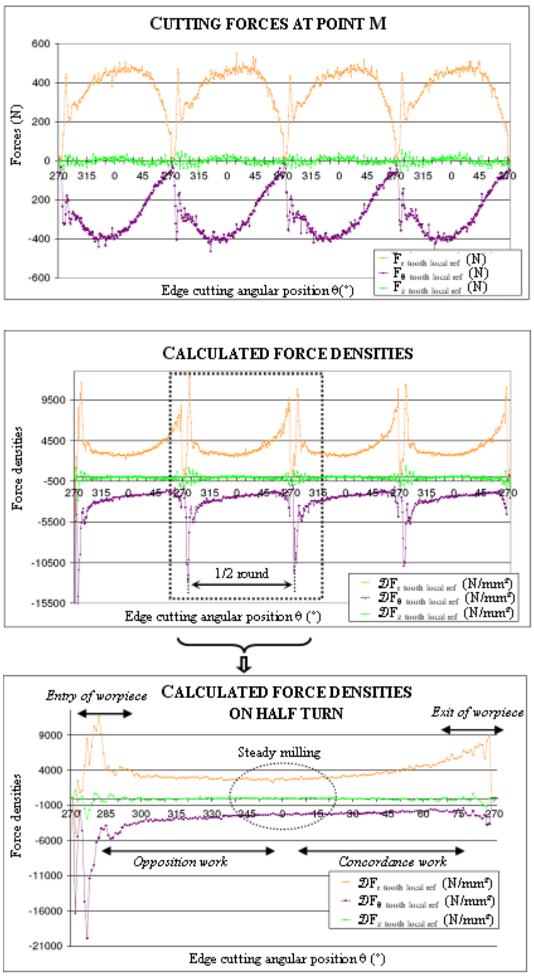
When the point M representing the cutting edge is aligned with the feed direction, i.e. $\theta = 0°$, Δer is equal to the scheduled feed rate f (Fig. 7).

The advantage of this method is in the fact that the calculation is based on a theoretical approach and used with experimental data (encoder information) to fit to reality. Besides, the real undeformed chip section, $S_{chip}(t)$ is known at any time of the cutting operation (Fig. 6).



$Vc = 80m.mn^{-1}$, $a_p = 2mm$, $f = 0.08mm.tooth^{-1}$, $\gamma_0 = 0°$

Fig. 7. Example of real instantaneous radial feed and chip section.



$Vc = 80m.mn^{-1}$, $a_p = 2mm$, $f = 0.08mm.tooth^{-1}$, $\gamma_0 = 0°$

Fig. 8. Example of calculated force densities.

3.2. Forces densities

During tests, the six cutting actions of the tool under the workpiece can be measured and then calculated at the desired reference point. In this study, only three cutting force components (and not moments) have been studied (Fig. 8). As equivalent as forces, moments will be treated in a future study.

For all tests force densities have been calculated (Fig. 8). A steady area can be shown on the different curves around $\theta(t) = 0°$, when the chip section is maximum, i.e. when Δer (t) is equal to the feed rate f. Thus, three force densities (one per force component) can be found. These three values taken in the stabilized area (Fig. 8) will be used as output parameters and studied in our test design.

3.3. Validation

The test design allows the control influential input parameters (a_p, f, V_c, γ_0), in their chosen variation range, in order to predict response values (or observed parameters: $\mathcal{D}F_r$, $\mathcal{D}F_\theta$, $\mathcal{D}F_z$) with a multi-linear function of all input parameters and all of their interactions. Moreover, for the factor values included in the variation range, output quantities ($\mathcal{D}F_r$, $\mathcal{D}F_\theta$, $\mathcal{D}F_z$) can be determinated with the test design method. Force density models for a steady area are obtained with this equation:

$$[\mathcal{D}\, F_i] = [M] + [A] \cdot [F] \qquad (8)$$

with: [M]: force density $\mathcal{D}F_i$ average values matrix

[A]: factors matrix

and :

$$[F] = [V_c \quad f \quad a_p \quad \gamma_0 \quad V_c \cdot f \quad V_c \cdot \gamma_0 \quad f \cdot a_p \quad f \cdot \gamma_0 \quad a_p \cdot \gamma_0]^T$$

[M] and [A] are two coefficient matrices and depend on the couple tool-material.

Thereafter, this model could be extended to all cutting operations and not only at the steady force densities area as in [2, 9, 12, 13].

