APPLICATION OF ACOUSTIC EMISSION ON END MILLING MODELLING

Anna Carla Araujo
annaaraujo@cefet-rj.br
CENTRO FEDERAL DE EDUCACAO TECNOLOGICA – CSF – RJ
Mechanical Engineering Department
Av. Maracanã, 229 – sala E310 – CEP: 20271-110

Jose Luis Silveira
jluis@mecanica.ufrj.br
PEM/COPPE/UFRJ
P.O. Box 68503 - 21945-970 Rio de Janeiro, RJ, Brazil

Abstract. *Application of acoustic emission technique for on-line monitoring of various manufacturing processes such as punch stretching, drawing, blanking, forging, machining and grinding has been reviewed and discussed. During the past several years has established the effectiveness of acoustic emission sensing methodologies for machine condition analysis and process monitoring. AE has been proposed and evaluated for a variety of sensing tasks as well as for use as a technique for quantitative studies of manufacturing processes. Acoustic emission generated during the end milling processes using a unique tool can give useful information of the detected wear and friction properties on tool/chip contact coefficients. The AE wear information can be added to the force prediction models developed for non-wear tools to include the edge force component.*
Keywords: *force model, end milling, acoustic emission*

1. INTRODUCTION

The optimization of the manufacturing process plays an important role in improving productivity and, for this, monitoring and prediction are becoming increasingly necessary in the industry. The force prediction was insistently studied and different types of models were developed. Machining is a complex process regarding the mechanical behavior of the material because it should describe a plastic deformation with a complex temperature distribution in a region with an open boundary as the tool-chip contact length is not fixed.

The mechanistic models achieved more accurate prediction with only the information of the tool and work piece geometry and materials and the machining parameters known by the operator. Those models use cutting energy parameters calibrated for a tool work piece pair of materials as a function of the velocities and chip thickness. The parameters not included on the model are implicit on the function although those functions are calibrated for a non wear tool. As the tool is being used the force will change not only because of the tool geometry but also because of the tool-chip contact. As tool wear affects finished surface, there is a need to develop tool wear monitoring systems which alert the operator to the state of the tool. Besides the wear information can also be used to optimize the force prediction during the work to change the parameters and improve tool life.

In this work, the edge cutting force is a function of the tool wear monitored by acoustic emission.

2. ACOUSTIC EMISSION

Acoustic emission is the class of phenomena whereby transient elastic waves are generated by rapid release of energy from a localized sources inside the material that travels through the work piece until the located sensor [Li, 2002].

One advantage of acoustic emission monitoring is the signal frequency range much higher than that of the machine vibrations and environmental noises that does not interfere with the cutting operation.

Research has shown that acoustic emission has been successfully used in laboratory tests to detect tool wear and fracture in single point operations. Based on the analysis of AE signal sources [Li, 2002], AE consists of continuous signals, associated with shearing in the primary zone and wear on the tool face and flank, and transient signal result from tool fracture or chip breakage.

2.1. Brief review of acoustic emission on machining modelling in last years

Dornfeld [1980] and Kasibu [1981], first related the AE to the modeling of cutting and compared the RMS signal to the fundamentals cutting parameters. Based on the orthogonal cutting a relationship between RMS voltage and the fundamental parameters was developed.

For a general case, the rate of energy dissipation is given by:

$$\dot{W} = \int_U \sigma_{ij} \dot{\epsilon_{ij}} dU \tag{1}$$

where W is the energy from plastic deformation, σ_{ij} the stress which causes plastic strain ϵ_{ij}.

The energy used for primary shear deformation can be analytically written as a function of shear stress τ_s, shear angle ϕ, rake angle α and cutting velocity v_c:

$$\dot{W}_s = bt\tau_s \frac{\cos(\alpha)}{\sin(\phi)\cos(\phi-\alpha)}.v_c \tag{2}$$

and from secondary zone, considering sticking and sliding friction is:

$$\dot{W}_f = \frac{1}{3}\tau_s b(l+2l_{sd})\frac{\sin(\alpha)}{\sin(\phi)\cos(\phi-\alpha)}.v_c \tag{3}$$

where b is the width of cut, l the friction contact length, l_{sd} the sliding friction length.

