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INFLUENCE OF THE ESTIMATION OF CUTTING FORCE COEFFICIENTS IN MICROMILLING

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ABSTRACT

This paper presents a new model for the estimation of cutting forces in micromilling based on specific cutting pressure. The proposed model includes three parameters which allow to control the entry of the cutter in the workpiece and which consider also the errors in the radial position of the cutting edges of the tool.

The presented model is orientated to adaptive control in the micromilling process so that variations in the cutting conditions during the machining process are easily treated by this model and taken into account in the control algorithms for the process optimization.

The accuracy of the estimated parameters of the cutting force expression plays a vital role in the resulting cutting force. For this reason, the influence of the fitting of the cutting force coefficients is analyzed.

Keywords: cutting force model, micromilling, specific cutting pressure

1. INTRODUCTION

The use of micromilling is becoming more common in manufacturing since the demand of miniaturized components has increased. For this reason a great effort is being made in this area. Most of the research to date has dealt with the prediction of cutting forces and a great number of different force models have been developed.

An important work in the development of end milling force models is due to Tlusty and MacNeil [1]. They developed a closed form formulation for the evaluation of cutting forces. The variations of cutting force with respect to cut geometries are also discussed in their paper. In the work presented by Engine and Altintas [2], a generalized geometric model for milling cutters is presented. Kline and DeVor [3] studied the important effect of cutter runout on the chip production and incorporated these effects into their model. Sutherland and DeVor [4] improved the same model by taking into consideration the static deflection of the cutter. Similar work is done by Feng and Menq [5], they considered also the effect of runout and propose a procedure to identify the cutting coefficients. More recently, Gradisek [6] and Yun [7] have focused on the determination of specific force coefficients. However, little work has been reported on micromilling process. On this matter the work developed by Bao and Tansel [8] must be highlighted. They consider the real chip thickness to evaluate the milling forces.

The basic difficulty revealed is to fix a model of chip formation that combines the opposed characteristics of simplicity and similarity to the real phenomenon. The interest of estimating these forces by means of simple and reliable models instead of more complex models, resides in the possibility of its incorporation in control algorithms, in a better tool monitoring, in a faster detection of the tool breakout and in a faster on-line optimization of the cutting process.

The proposed model is a mechanistic model. These models are generally applied in industry. The cutting forces are calculated on the basis of the engaged cut geometry, the undeformed chip thickness distribution along the cutting edges, and the empirical relationships that relate the cutting forces to the undeformed chip geometry. This relation is through a proportional constant called the specific cutting force coefficient or specific cutting pressure and depends on the cutter geometry, cutting conditions and workpiece material properties.

The quality of the force predictions relied heavily on the quality of the input information. Therefore the estimation of the specific cutting pressure plays a vital role in the resulting cutting force. This paper presents an analysis of different ways of fitting the cutting force coefficients and the effect of the selected fit on the estimated cutting force.

2. DEVELOPMENT OF A MECHANISTIC FORCE MODEL

Many researchers have been interested in a precise cutting force prediction for end milling process. In most cases the estimated cutting force coefficients are found under ideal machining conditions and the measured forces are free from perturbations. However, the precision of the estimation of the specific cutting pressure decreases when machining conditions are different.

Some phenomena have also been considered in cutting force modelling like tool deflection and runout. In micromilling, the runout due to the position error of the tool in the tool holder or spindle is supposed to be clearly noticed, but the experiments and measurements made, offer different results. These errors are very small and therefore negligible even in micromilling.

The main problem in micromilling that affects the tool runout is due to the tool itself and it comes directly from tool manufacturing. This error is due to an asymmetric position of the cutting edges and during cutting some flutes cut less material than others.

Owing to these significant errors a new model is proposed. This closed form equation makes it especially suitable for an on-line control of the micromilling process. The cutting forces can be determined by the following equations:

$$\begin{aligned} F_{t,j}(\varphi) &= k_t \; p_j \; h_j \; q_j \; a_p \\ F_{r,j}(\varphi) &= k_r \; p_j \; h_j \; q_j \; a_p \end{aligned} \tag{1}$$

kt can be expressed as a potential function:

$$k_t = k_s \, h^{-m} \tag{2}$$

where ks and m are constants that depend on the workpiece material and the milling tool.

In the proposed model the chip thickness is multiplied by a coefficient p_j that represents the deviation of the cutting edge position with relation to a reference edge.

$$p_j = \frac{D - 2\,\Delta r_j}{D} \tag{3}$$

Likewise, the depth of axial cutting is affected by a coefficient q_j which indicates the effective cutting width at the entrance and at the exit of the cutting edge along the arc of contact. The value of this parameter depends on the angular position of the edge in each revolution of the tool.

