MODELING AND SIMULATION OF CUTTING TOOL EDGE ERRORS ON PRECISION MILLING

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Abstract. *The runout movement of the cutting tool is prejudicial to precision manufacturing. It produces errors in the machined part, variation in the tool life and premature tool breakage. The position and orientation of the cutting tool edge is determined by the tolerances of the spindle, the toolholder and the cutting tool. It is advisable to measure the runout of the tool mounted on the spindle before cutting begins. But in some manufacturing practices this a time consuming task and cannot be carried out. Furthermore the choice of the tolerances of the elements is seen as an art based upon the experiences of individual designers and operators. In this paper, an approach to analyzing the cutting tool edge position and orientation variations due the spindle elements tolerances is applied. A simulation is performed based on a synthesis of elements errors and a sensitivity analysis is carried out*

Keywords: *precision milling, tool runout, excentricity, toolholder*

1. Introduction

The need for improvements in machining accuracy has been increasing over the years. This means that the workpieces must be produced with tighter tolerances attaining high productivity and low production cost. As pointed out by Chartier (2003), the improvement of the concentricity and repeatability of toolholders increases the tool life and accuracy of the machined workpiece. Figure 1 illustrates a typical precision milling process, where the rough part of the workpiece is removed by the cutting edge 1 while the cutting edge 2 finishes the workpiece surface.

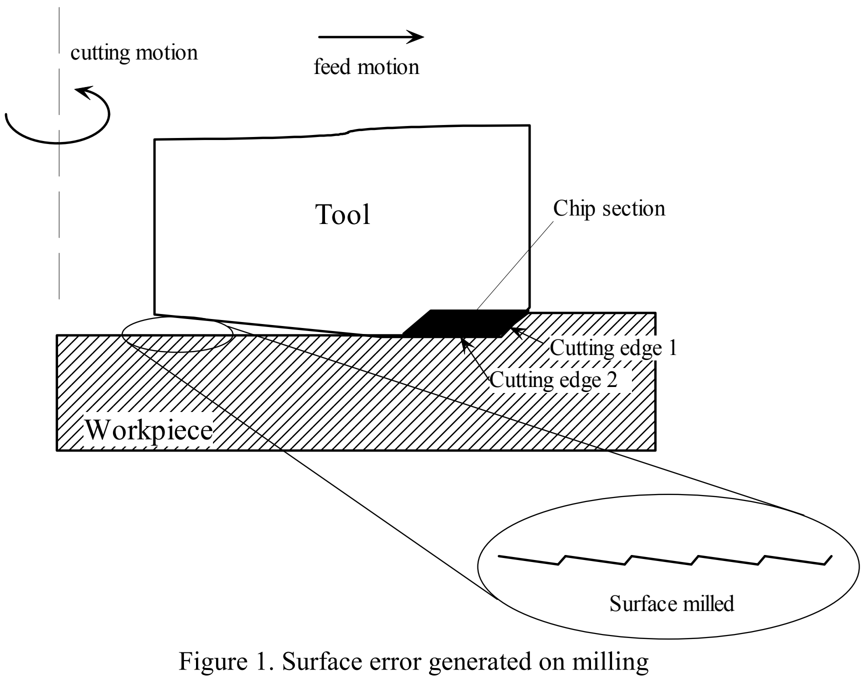

Figure 1. Surface error generated on milling

The principal cause of inaccuracy machined surfaces is the movement of the cutting edges (Li and Liu, 2002). The position and orientation error of the cutting tool edges are the mains factors responsible for the surface roughness and for the surface form error (Baek, 2001, Degner, 1979).

To achieve the required workpiece characteristics, the machining process must be performed with high process safety (Westkämper 1993). In other words, the influencing factors must be known and controllable. However, many factors act on the manufacturing process so that it becomes a complex task, requiring complex skills to machine workpiece with high accuracy. According to Luttervelt et al. (1999), “in industrial practice, the control of the workpiece precision still relies on the production experience of the process planners and machine tool operators or trial runs”.