The RMS signal according to Kasibu [1981] is written as:

$$RMS = C_1 \left[\tau_s b v_c \left(t\frac{\cos(\alpha)}{\sin(\phi)\cos(\phi-\alpha)} + \frac{l+2l_{sd}}{3}\frac{\sin(\alpha)}{\sin(\phi)\cos(\phi-\alpha)}\right)\right] \tag{4}$$

where C_1 is a constant experimentally defined.

Rangwala [1991] compared the theoretical RMS signal with the experimental signal and claimed that this relation is proportional to the contact length.

Using True Mean Square (TMS) signal Liu [1991] modeled acoustic emission for monitoring of peripheral milling process including rubbing and the three regions of energy involved on the cutting process: primary shear, secondary shear and rubbing regions. An equation similar to Equation 5 were developed for this case.

Saini [1996] also modeled the energy based on the cutting force and cutting models considering primary and secondary regions. The relation between predicted and experimental signals was linear for turning operations and signal losses due to propagation were included on the model. The experiment used the oscilloscope to analyze the signal.

Wilcox [1997] monitored the face milling to identify the changes on the cutting as flank wear, rake angle and edge breakdown. The AE sensor is positioned on the piece and the dynamometer is also used for the monitoring of process. The continuous RMS value compute the tertiary zone with a constant value C_1 can be written as:

$$RMS = C_1 \left[\tau_s b v_c \left(t \frac{\cos(\alpha)}{\sin(\phi)\cos(\phi-\alpha)} + \frac{l+2l_{sd}}{3} \frac{\sin(\alpha)}{\sin(\phi)\cos(\phi-\alpha)} + C_2 \right) \right] \tag{5}$$

Li [1998] monitored small diameter drills for real-time detection of the breakage and positioned the sensor on the tool holder using a magneto fluid between the main spindle and the sensor apparatus. This work used wavelet transform to analyze the AE signal.

Chungchoo [2000] created new parameter for monitoring oblique turning by AE Total energy and total entropy of force signals were modeled and analyzed thru pattern recognition.

Shao [2004] considered monitoring to change the cutting power model in milling. The experimental results show that there is a signifcant change in force measurement with the cutting edge wear.

2.2. RMS variation with cutting edge wear

Not considering the variation of the shear angle, the sliding lenght and the lenght of the tool-chip contact change as the cutting edge wears. It can be seen on the Equation 5. In order to quantify the variation of the RMS level with the wear ϖ the Equation 5 can be derived:

$$\frac{d}{d\varpi} RMS = C_3(l + 2l_{sd}) \tag{6}$$

This variation must be included on the force prediction.

3. PREDICTING CUTTING FORCE WITH EDGE CONTRIBUTION

The instantaneous differential cutting force for one single tooth was proposed by Martelotti [Tlusty, 1975] as:

$$d\vec{F}_{cutting} = \vec{K}_{cutting}\, t\, db \tag{7}$$

where t is the uncut chip thickness, db is an increment of the depth of cut and $\vec{K}_{cutting}$ is a vector with the specific cutting force coefficients.

More recently this expression has been rewritten (Armarego, 1989) by adding the edge contribution:

$$d\vec{F} = d\vec{F}_{edge} + d\vec{F}_{cutting} \tag{8a}$$

$$d\vec{F} = \vec{K}_{edge}\, db + \vec{K}_{cutting}\, t\, db \tag{8b}$$

where $\vec{K}_{edge}$ is called specific edge force vector.

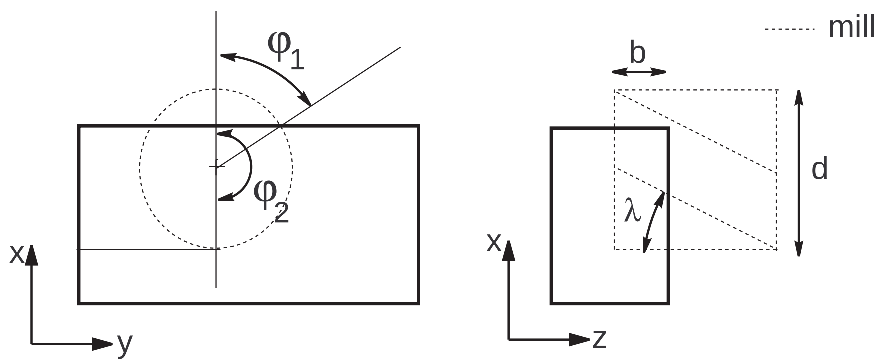

Figure 1. Milling geometry

The uncut chip thickness t for end milling is written as:

$$t = s_t \sin\phi \tag{9}$$

where ϕ is the angle of the cutting element measured in relation to the normal direction of the feed per tooth s_t,

$$s_t = \frac{v_f}{\omega\, N_t} \tag{10}$$

where v_f, ω and N_t are respectively the feed velocity, the rotation and the number of teeth.