Therefore, the resulting force along an edge of the tool can be estimated as follows:

$$F_j(\varphi_j) = k_s \, q_j \, a_p \, p_j \, f_t^{1-m} \cos^{1-m}\left(\varphi_e + \frac{\varphi_t}{2} + \Delta\varphi_j \right) \tag{4}$$

3. DETERMINATION OF THE CUTTING FORCE COEFFICIENTS

The precision of the estimation of cutting forces depends on the force model developed and on the procedure to determine the cutting force coefficients. Only a few researchers have directed attention toward the determination of specific cutting forces. The most widely used relation is the potential. The tangential force has then the following expression:

$$dF_t = k_t\, dA = k_s\, h^{-m} h\, dz = k_s\, f_t^{1-m} \cos^{1-m} \phi\, dz \tag{5}$$

The results obtained with a polynomial fitting are just as good as potential fittings, and in addition the integration of the cutting force is easier.

$$dF_t = k_t\, dA = (ah^2 + bh + c)h\, dz = \left(ah^3 + bh^2 + ch\right) dz =$$
$$= \left(a\, f_t^3 \cos^3 \phi + b\, f_t^2 \cos^2 \phi + c\, f_t \cos \phi\right) dz \tag{6}$$

If chip thickness is very small as is normal in micromilling, then the previous equation can be simplified, resulting in the following:

$$dF_t = \left(bh^2 + ch\right) dz = \left(b\, f_t^2 \cos^2 \phi + c\, f_t \cos \phi\right) dz \tag{7}$$

Therefore this justifies that models which calibrate with lineal functions of chip thickness obtain good results in some cases.

In micromilling a good fitting of these cutting coefficients is difficult to obtain due to small values of chip thickness where specific cutting pressures increase non-linearly. This non-linear behaviour is commonly termed the size-effect.

The specific cutting pressures are typically obtained from calibration tests. Usually, the calibration of the cutting force model is performed by running tests at different combinations of spindle speed, feed rate and depth of cut. These tests are conducted using a single cutting flute to avoid the effect of overlapping of cutting edges. However, end milling operations in the industry are typically performed using tools with multiple cutting edges and high values for the helix angle.

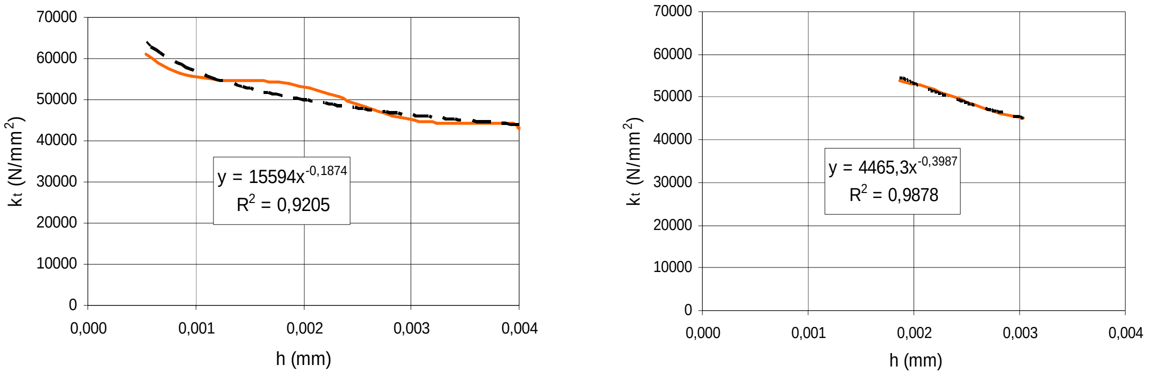

Figure 1. Different fittings for kt with different tool engagement angle range (d=0,4 mm, ft=0,004 mm, ap=0,15 mm, 18000 rpm)

