DETERMINATION OF POWER CONSUMPTION IN MILLING

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In this paper the influence of mechanical actions (forces and moments) generated by the tool/workpiece/chip contact during the machining process through milling is studied. To understand the phenomena generated by the cutting process, the measurement of the mechanical actions is absolutely necessary. Therefore, highlighting the forces and moments on the three directions is achieved by using two dynamometers QZZ2 and Kistler 9257b, and the development of a calculation algorithm that allows the transport of the moments from the center of the measuring system (dynamometer) at the tip of the tooth. Based on the mechanical actions' theory, the power consumed during the cutting process is determined. A comparative study on the power consumed during the cutting processis undertaken.

Keywords: milling, tool position, cutting moment, cutting power

1. Introduction

During the cutting process a series of geometric, kinematic and dynamic parameters were taken into consideration, as well as their variations, leading to 2D and even 3D models [1, 2, 3, 4, 5]. These parameters are the thermodynamic behavior subject of study of the process as well as the machine tool's being obtained based on the actions generated by the process, energy balance. This energy balance, as shown by a number of researchers [6, 7, 8], responds upon the forces as well as the moments as a result of the tool/piece/chip contact. This theory of the mechanical actions is based on the torsor theory [9, 10, 11, 2, 12], being validated by highlighting the moments at the tip of the tool for turning [13, 2, 12], drilling [14, 15] and milling, respectively [5].

The first measurements made of the moments related to the tool during machining, were made using a dynamometer with six components developed at the Bordeaux University 1 [10, 5]. The measurements reflected the moments' presence at the tip of the cutting tool, not evaluated by conventional cutting models [16, 11, 2, 12].

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For the purpose of estimating the power consumption as accurately as possible, a study on the calculating relations of the cutting power during milling was conducted. The consumed power during face milling was calculated using formulae provided in the literature, then the instantaneous power consumed was calculated during the face milling using the torsor model [13, 6, 2, 8, 17]. Finally, the results obtained from these calculation formulae were compared. An analysis and comparison of two dynamometers Kistler 9257B and QZZ2 was realized as well. These dynamometers are capable of measuring the 6 components of the mechanical cutting actions torsor.

2. Experimental approach

The tests were carried out on a three axis CNC vertical machining center with 11 kW power in the spindle motor. The workpiece material was 42CrMo4 steel and it's Brinell hardness was determined in the range of 243 HB. The workpiece was a plate, with dimensions 45x88mm, directly fixed on the dynamometer.

During the tests, the complete torsor of mechanical actions of the tool on the workpiece was measured with QZZ2 dynamometer, which has the possibility to measure simultaneously 6 components (3 forces and 3 moments) and a Kistler 9257B dynamometer. The chosen cutting tool is a milling cutter with a SEMN 120308T insert (without coating, chip break etc.) with a positive cutting geometry. The milling cutter has the following geometric parameters: diameter d=63 mm and approach angle of the cutting edge k_r=45º. The insert has been purposely chosen with simple geometry and only a single tooth was used in order to obtain the cutting actions' evolution. The measurements are evaluated in X cutting direction with a cutting speed v_c=120 m/min, feed rate f=0.1 mm/rev and a depth of cut a_p=2 mm. The machine tools axes correspond with the dynamometer axes.

3. Power consumption

A comparative analysis is achieved between the results obtained based on the different calculation formulae of the cutting power available in literature.

3.1. The theoretically estimated power

The cutting power will be estimated with the help of calculating formulae available in tools manufacturers catalogues (WALTER, SECO, ISCAR, SANDVIK). The net cutting power necessary during the milling cutting process is calculated by the formula:

$$P_n = \frac{a_p \cdot a_e \cdot v_f \cdot k_c}{60 \cdot 10^6} \quad \text{[kW]} \tag{1}$$

where a_p - depth of cut [mm], a_e – width of cut [mm], v_f – feed speed [mm/min] and k_c specific cutting force [N/mm^2]

3.2. The experimental power with the moments' involvement

Taking in consideration the results obtained at the University of Bordeaux [9, 10, 11, 2, 12, 13, 14, 5], which demonstrated that aside from forces, moments exist at the tip of the tooth, power formulae can be expressed including the components of the forces as well as the moments. The total mechanical energy consumed as a result of the cutting process, can be written as being a vector product between the complete torsor of mechanical actions of the workpiece on the tool and kinematic torsor of the tool in relation to workpiece [5], equation (2):

$$P_{tool \to workpiece} = \lfloor \tau_{workpiece \to tool} \rfloor \otimes \lfloor \upsilon_{tool\,/\,workpiece} \rfloor \quad (2)$$

Calculating the vector product, the power formula becomes:

$$P = \vec{R} \cdot \vec{v} + \vec{M} \cdot \vec{\omega} \quad (3)$$

where $\vec{R}$ is the force component vector and the $\vec{M}$ is the moment component vector.