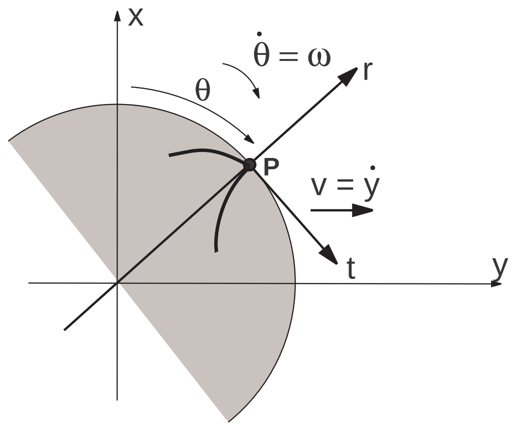

Figure 2. Milling Tool Referential

The cutting tool pieces can be calculated by

$$db = \frac{d}{2\,\tan\lambda} d\phi \tag{11}$$

where d is the tool diameter and λ is the helix angle, as shown in Fig. 1.

The angle δ is calculated by

$$\delta = \frac{2\,b\tan\lambda}{d} \tag{12}$$

where b is the depth of cut.

The angle δ is used to classify the cutting geometry as type I or type II [Tlusty, 1975] according to the angles φ_1 and φ_2 which are, respectively, the entry and exit angles. For type I, δ is less or equal $\varphi_2 - \varphi_1$ and for type II, δ is greater than $\varphi_2 - \varphi_1$ (Fig. 1) [Araujo, 1999].

In order to obtain the force acting in one tooth, the following integration is performed over the whole tooth length engaged in the cutting:

$$\vec{F} = \int \vec{K}_{edge} db + \int \vec{K}_{cutting}\, t\, db \tag{13}$$

In this paper the specific cutting and edge force coefficients are assumed to be constants, considering this and eliminating t and db, the force expression for a tooth is rewritten as:

$$\vec{F} = \vec{K}_{edge} \int \frac{d}{2\,\tan\lambda} d\phi + \vec{K}_{cutting} \int \left(s_t\,\sin\phi\right) \frac{d}{2\,\tan\lambda} d\phi \tag{14}$$

The total force acting in the tool, considering the N_t teeth of the mill, is calculated by the sum:

$$\vec{F} = \sum_{i=1}^{N_t} \vec{F}_i \tag{15}$$

A fixed point **P** in the periphery of the tool is chosen to describe the angular position θ of the tool and the variation of the milling force with the tool rotation ω (Fig. 2):

$$\vec{F}(\theta) = \vec{K}_{edge} h(\theta) + \vec{K}_{cutting} A(\theta) \tag{16}$$

where $h(\theta)$ is a function of the cutting height and $A(\theta)$ is a function of the cutting area, which accumulate the contribution of the N_t teeth of the tool and are, respectively, given by:

$$h(\theta) = \sum_{n=1}^{N_t} h_n(\theta) \tag{17}$$

$$A(\theta) = \sum_{n=1}^{N_t} A_n(\theta) \tag{18}$$

Table 1. Integration limits for each phase.