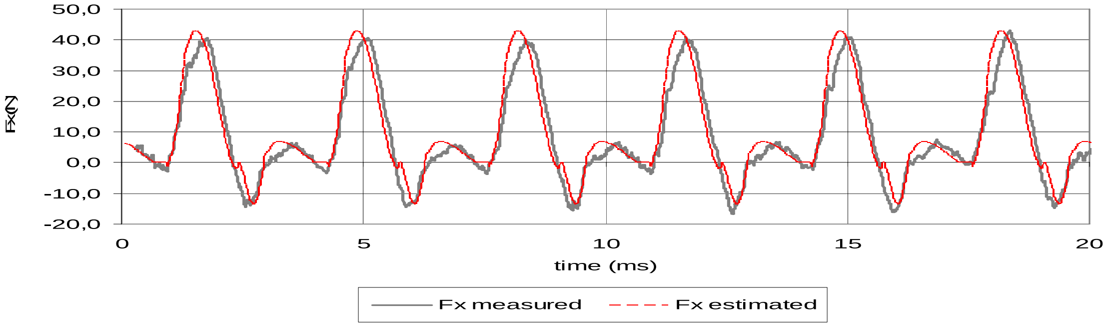

Figure 2. Estimated and measured forces considering the first fitting of fig.1

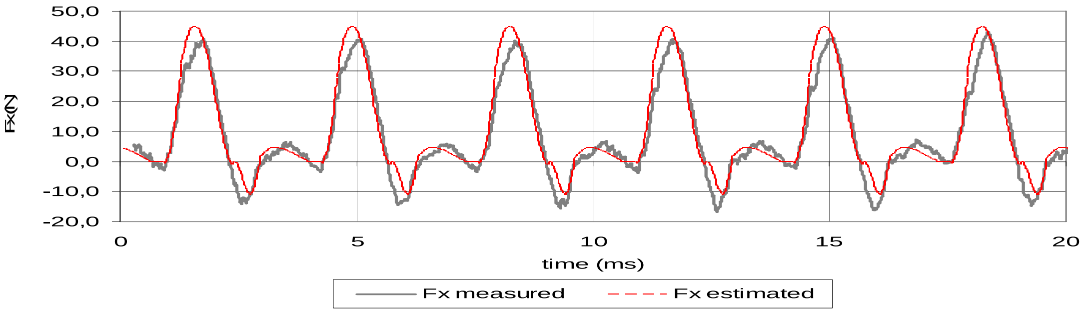

Figure 3. Estimated and measured forces considering the second fitting of fig.1

4. EXPERIMENTAL RESULTS

To verify the proposed cutting force model, more than 200 hundred experiments have been performed on aluminium and steel alloys using tools with diameters varying from 0,2 to 0,8 mm.

To permit rapid calculation of cutting forces in an on-line environment, only one revolution of the cutter is needed to obtain cutting coefficient data.

To find the best fitting, different experiments were performed in up-milling, down-milling and slot milling conditions. The results have shown that an adequate selection of the tool engagement angle range may improve the estimated cutting force coefficients (figure 3). The transients of the cutter in the workpiece show some instability in the values of cutting forces. The best estimation is obtained in slot milling tests.

5. CONCLUSIONS

This paper has presented an improved method for the estimation of cutting forces in endmilling process. This new model presents a simple analytical expression and it shows an efficient procedure to determine runout errors in micromilling tools.

The accuracy of the force predictions depends heavily on the estimation of the specific cutting pressure. This paper has presented an analysis of different ways of fitting the cutting force coefficients and the effect of the selected fit on the estimated cutting force as well.

To determine the cutting coefficients only one cutter revolution is needed, generating accurate predictions of the force. Improved results are obtained selecting the adequate range of the tool engagement angle.

6. REFERENCES

[1] J. Tlusty, P. MacNeil. Dynamics of cutting forces in end milling. Annals of CIRP. v. 24/1. p. 21-25, 1975.

[2] S. Engin, Y. Altintas. Generalized modelling of milling mechanics and dynamics: Part I and Part II - University of British Columbia. Department of Mechanical Engineering.

[3] W.A. Kline, R.E. DeVor. The effect of run-out on cutting geometry and forces in end milling. Int. J. Machine Tool Design and Research, v. 23, n. 2/3, p. 123-140, 1983.

[4] J.W. Sutherland, R.E. DeVor. An improved method for cutting force and surface error prediction in flexible end milling systems. J. Eng. for Industry, v. 108, p. 269-279, Nov 1986.

[5] H.Y.Feng, C.H.Menq. The prediction of cutting forces in the ball-end milling process. Part I and Part II. Int. J. Machine Tools & Manufacture, v. 34, p. 697-719, 1994.

[6] J. Gradisêk, M. Kalveram, K. Weinert. Mechanistic identification of specific force coefficients for a general end mill. Int. J. Mach.Tools & Manufacture, v. 44, p. 401-414, 2004.

[7] W.S. Yun, D.W. Cho. Accurate 3-D cutting force prediction using cutting condition independent coefficients in end milling. Int. J. Machine Tools & Manufacture, v. 41, p. 463-478, 2001

[8] W.Y. Bao, I.N. Tansel. Modelling micro-end-milling operations. Part I and Part II. Int. J. Machine Tools & Manufacture, v. 40, p. 2155-2192, 2000.

[9] I.N. Tansel, W.Y. Bao, N.S. Reen, C.V. Kropas-Hughes. Genetic Tool Monitor (GTM) for micro-end-milling operations. Int. J. Machine Tools & Manufacture, v. 45, p. 293-299, 2005.