To validate this method, the linear evolution of parameter is checked with an audit of assumptions based on test design. As a result, Fig 9 represents test design model responses on first axis and test responses on the second one (the six mechanical cutting edge actions are calculated at the tooth (M) in the cutting reference (e_r, e_θ, e_z)). For each output parameter ($\mathcal{D}F_r$, $\mathcal{D}F_\theta$, $\mathcal{D}F_z$), linearity error can be evaluated with the ratio between d and L characterizing the defect test design model For $\mathcal{D}F_r$, a maximum error of 1.57 % can be calculated; and for $\mathcal{D}F_\theta$ and $\mathcal{D}F_z$ respectively 1.69 % and 17.84 %. Therefore, feed density $\mathcal{D}F_r$, and cutting density $\mathcal{D}F_\theta$, can be assumed as a linear change. For axial force density $\mathcal{D}F_z$, no conclusion can be given. Indeed, cutting configuration (cutting edge aligned with the axis z) implies that axial force is theoretically zero, measurements taken have confirmed this observation.

3.4. Analysis

The radial and cutting force density ($\mathcal{D}F_r$, $\mathcal{D}F_\theta$) linearity function of input parameters is confirmed by this study.

Table 4

Input parameters and theirs interactions: degree of influence

		Output parameters	
		$\mathscr{D} F_r$	$\mathscr{D} F_\theta$
Input parameters	Vc	-2.65%	3.74%
	f	**-49.43%**	**-38.64%**
	a_p	-3.38%	5.57%
	γ_0	**-31.22%**	**-18.16%**
Interactions	Vc -f	-0.19%	**-10.93%**
	Vc - a_p	1.84%	0.78%
	Vc - γ_0	0.35%	-2.88%
	f - a_p	0.34%	**-8.06%**
	f - γ_0	5.68%	2.34%
	a_p - γ_0	4.93%	**8.89%**

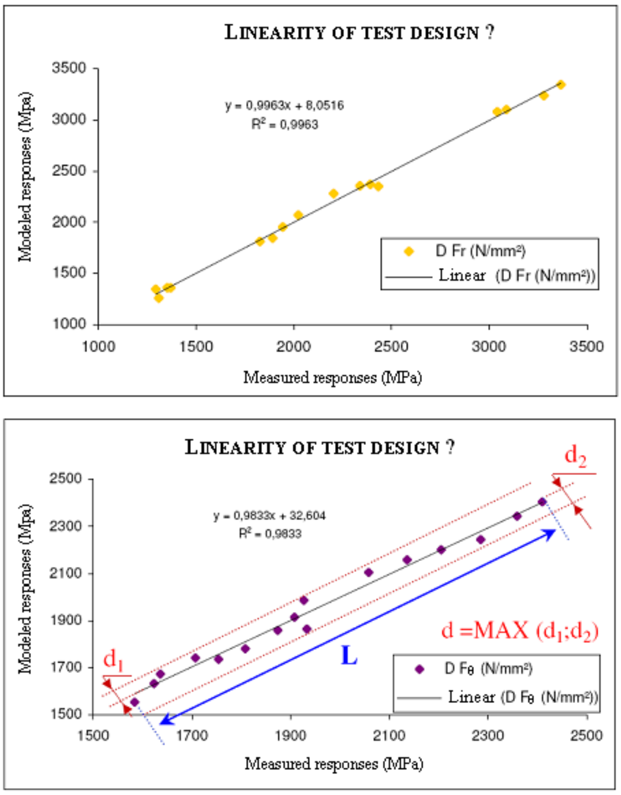


Fig. 9. Test design linearity validation.

Thus, these densities can be modeled by a linear expression of input factors and their interactions (Eq. 8).

This analysis is in accord with models and studies presented in the literature [2; 9, 12, 13]. Indeed, empirical coefficients, called specific pressure or cutting specific coefficient, are used in the cutting experimental model. They are involved with influenced cutting parameters in relationships to predict cutting forces.

Moreover, when the test design validity is verified, an analytical linear relationship between input parameters (a_p, f, V_c, γ_0) and studied outputs, force density ($\mathscr{D}F_r$, $\mathscr{D}F_\theta$, $\mathscr{D}F_z$), can be get with the test design method. The degree of influence of input factors and the degree of influence of interaction on test design outputs ($\mathscr{D}F_r$, $\mathscr{D}F_\theta$, $\mathscr{D}F_z$) can be also obtained. These are listed in Table 4.