The workpiece accuracy is specified by errors in the dimensions and form of the workpiece surfaces. It is essentially determined by the difference between the planned and actual tool path. Factors like deformations under cutting forces, weight and thermal deformations, cutting tool wear, control system accuracy, clamping characteristics, dynamic imbalance and the machine tool accuracy influence the variation of the tool path relative to the workpiece. Therefore, the main factor in producing more precise workpieces is the machine tool accuracy. The machine tool is a system composed by various elements, which carry the workpiece and the cutting tool and hence determines their relative positions. Errors caused by inaccuracy of the machine tool elements will reflect on the machined workpiece. Some studies have reported the influence of the geometric accuracy of the machine tool on the position of the workpiece and tool (Srivastava and Veldhuis, 1995, Ramesh and Mannan, 2000, Murty 1996). A more comprehensive study on machine tool errors is presented by Weck (1996). Practical recommendations for increasing accuracy in machining are found in Reshetov and Portman (1988). On machine tools, the position of the workpiece depends, basically, on the flatness of the table, straightness of guideways and the mutual squareness of the X and Y guideways (Weck, 1996). The spindle system is an important part of the machine tool because it is responsible for the cutting tool edge positioning and movement. Hence the improvement on the spindle system accuracy contributes to machine workpiece with high accuracy. In this paper it is developed an approach to simulate variation in the cutting tool edge position and orientation, caused by errors originating from the chain spindle nose/holder/tool elements and a sensibility analysis is carried out.

2. The accuracy of the spindle system

Tlusty (2000) points out that “the most important part of the structure, the heart of the machine tool, is the spindle”. As shown in Figure 2, the spindle is a system composed by a spindle nose, toolholder and cutting tool.

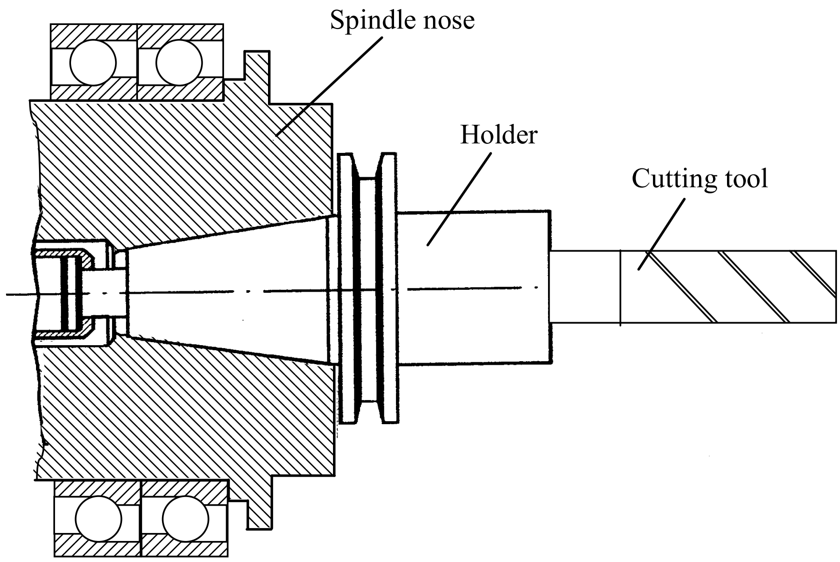

Figure 2. Elements of a Spindle System

The spindle shaft is mounted in the headstock by bearings for the radial and axial support. The spindle errors are caused by bearing mounting inaccuracy, and bearing tolerance quality, that lead to rotational and angularity errors of the spindle axis (Weck, 1997, Milberg, 1992, Balakschin, 1953). Deformations under cutting forces, weight and thermal variations also contribute to the eccentric movement of the cutting tool but they are not treated in this work.

The toolholder provides the standard connection between various cutting tools and the machine spindle. This connection influences the accuracy, repeatability, balance and rigidity of the spindle system. The goal is obviously to have the cutting tool axis rotating on the exact same axis of the spindle. There are variations in the toolholder quality from manufacturer to manufacturer, influencing the cutting tool positioning. Yang (2000) suggested some modifications in the design of the toolholder to avoid wear and corrosion damage due to fretting conditions caused by vibrations between the spindle and toolholder. The mounting of the holder in the spindle nose and the cutting tool in the holder contribute strongly to the variation in tool edge position. Since this procedure will be repeated n times and with different holders and tools, the cutting tool edge position will vary. Inaccuracy of the cutting edge geometries of multiple-blade tools leads to an unequal cutting condition, and hence different cutting forces and tool wear on the edges.