	Type I		Type II	
Phase	$L_1(\theta)$	$L_2(\theta)$	$L_1(\theta)$	$L_2(\theta)$
For $e_1 < \theta \leq e_2$ - Phase A	φ_1	θ	φ_1	θ
For $e_2 < \theta \leq e_3$ - Phase B	$\theta - \delta$	θ	φ_1	φ_2
For $e_3 < \theta \leq e_4$ - Phase C	$\theta - \delta$	φ_2	$\theta - \delta$	φ_2

Table 2. Variables values

	Type I	Type II
e_1	φ_1	φ_1
e_2	$\varphi_1 + \delta$	φ_2
e_3	φ_2	$\varphi_1 + \delta$
e_4	$\varphi_2 + \delta$	$\varphi_2 + \delta$

The height function $h_n(\theta)$, i.e., the height of a tooth (n) engaged in the cutting and the chip cross-sectional area function $A_n(\theta)$ for a tooth (n) are calculated, respectively, by:

$$h_n(\theta) = \int_{L_1(\theta+\xi(n-1))}^{L_2(\theta+\xi(n-1))} \frac{d}{2\,\sin\lambda}\, d\varepsilon \tag{19}$$

$$A_n(\theta) = \int_{L_1(\theta+\xi(n-1))}^{L_2(\theta+\xi(n-1))} \frac{s_t\, d}{2\,\sin\lambda} \sin\varepsilon\, d\varepsilon \tag{20}$$

where the limits L_1 and L_2 are determined for each cutting phase of θ (Table), ξ is the angle between the teeth and the values of e_1, e_2, e_3 and e_4 are taken from Table .

Fig. 3 shows the chip cross-sectional area $A_1(\theta)$ for the first tooth of an end milling tool with four teeth ($\xi = 90^o$) and having type I geometry, with $\varphi_1 = 30^o$ and $\varphi_2 = \pi/2$.

The force components are decomposed in the tool referential t, r, z (tangential, radial and axial directions) in which the specific force coefficients are assumed to be constants:

$$\vec{F}(\theta) = \begin{bmatrix} F_t(\theta) \\ F_r(\theta) \\ F_z(\theta) \end{bmatrix} = A(\theta) \begin{bmatrix} K_{ct} \\ K_{cr} \\ K_{cz} \end{bmatrix} + h(\theta) \begin{bmatrix} K_{et} \\ K_{er} \\ K_{ez} \end{bmatrix} \tag{21}$$

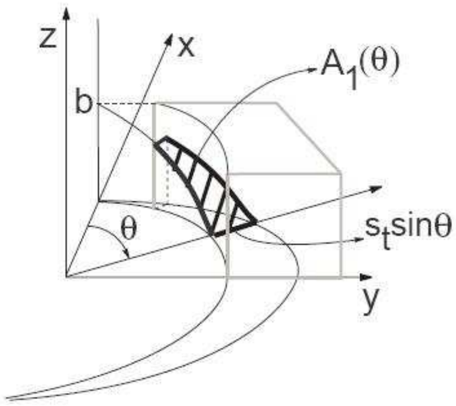

Figure 3. Chip Cross-sectional Area

To rewrite it on the machine referential x, y, z in which the force components are usually recorded in machining tests, a rotation matrix $R_n(\theta)$ is written for each tooth (n):

$$R_n(\theta) = \begin{pmatrix} \cos(\theta + \xi\,(n-1)) & \sin(\theta + \xi\,(n-1)) & 0 \\ \sin(\theta + \xi\,(n-1)) & -\cos(\theta + \xi\,(n-1)) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{22}$$

Thus the cutting force is rewritten in the more appropriate referential x, y, z as:

$$\begin{bmatrix} F_x(\theta) \\ F_y(\theta) \\ F_z(\theta) \end{bmatrix} = A_R(\theta) \begin{bmatrix} K_{ct} \\ K_{cr} \\ K_{cz} \end{bmatrix} + h_R(\theta) \begin{bmatrix} K_{et} \\ K_{er} \\ K_{ez} \end{bmatrix} \tag{23}$$

where the rotated area function $A_R(\theta)$ and the rotated length function $h_R(\theta)$ are, respectively, given by:

$$A_R(\theta) = \sum_{n=1}^{N_t} R_n(\theta)\, A_n(\theta) \tag{24}$$

$$h_R(\theta) = \sum_{n=1}^{N_t} R_n(\theta)\, h_n(\theta) \tag{25}$$

To simplify the following calculations, $S_1(\theta)$, $S_2(\theta)$, $S_3(\theta)$ and $S_4(\theta)$ are defined:

$$S_1(\theta) = \sum_{n=1}^{N_t} A_n(\theta)\, \cos(\theta + \xi\,(n-1)) \tag{26a}$$

$$S_2(\theta) = \sum_{n=1}^{N_t} A_n(\theta)\, \sin(\theta + \xi\,(n-1)) \tag{26b}$$

$$S_3(\theta) = \sum_{n=1}^{N_t} h_n(\theta)\, \cos(\theta + \xi\,(n-1)) \tag{26c}$$

$$S_4(\theta) = \sum_{n=1}^{N_t} h_n(\theta)\, \sin(\theta + \xi\,(n-1)) \tag{26d}$$