With the components of vectors, one obtains:

$$P = F_x \cdot v_x + F_y \cdot v_y + F_z \cdot v_z + M_x \cdot \omega_x + M_y \cdot \omega_y + M_z \cdot \omega_z \quad (4)$$

where F_x, F_y, F_z are the cutting forces [N], M_x, M_y, M_z - cutting moments [Nm], v_x, v_y, v_z - cutting speed [m/min], ω_x, ω_y, ω_z - angular velocities [rad/sec].

Because they are not kinematic components, v_z=0, ω_x=0 and ω_y=0. The total mechanical power is reduced into a new, simple relation:

$$P = F_x \cdot v_x + F_y \cdot v_y + M_z \cdot \omega_z \quad (5)$$

This is the formula to obtain the power consumption in the center of the dynamometer with the forces and moments provided by dynamometer. But to be closer to reality, one has to obtain this power at the tip of the tooth. For this it is necessary to determin the milling cutter's theoretical trajectory during machining and then to obtain the moments at the tip of the tooth by moving of the moment from the center of dynamometer in the center of the tool, then at the cutter's tooth tip in the edge cutting zone.

To achieve this purpose a mathematical algorithm is necessary as follows:

-determining the milling cutter's theoretical trajectory during machining

The instantaneous linear position and the instantaneous angular position of the milling cutter was obtained realizing a calculation algorithm, obtaining the instantaneous linear position of the cutting tool along the machining axis *X*, with the relation:

$$X_s = X_{s-1} + \frac{v_f \cdot \Delta t}{60} \tag{6}$$

where v_f is feed speed [mm/min] and Δt sample acquisition time [sec] of the dynamometers.

Instantaneous linear position of milling cutter on *Y* axis is zero because the milling cutter does not move on the *Y* axis. Instantaneous linear position of milling cutter on *Z* axis is the distance from the surface of the workpiece to surface of the dynamometer. Thus the position of the cutting tool's center is known in point *S(t)* with the relation:

$$S_{calcul}(t): \begin{cases} X_s(t) \\ Y_s(t) \\ Z_s(t) \end{cases} \tag{7}$$

This represents the distance $\overrightarrow{SO}$ necessary for the moment's transport from the center of dynamometer to the center of the cutter (fig. 1). Then the cutter angular position $\Delta\theta$ is calculated with the relation:

$$\Delta\theta = 6 \cdot n \cdot \Delta t \quad [°] \tag{8}$$

The instantaneous angular position $\theta(t)$ of the cutter will be:

$$\theta_n = \theta_{n-1} + \Delta\theta_n \quad [°] \tag{9}$$

The 360° cycle is repeated for the entire machining process.

Summing the two distances $\overrightarrow{OS}$ and $\overrightarrow{SD}$, the $\overrightarrow{OD}$ distance necessary for the moment transport from the center of the dynamometer to the tip of the cutter's tooth is obtained. Thus, all data allows the coordinates' calculation of point pilot *D* in reference to $\left(D, \vec{X}, \vec{Y}, \vec{Z}\right)$

$$D_{calcul}(t): \begin{cases} X_D(t) = X_S(t) + R \cdot \cos(\theta(t)) \\ Y_D(t) = Y_S(t) + R \cdot \sin(\theta(t)) \\ Z_D(t) = Z_S(t) \end{cases} \tag{10}$$

- obtaining the moments at the tip of the tooth

With the known position the transport of the moment from the center of dynamometer is achieved in the center of the tool, then at the cutter's tooth tip in the area of cutting (fig.1).