In the shop floor the machinist measures the tool's runout on the machine tool using an indicator, then taps the high spot with the mallet, mounting the toolholder into the spindle nose until the runout is appropriate. However, this process takes time. Some CNC machine tools have already a monitoring system to measure the static cutting tool runout. The dynamic runout occurs during machining and is more complex. In some works, methods to identify the runout during the milling process are described based on monitoring the cutting forces (Wang and Zheng, 2003). An approach to predict the cutting forces in end-milling including modeled eccentricity effects has been presented by Armarego and Deshpande (1989). In his investigation, it was observed an 18 to 20 μm eccentricity of the cutting tool for a 2 μm tool runout and tooth geometrical variations. However, when the cutter was held in a old holder an eccentricity of 40μm was observed. A method for compensation of dynamic runout in face-milling is pointed out by Sastry et al. (2000).

The static runout of the cutting tool is associated with the mechanical coupling characteristics. With the increase in modular and reconfigurable machine tools, more attention has been given to the mechanical coupling. Some studies have been conducted to analyze and improve the repeatability of elements coupling for machine tools (Li at el., 2000), but not much attention has been given to the spindle system. The factors, that lead to inaccurate cutting tool edge position and orientation depend on machine tool spindle accuracy, the holder mounting in the nose spindle, the tool mounting in the holder and the tool accuracy. Due to the combined variations in these factors, the position and orientation of the cutting tool edge have stochastic characteristics.

Through the simulation of the machining process, a good machining performance and a better control of the accuracy of workpieces can be achieved (Luttervelt and Peng, 1999). Liu and Huang (2001) simulated the dimensional and geometric accuracy of a machined component, through manufacturing error synthesis, where the accuracy of the machine tool, workpiece fixture and cutting tool were taken into account. Although, many works have been conducted to study the machine tool accuracy, relatively little attention has been paid to the problem of the accuracy of cutting tool position when mounting the tool in the spindle.

3. Description and Formulation of the Problem

Figure 3 represents the spindle system where the relative position of the cutting tool edge is modeling using frame chains.

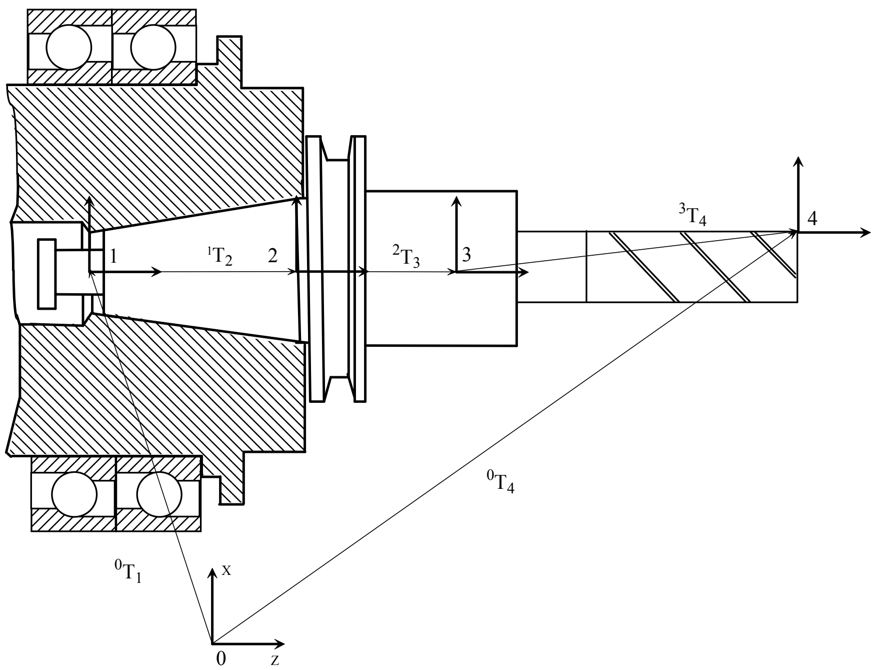

Figure 3. Kinematic modeling of the cutting tool edge position

Where $^0T_1$ is the position of the machine spindle nose relative to a fixed reference point on the machine tool, $^1T_2$ the position of the holder relative to the machine spindle nose, $^2T_3$ the position of the tool reference point relative to the holder, $^3T_4$ the position of the cutting tool edge relative to the tool reference and $^0T_4$ the position of the tool point in relation to a fixed reference on the machine tool.