Rewriting the Equation 23, the force can be expressed by:

$$\begin{bmatrix} F_x(\theta) \\ F_y(\theta) \\ F_z(\theta) \end{bmatrix} = \begin{bmatrix} S_1(\theta) & S_2(\theta) & 0 & S_3(\theta) & S_4(\theta) & 0 \\ S_2(\theta) & -S_1(\theta) & 0 & S_4(\theta) & -S_3(\theta) & 0 \\ 0 & 0 & A(\theta) & 0 & 0 & h(\theta) \end{bmatrix} \begin{bmatrix} K_{ct} \\ K_{cr} \\ K_{cz} \\ K_{et} \\ K_{er} \\ K_{ez} \end{bmatrix} \tag{27}$$

or in a more compact notation:

$$\mathbf{F}(\theta) = \mathbf{J}(\theta)\ \mathbf{K} \tag{28}$$

The Equation 28 can be easily calculated, as the specific pressures are constant in θ. For given experimental force components $\mathbf{F}(\theta)$ and for each point θ, the following equation can be solved:

$$\mathbf{K} = \mathbf{J^{-1}}(\theta)\mathbf{F}(\theta) \tag{29}$$

From the results obtained for each point θ, an the average value $\overline{K}$ of the specific pressures can be obtained for the whole rotation.

4. RMS LEVEL INFLUENCE ON THE EDGE COEFFICIENT

Using the mechanistic approach, the calibration for the cutting pressure is done for a range of cutting velocity and spindle speed. In this method, the specific pressure is also calibrated for a range of wear using the information from the RMS signal and the information is added to the cutting edge pressure K_e.

$$\begin{bmatrix} F_x(\theta) \\ F_y(\theta) \\ F_z(\theta) \end{bmatrix} = \begin{bmatrix} S_1(\theta) & S_2(\theta) & 0 & S_3(\theta) & S_4(\theta) & 0 \\ S_2(\theta) & -S_1(\theta) & 0 & S_4(\theta) & -S_3(\theta) & 0 \\ 0 & 0 & A(\theta) & 0 & 0 & h(\theta) \end{bmatrix} \begin{bmatrix} K_{ct} \\ K_{cr} \\ K_{cz} \\ K_{et}(\varpi) \\ K_{er}(\varpi) \\ K_{ez}(\varpi) \end{bmatrix} \tag{30}$$

The force for a new tool, with no wear, is calculated based on the mechanistic model. The calibration is done for a tool and workpiece pair of materials. Afterwise begin the tool wear and the force changes behavior. The purpose in this paper is add wear information to the model using the RMS signal variation from initial measurements to the wear stage to predict. The wear information in the model is located at the K_{edge} and to add the contribution to this parameter, the mean value of the RMS is divided by the inicial mean value to obtain the coefficinte $K_(\varpi)$ during the monitoring.

$$K_e(\varpi) = K_{\varpi}.K_e \tag{31}$$

5. RESULTS AND DISCUSSIONS

The algoritm presented on Araujo [2001] is used to calculate the force without wear and the specific pressure is multiplied by a factor that corresponds to the wear contribution to the force.

The experimental result from Altintas [1996] (Figure) is used to calculate the specific pressures and to apply the wear model mofication. The process was up milling using the parameters: $d = 18.1mm$, $s_t = 0.05mm/th$, $N_f = 4$, $\lambda = 30^o$, $v = 11mm/min$, $b = 5.08mm$, $\varphi_2 = \pi$ and an Ti6Al4V Alloy workpiece.

Figures 5 and 6 show the results adding an contribution of 10% and 30% on the edge especific pressure and comparing the data with and without the tool wear in both cases. The cutting specific pressure is taken from the experimental data as in Araujo [2001].