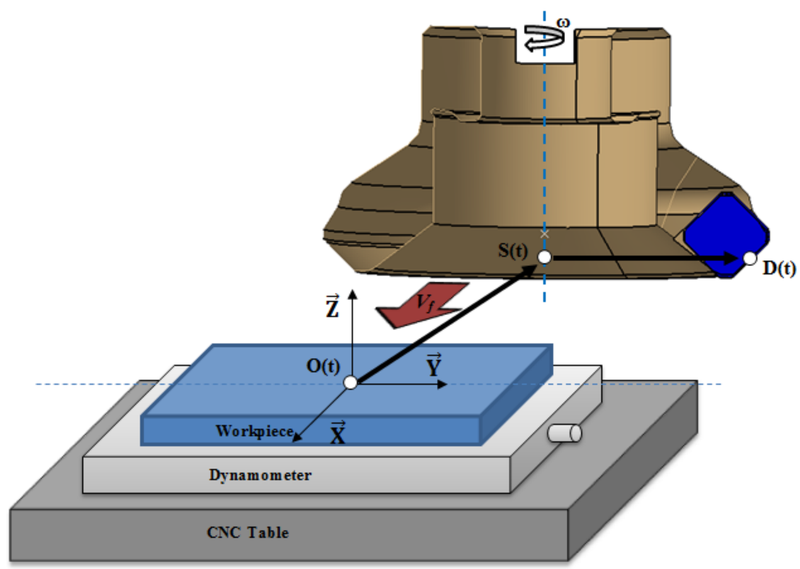

Fig. 1. The moments transport from point *O* (center of the dynamometer) in point *S* (center of the tool) and in point *D* (tip of the tooth).

A dynamometer allows the measurement of the complete torsor of mechanical actions (forces and moments) of the cutting tool on the piece in point *O* in its fixed reference point $\left(O, \vec{X}, \vec{Y}, \vec{Z}\right)$

$$\left\{\tau_{dyn}\right\} = {}_{O}\begin{Bmatrix} \vec{R} \\ \overrightarrow{M/_{O}} \end{Bmatrix}_{\left(\vec{X},\vec{Y},\vec{Z}\right)} \tag{11}$$

With the instantaneous cutter position calculated at point *S(t)*, the transport of the moments is performed from the center of dynamometer (point *O(t)*) to the milling cutter center (point *S(t)*).

$$\overrightarrow{M/_{S}} = \overrightarrow{M/_{O}} + \overrightarrow{SO} \wedge \vec{R} \tag{12}$$

With the instantaneous milling cutter position calculated at point *D(t)*, the transport of the moments is performed from the milling cutter center (point *S(t)*) to the tooth tip (point *D(t)*).

$$\overrightarrow{M/_{D}} = \overrightarrow{M/_{S}} + \overrightarrow{DO} \wedge \vec{R} \tag{13}$$

The power calculated based on the formulae given by the different tool manufacturers represents the average power used during milling. In order to compare this power with the cutting power calculated based on the formula that contains the forces and moments one have to calculate the instantaneous power during milling. Then, is possible to calculate the average power during a revolution of the tool (considering the same value, while the milling cutter is totally engaged in the workpiece).

3.2.1. Calculation of the instanteneous power during milling

The instantaneous power consumed during milling P_c will be calculated, with forces and moments measured with the Kistler 9257B dynamometer and compared to the forces and moments measured with the QZZ2 dynamometer.

Considering the mechanical actions variable direction and the speed a relation is proposed in which these are decomposed based on the machine tool's axis direction of the reference system. The power is determined as a sum of the powers calculated according to speed projections and mechanical actions on the system's axis (fig. 2).

$$P_c = \left|F_x\left(v_{cx} + v_f\right)\right| + \left|F_y \cdot v_{cy}\right| + \left|M_z \cdot \omega_z\right| \quad (14)$$

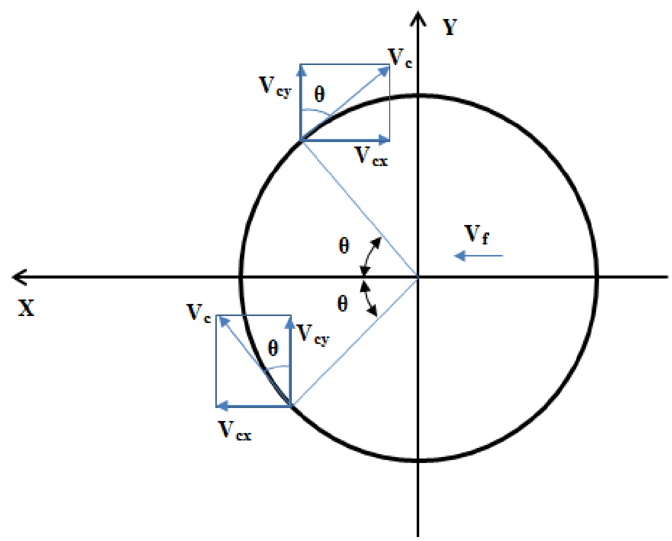

Fig. 2. Decomposing the cutting speed on the directions of the axes of the reference system