In this work the runout and tilt of the cutting tool will be considered to be symmetrical. Then the modeling can be simplified by analyzing it in one plane. When the parts are mounted the position and orientation of the cutting tool are modified from the ideal case, depending on the tolerance of the elements and the coupling conditions. The element shapes can vary in form and position so that when they are mounted, an error originated from one part often propagates to others through the surface matings. Variations in part shapes are mainly related to the manufacturing process or surface wear. Since the parts are mounted several times, the same contact conditions are not maintained. Hence a non-repeatability of position and orientation is caused mainly by variations in thermal, force and coupling conditions. Thermal variations due to working temperature differences between spindle and holder cause variations in the part sizes and modify the relative positioning at the time of mounting. The coupling procedure causes a friction force in the opposite direction to the movement. It is feasible that the required position is not regained when the coupling force varies greatly. The Surface finish, coefficient of friction, contact points and local stiffness influence coupling conditions. Depending on the contact area and the variation in the applied force, position and orientation variations can occur between the parts (Suzuki et al. 1996). Since deflections due to coupling conditions are not as significant as dimensional and form errors the parts can be modeled as rigid bodies.

An analysis based on connective assembly model is carried out to predict the iteration between the parts. This procedure allows a sysnthesis of the geometrical tolerance of the parts that are assembled. It is constituted by a sequence of reference frames that share a mating surface or axis. Homogeneous transformation matrices describe the relative position and orientation of the frames, so that the tolerance specification is transformed into rotation and translation of the part that is in contact with the surface (De Napoli et al. 2001, Whitney 2004).

Slocum (1992) presents the homogeneous transformation matrix as follows:

$$ {}^{R}T_{n} = \begin{bmatrix} O_{ix} & O_{iy} & O_{iz} & P_{x} \\ O_{jx} & O_{jy} & O_{jz} & P_{y} \\ O_{kx} & O_{ky} & O_{kz} & P_{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

Connecting N rigid bodies in series the orientation and position of the cutting tool edge with respect to the machine tool reference can be expressed by the transformation:

$$ {}^{R}T_{n} = \prod_{m=1}^{N} {}^{m-1}T_{m} = {}^{0}T_{1}\,{}^{1}T_{2}\,{}^{2}T_{3} \cdots \tag{2} $$

Errors can cause a small displacement modifying the position and rotation of the frame which are given by the matrix:

$$ E_{n} = \begin{bmatrix} 1 & -\varepsilon_{z} & \varepsilon_{y} & \delta_{x} \\ \varepsilon_{z} & 1 & -\varepsilon_{x} & \delta_{y} \\ -\varepsilon_{y} & \varepsilon_{x} & 1 & \delta_{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Finally the actual HTM is expressed by considering the position frame and the related error:

$$ {}^{R}T_{n\,err} = {}^{R}T_{n}\,E_{n} \tag{4} $$

4. Simulation Study

The purpose of this analysis is to determine the expected value of the cutting tool edge position and orientation in relation to a fixed coordinate on the machine tool. The transformation of coordinates between the elements from the tool to a fixed reference on the machine is achieved through the HTM equations, resulting in:

$$ {}^{0}T_{4} = {}^{0}T_{1} \cdot E_{1} \cdot {}^{1}T_{2} \cdot E_{2} \cdot {}^{2}T_{3} \cdot E_{3} \cdot {}^{3}T_{4} \cdot E_{4}, \tag{5} $$

where:

$$
{}^{0}T_1 \cdot E_1 = \begin{bmatrix} 1 & 0 & \varepsilon_{y1} & X_1 + \delta_{x1} \\ 0 & 1 & 0 & 0 \\ -\varepsilon_{y1} & 0 & 1 & Z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}
$$