The main influential factors on force densities for which linearity is verified are highlighted with test design (Fig. 9, Table 4). For radial and cutting densities effort, $\mathscr{D}F_r$ and $\mathscr{D}F_\theta$, the main influential factors are: in first place feed rate f, cutting angle γ_0, and with less effect workpiece thickness a_p. Once again, specific coefficient, i.e. cutting force density $\mathscr{D}F_\theta$ in this work, proposed in cutting empirical models is validated. Indeed in these models, specific pressure is expressed and adjusted with feed rate f, and cutting angle γ_0 values. In addition, cutting force F_θ and radial force F_r can be modeled in the same way through an empirical factor: force density respectively $\mathscr{D}F_\theta$ and $\mathscr{D}F_r$.

For factor interactions, radial force density, $\mathscr{D}Fr$ is influenced by *feed rate-cutting angle* interaction which is a combination of the two most influential factors. For the cutting force density, $\mathscr{D}F_\theta$, essential interactions, *cutting speed-feed rate*, *feed rate-workpiece thickness* and *workpiece thickness-cutting speed*, are very influential factors combining (*feed rate* and *cutting angle*) with other parameters. Nonetheless, interaction influence degree is less than factor influence degree (Table 4), so in first approximation, only influential factors may be selected to develop an empirical model.

4. CONCLUSIONS AND PROSPECTS

Presented tests are part of the understanding and the modeling of the cutting phenomena in the milling operation. Thus, the aim is to establish a reliable approach and to propose a complete empirical model, including cutting moments, to consider a comprehensive energy balance.

In this approach, chip section is calculated by a new original method. Thus, this calculation is based on measures in order to fit reality. This purpose of this approach is to know real undeformed chip section at any time during machining, which allows to compute force densities at any time and not only in a particular milling position. In addition, these tests have highlighted linear evolution of radial force density $\mathscr{D}F_r$ and cutting force density $\mathscr{D}F_\theta$, which confirms experimental coefficients and cutting models as those proposed in the literature. Thus, radial and cutting force models, F_r and F_θ, should be based on this study's results. Hence, radial force F_r and cutting force F_θ will be a linear expression of real instantaneous deformed chip section $S_{chip}(t)$, radial and cutting force densities, $\mathscr{D}F_r$ and $\mathscr{D}F_\theta$.

The aim of a future study will be to better understand occurred phenomena in milling operation and especially for the cutting moment. Thereafter, applying the proposed approach, new experimental factors will be developed: cutting moment densities. The first objective will be to establish a six components experimental cutting model (3 forces and 3 moments) depending on kinematic and geometric parameters.

Moreover, it is important to recall in milling operation, complete energy balance (computed with the 6 cutting actions) is even more influenced by cutting moments when tool speed rotation is higher (especially in the case of high speed machining). It should also be noted radial force F_r is not often taken into account because its influence in an energy balance of a "conventional speeds" machining is often erased by low feed speed. However, in the case of high-speed machining where translation and rotation speeds are more important, it will be necessary to take into account the six components of cutting actions, including radial force and the three moment components to better calculate and to be close to the real cutting power consumption.

Thus, the work presented confirms the cutting force model and shows that future studies have to be realized to model the cutting moments. So in a further work, the six component experimental model will be based on this work.

Then, a second objective is to develop, through this study and specific equipment on a high speed CNC milling machine, an energetic criterion characterizing all cutting actions in order to optimize cutting machining conditions. An essential feature of this criterion is to get maximum information on machining operation and allow transposing results to another cutting operation and/or machining process.

Finally, a semi-analytical energetic milling cutting model will be developed for high speeds taking into account theoretically the previously experimental approach and our earlier work on turning [10] and drilling operations [6, 11].

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Authors:

Eng, Gaëtan ALBERT, PhD student, University of Bordeaux, CNRS, UMR 5469, Laboratoire de Mécanique Physique, EA 496, Laboratoire de Génie Mécanique et Matériaux de Bordeaux Bordeaux, F33000, France.

E-mail: gaetan.albert@u-bordeaux1.fr

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, Raynald LAHEURTE, Assoc. Prof., University of Bordeaux, UMR 5469, Laboratoire de Mécanique Physique, EA 496, Laboratoire de Génie Mécanique et Matériaux de Bordeaux Bordeaux, F33000, France.

E-mail: raynald.laheurte@u-bordeaux1.fr

PhD, Olivier CAHUC, Assoc. Prof. HDR, Université de Bordeaux, CNRS, UMR 5469, Laboratoire de Mécanique Physique, EA 496, Laboratoire de Génie Mécanique et Matériaux de Bordeaux Bordeaux, F33000, France.

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