The cutting speed decomposition on the axis directions of the reference system is done knowing the value v_c and the value of the angle θ representing the instantaneous position of the cutting edge.

$$v_{cx} = v_c \cdot \sin\theta \quad (15)$$

$$v_{cy} = v_c \cdot \cos\theta \quad (16)$$

The computation relation of instantaneous power during milling P_c is:

$$P_c = \left|F_x\left(v_c \cdot \sin\theta + v_f\right)\right| + \left|F_y \cdot v_c \cdot \cos\theta\right| + \left|M_z \cdot \omega_z\right| \quad (17)$$

P_c is the cutting instantaneous power consumed during milling

The zone where the milling cutter is totally engaged in machining is considered to express the maximum cutting power consumed during milling depending on the angular position θ at the tool's center in point S as well as at the tip of the tooth in point D (fig. 3). The power consumption distribution is achieved: the power consumed by the term containing the cutting moments and the total consumed power by the two terms.

By comparative analysis of the cutting maximum power used by every term, one can note that the power consumed by the term that contains the cutting moments reaches 50% at the center of the tool and 60% at the tip of the tooth.

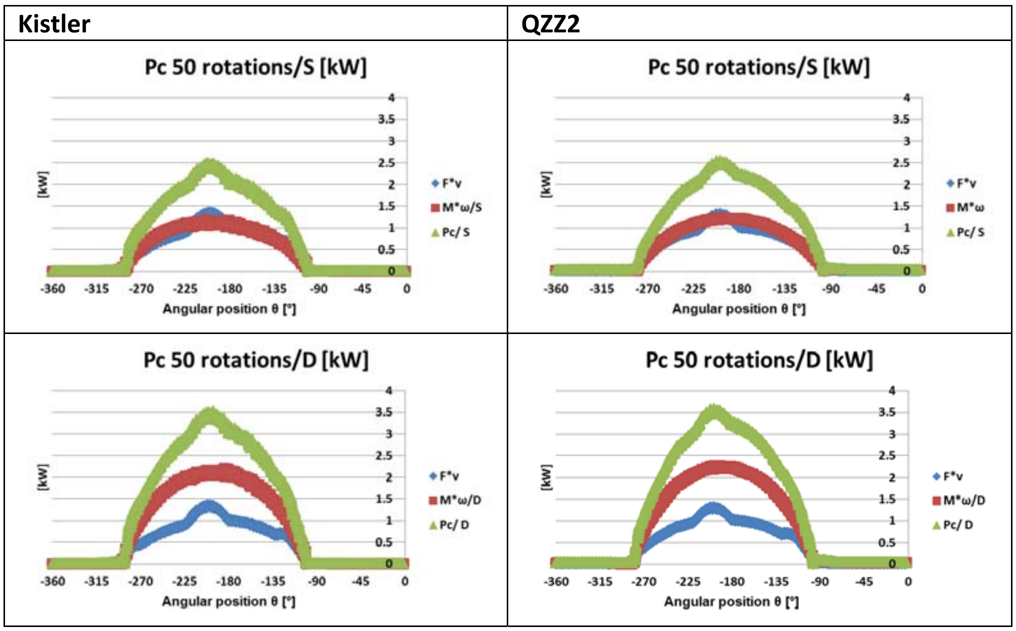

Fig. 3. Power P_c according to the angular position θ

3.2.2. The calculation of average power during a revolution of the tool

The power calculated based on the formulas given by the different tool manufacturers represents the average power used during milling. To compare with the cutting power calculated based on the formulae that contains the forces and moments, the average power per revolution of the milling tool is calculated when the milling cutter is totally engaged in the workpiece (fig. 4).