$$
{}^{1}T_2 \cdot E_2 = \begin{bmatrix} 1 & 0 & \varepsilon_{y2} & \delta_{x2} \\ 0 & 1 & 0 & 0 \\ -\varepsilon_{y2} & 0 & 1 & Z_2 + \delta_{z2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}
$$

$$
{}^{2}T_3 \cdot E_3 = \begin{bmatrix} 1 & 0 & \varepsilon_{y3} & \delta_{x3} \\ 0 & 1 & 0 & 0 \\ -\varepsilon_{y3} & 0 & 1 & Z_3 + \delta_{z3} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}
$$

$$
{}^{3}T_4 \cdot E_4 = \begin{bmatrix} 1 & 0 & 0 & X_4 + \delta_{x4} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Z_4 + \delta_{z4} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}
$$

The ${}^{0}T_1 \cdot E_1$ matrix achieves the spindle runout δ_{x1}, angularity error ε_{y1} and the position relative to the machine tool reference X_1, Z_1. The influence of the precision of mounting the toolholder into the spindle nose δ_{x2}, δ_{z2}, ε_{y2} and the relative position between the spindle and the spindle nose/toolholder Z_2 are described by ${}^{1}T_2 \cdot E_2$. The matrix ${}^{2}T_3 \cdot E_3$ brings together the influence of the precision of mounting the tool shank into the holder δ_{x3}, ε_{y3}, the accuracy with which the operator mounts the tool in the Z-direction δ_{z3} and the relative position of the cutting tool in relation to the holder reference frame Z_3. Finally, ${}^{3}T_4 \cdot E_4$ describes the cutting tool edge position X_4, Z_4 and its precision δ_{x4}, δ_{z4}.

The equations 6,7,8,9 are substituted into the equation 5 to obtain the position of the cutting edge in the X- and Z-directions. The analysis includes up to the second-order terms and they are given as follows.

$$
\begin{aligned}
P_x = {} & X_1 + X_4 + \delta_{x1} + \delta_{x2} + \delta_{x3} + \delta_{x4} + \varepsilon_{y1} \cdot Z_2 + \left(\varepsilon_{y2} + \varepsilon_{y1}\right) Z_3 + \left(\varepsilon_{y1} + \varepsilon_{y2} + \varepsilon_{y3}\right) Z_4 \\
& + \varepsilon_{y1} \cdot \delta_{z2} + \left(\varepsilon_{y1} + \varepsilon_{y2}\right) \delta_{z3} + \left(\varepsilon_{y1} + \varepsilon_{y2} + \varepsilon_{y3}\right) \delta_{z4} - \varepsilon_{y1} \cdot \varepsilon_{y2} \cdot X_4
\end{aligned} \tag{10}
$$

$$
\begin{aligned}
P_z = {} & Z_1 + Z_2 + Z_3 + Z_4 + \delta_{z2} + \delta_{z3} + \delta_{z4} - \left(\varepsilon_{y1} + \varepsilon_{y2} + \varepsilon_{y3}\right) X_4 - \varepsilon_{y1} \cdot \delta_{x2} \\
& - \left(\varepsilon_{y1} + \varepsilon_{y2}\right) \delta_{x3} - \left(\varepsilon_{y1} + \varepsilon_{y2} - \varepsilon_{y3}\right) \delta_{x4} - \varepsilon_{y1} \cdot \varepsilon_{y2} \cdot Z_3 + \left(-\varepsilon_{y1}\varepsilon_{y2} + \varepsilon_{y1}\varepsilon_{y3} + \varepsilon_{y2}\varepsilon_{y3}\right) Z_4
\end{aligned} \tag{11}
$$

and the angularity error on y is:

$$
O_{iz} = -O_{kz} = \varepsilon_{y1} + \varepsilon_{y2} + \varepsilon_{y3} \tag{12}
$$