6. CONCLUSIONS

It is possible to compute wear in the mechanistic end milling model with edge parcel and it can justify a consider force increase. It is needed experimental force results to validate the model using the RMS signal to compare with the measured force. Acoustic emission can be applyed to other metal cutting prediction as in drilling and turning.

7. ACKNOLEDGEMENTS

The authors would like to gratefully acknowledge the PRODOC fellowship received from CAPES, a Brazilian council for scientific and technological development, and the Mechanical Engineering Department PEM/COPPE for the research support.

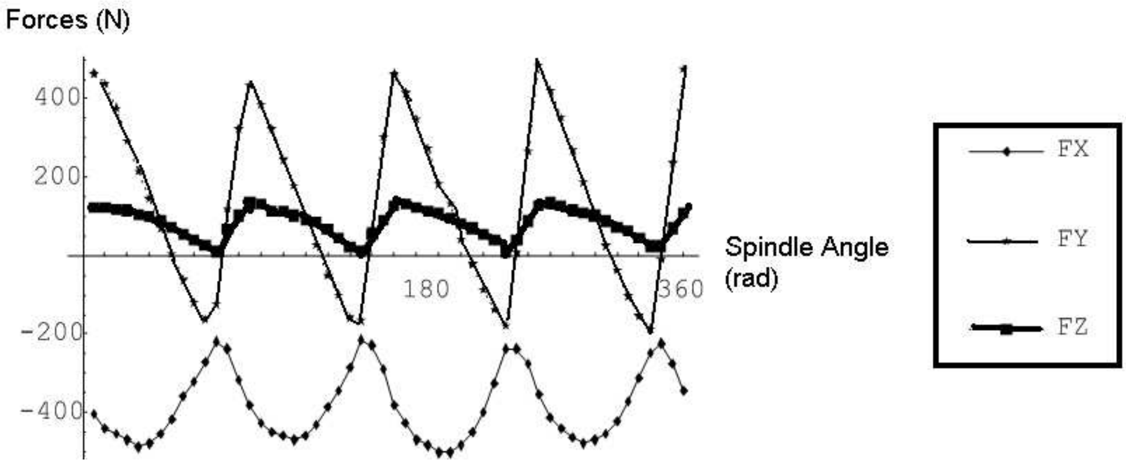

Figure 4. Experimental data from Altintas [1996]