$$P_{avg/rev} = \frac{1}{t_{rot}} \sum_{i=1}^{n} \left[\left(P_{ci}(\theta) + P_{ci+1}(\theta) \right) \frac{\Delta t}{2} \right] \tag{18}$$

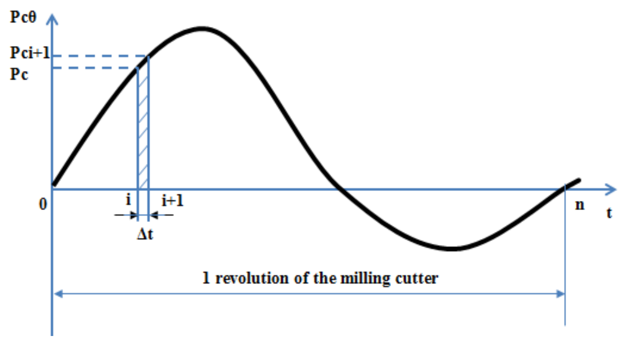

Fig. 4. The average power for a revolution of the milling cutter $P_{avg/rev}$

The average power per revolution is calculated and the results are:

For Kistler 9257B dynamometer the average power at the center of the milling cutter is $P_{avg/rev}$ =0,84 kW and the average power at the tip of the cutter's tooth reaches $P_{avg/rev}$=1,22 kW.

For QZZ2 dynamometer the average power at the center of the milling cutter is $P_{avg/rev}$ =0,87 kW and the average power at the tip of the cutter's tooth reaches $P_{avg/rev}$ =1,26 kW.

Through a comparative analysis of average cutting power used by every term, it is observed that the power used by the term that contains the cutting moments reaches 50% at the center of the tool. Figure 5 presents the results obtained by the estimation of the average power consumption through the formulae provided by manufacturers and by results obtained through experiments. The difference of power between the torsor model applied to cutting [11,16] and models provided by tools manufacturers consist by the moments component that highlight the existence of moments generated by the tool/chip friction from secondary shear zone [11, 2, 17] reaching in this case up to 45%, influence that was found and analyzed in [8, 3, 2, 13, 14].

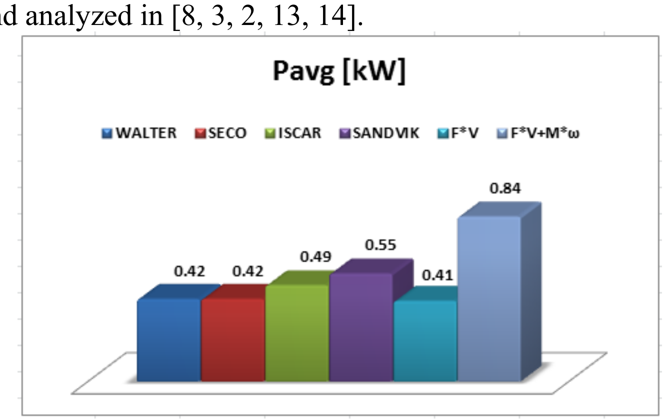

Fig. 5. Average cutting power P_{avg}

6. Conclusions

This study presents aspects concerning the determination of the power consumption during face milling. A comparison of results obtained with different formulae that exist in the literature was accomplished. Using the general form of power, the cutting power was calculated using data from many tool manufacturers, such as: Sandvik, Iscar, Walter, Seco, each presenting particularities of calculation. This is the average power consumed in milling. To compare with the cutting power [6, 2, 5, 17] that contains the complete torsor, the average power per revolution of the milling tool is calculated when the milling cutter is totally engaged in the workpiece. For this research the instantaneous position at tip of the tooth is determined using the transport moment theory.

By practical approach the maximum cutting power used was evaluated during milling. The mechanical actions were measured with the two dynamometers QZZ2 [5, 9] and Kistler 9257B, therefore a presentation of comparative analysis of the cutting distribution of power used by every component of the mechanical action torsor was possible.

In perspective the development of the determination algorithm of the cutting tool's position is proposed in several applying configurations through milling, thus enabling the locating at any time of the position of the cutter's teeth. One also proposes the development of calculating power required in cutting through the inclusion of moments. The ultimate goal is to integrate the cutting moments and the calculating algorithm of the cutter's instantaneous position to achieve a dynamic three dimensional model applicable during the milling process.

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