The equations (10, 11 and 12) are tested with a set process parameters were chosen as follow: distance between the machine reference frame and the spindle reference frame X_1=0 and Z_1=0; distance between spindle and toolholder Z_2=50; distance between toolholder and cutting tool frame Z_3=30; length and the radius of the cutting tool X_4=5 and Z_4=100 mm; spindle runout δ_{x1}=8 μm and angular error ε_{y1}=0.01 ° ($1.7 \cdot 10^{-4}$ rad); toolholder mounting into the spindle nose δ_{x2}=8 μm, δ_{z2}=9 μm, ε_{y2}=0.01 ° ($1.7\cdot10^{-4}$ rad); tool shank mounting into the holder δ_{x3}=8 μm, δ_{z3}=10 μm, ε_{y3}= $5\cdot10^{-4}$ rad) and cutting tool edge precision δ_{x4}=10 μm, δ_{z4}=10 μm.

The results reveal that the variation in the X-direction is greater than in the Z-direction. The positioning error in the X-direction was 0.4 mm and in the Z-direction was 0.017 mm. It was already expected because the rotational errors of the contact parts in Y-direction have a considerable influence on X-direction when they propagate through the elements. The simulated angular variation was about $2.4\cdot10^{-3}$ rad.

5. Sensibility Analysis

A sensitivity analysis was carried out in order to investigate which factors are the most important in variation of the cutting tool edge position and rotation. Using this information, it becomes very simple to focus the design or the manufacture attention only on those items that contribute to the bigger variation of the system. The mathematical definition of the sensitivity can be given as the derivate of the dependent variable at a particular point:

$$S = \frac{\partial(P_x, P_z, O_{iz})}{\partial f_i} \qquad (13)$$

Table 1 shows the results of the sensitivity take into account the characteristics of the spindle, the holder mounting in spindle nose, the tool mounting in holder and the cutting tool tolerances.

Table 1. Results of the sensibility analysis

	Spindle		Toolholder in the spindle nose			Tool in the toolholder			Cutting tool	
Error	δ_{x1}	ε_{y1}	δ_{x2}	δ_{z2}	ε_{y2}	δ_{x3}	δ_{z3}	ε_{y3}	δ_{x4}	δ_{z4}
O_{iz}	0	1	0	0	1	0	0	1	0	0
P_x	1	180	1	0	130	1	0	100	1	0
P_z	0	-5,1	0	1	-5,3	0	1	-5,2	0	1

Analyzing the sensibility in the cutting tool edge orientation the major influence factors are the spindle angular error, the effect of the toolholder mounting into the spindle nose and the cutting tool mounting into the toolholder all with a value of one. When the factors that cause the positional error of the cutting tool edge are compared, the influence factors related with angular errors have the greater influence in the X-direction. It can be seen that the spindle angular error causes 30 % more positional error then the toolholder mounting and 80 % more error then cutting tool mounting. The angular error of the elements system influence also in the Z-direction, although the influence values are smaller and negative. This means that when the angular errors increase the cutting tool edge position become smaller. All other errors related with the displacement in the X- and Z-directions have a sensibility value of one.

These results aim to predict the spindle elements tolerance when a determined accuracy in cutting tool edge movement is required. There is always a tendency to choose elements with high precision, but these are more expensive. Since the spindle and the spindle nose errors are not easy to eliminate, the simulation can aid in choosing a holder, within various stages of wear, and cutting tool tolerance for required machining conditions.

6. Conclusion

In this paper an approach to predicting the influence of the spindle elements of a machine tool on the cutting tool edge position and orientation was described. The model was developed using the Homogeneous Transformation Matrix. The runout and the angularity errors of the spindle, the error associated with the toolholder mounting into the spindle nose, the accuracy of tool mounting into the toolholder and the cutting tool precision were considered. A numerical example was conducted to demonstrate the effect of the spindle system element errors. A sensitivity analysis was carried out, showing that the displacement errors in the X- and Z-directions contribute only by about one. As was to expect, the angular errors showed to have a greater contribution in the cutting tool edge displacement and rotation.

The simulation results are considered helpful for finding the relationships between the elements and their possible influence on the cutting tool edge position and orientation variations. Further, this computational approach provides the process engineer with the possible ranges of the tool edge position and hence surface roughness, based on the element tolerances of the spindle system.

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