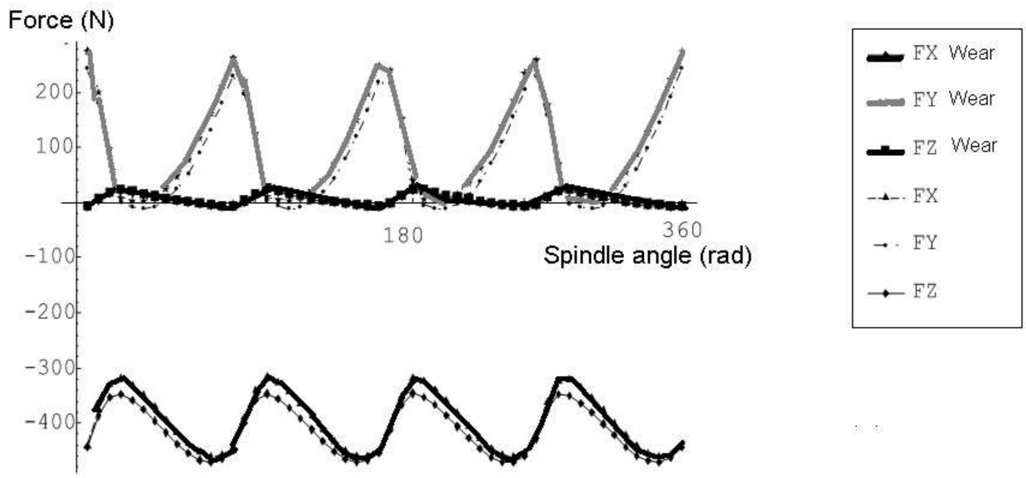

Figure 5. Example 1

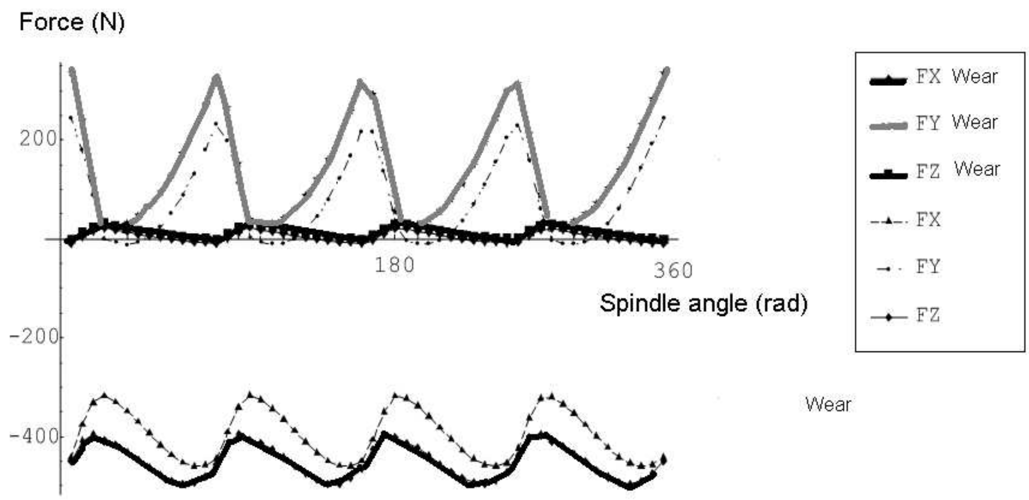

Figure 6. Example 2

8. REFERENCES

ALTINTAS, U. e LEE. **A General Mechanics and Dynamics Model for Helical End Mills**, In: Annals of CIRP, Vol. 45, No. 1, pp. pp.59-64, 1996.

ARAUJO, A. C. E SILVEIRA, J. L., **Models for the Prediction of Instantaneous Cutting Forces in End Milling**, In: Annals of 15th COBEM", p. CDROM. 1999.

ARAUJO, A. C. e SILVEIRA, J. L, **Analysis of the specific force on end milling**, In: Procedings of the 22nd iberian latin-american congress on computational methods in Engineering", 2001.

CHUNGCHOO e SAINI, **The total energy and the total entropy of force signals - new parameters for monitoring oblique turning operations**, International Journal of Machine Tools and Manufature, Vol. 40, pp. 1879-1897, 2000.

DORNFELD e KANNATEY-ASIBU**Acoustic emission during orthogonal metal cutting**, International Journal of Mechanical Science", Vol. 22, pp. 285-296, 1980.

KANNATEY-ASIBU e DORNFELD, **Quantitative Relationships for Acoustic Emission from Orthogonal Metal Cutting**, Journal of Engineering for Industry", Vol. 103, pp. 330-340, 1981**.**

LI, **Real-Time detection of the breakeage of small diameter drills with wavelet transform**, International Journal of Advanced Manufacturing Technology", Vol. 14, pp. 539-543, 1998.

LI, **A brief review: acoustic emission method for tool wear monitoring during turning**, International Journal of Machine Tools and Manufature", Vol. 42, pp. 157-165, 2002.

LIU e LIANG, **Analytica modeling of acoustic emission for monitoring peripheral milling process**, International Journal of Machine Tools and Manufature", Vol. 31, pp. 589-606, 1991.

RANGWALA e DORNFELD, 1991. **A study of acoustic emission generated during orthogonal metal cutting - spectral analysis**, Journal of Mechanical Engineering Science", Vol. 33/6, pp. 489-499.

SAINI e PARK, 1996, **A quantitative model of acoustic emission in orthogonal cutting operations**, Journal of Materials Processing", Vol. 58, pp. 343-350.

SHAO, W. E ZHAO, 2004, **A cutting power model for tool wear monitoring in milling**, International Journal of Machine Tools and Manufature", Vol. 44, pp. 1503-1509.

TLUSTY e MACNEIL, **Dynamics of Cutting in End Milling**, Annals of CIRP, Vol. 24, No. 1, pp. pp.213-221, 1975.

WILCOX, R. e SOUQUET, **The use of cutting force and acoustic emission signals for the monitoring of tool insert geometry during roush face milling**, International Journal of Machine Tools and Manufature, Vol. 37, pp. 481-494, 1997.