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Measurement of the Volumetric Thermal Errors for CNC Machining Center using the Star-type-styluses Touch Probe

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ABSTRACT

One of the major limitations of productivity and quality in metal cutting is the machining accuracy of machine tools. The machining accuracy is affected by geometric errors, thermally-induced errors, and the deterioration of the machine tools. Geometric and thermal errors of machine tools should be measured and compensated to manufacture high quality products. In metal cutting, the machining accuracy is more affected by thermal errors than by geometric errors. This paper models the thermal errors for error analysis and develops an on-the-machine measurement system by which the volumetric errors are measured and compensated. The thermal error is modeled by means of angularity errors of a column and thermal drift error of the spindle unit which are measured by the touch probe unit with a star type styluses and a designed spherical ball artifact (SBA). Experiments show that the developed system provides a high measuring accuracy, with repeatability of ±2μm in X, Y and Z directions. It is believed that the developed measurement system can be also applied to the machine tools with CNC controller. In addition, machining accuracy and product quality can be also improved by using the developed measurement system when the spherical ball artifact is mounted on a modular fixture

Key Words: Volumetric thermal errors, touch probe, temperature, on-machine measurement, spherical ball artifact, machining accuracy

1. Introduction

One of the major limitations on productivity and quality in metal cutting is machining accuracy of machine tools. The machining accuracy is affected by geometric errors, thermally induced errors, and deterioration of machine tools. Geometric and thermal errors of machine tools should be measured and compensated to manufacture products with high accuracy and high quality. Geometric errors are caused by the unwanted motions of machine elements, such as carriages, cross-slides and work-tables. The unwanted motions occur because of geometric imperfections and misalignments. Thermal errors result from thermal distortions of machine components due to internal or external heat sources, such as motors, bearings, hydraulic systems, and ambient temperature.

In metal cutting, the machining accuracy of machine tools is more affected by thermal errors than geometric errors[1,5] (about 40~70% of the occurring errors in machine tools result from thermal errors). Thermal errors caused by spindle heads are greater than those of the machine tool axes[6]. Therefore, to reduce the geometric and thermal errors of machine tools is a key requirement for improving machining accuracy.

Studies for improving machining accuracy of machine tools can be divided into the measurement/compensation[3-4,6-8] and errors reduction through design and manufacturing efforts of machine tools. The laser interferometer has been generally used for measurement of geometric errors of machine tools, and the circular test method and the kinematic ball bar have been used for the evaluation of the accuracy of machine tools. In addition, artifacts [6] and 1-D ball arrays have been also used for the error measurement.

The laser interferometer is well established metrology tool for the measurement of positioning errors, angular errors, straightness errors, and squareness errors with high accuracy and reliability. The disadvantage of this method, however, is that it requires too much time for the error measurement and error analysis.

The circular test method, the kinematic ball bar, and artifact have the advantages which include simple structure of the measuring system and easy measurement. These methods, however, have some problems which have difficulties to measure during the metal cutting and interfere with metal cutting, because the measuring instrument has to be installed onto the machine tools. Therefore, a simple way with high reliability is required in order to measure some errors in on-the-machine, to minimize measuring time, and to reduce idle time.

In this paper, the on-the-machine measurement method of machine tool errors using the spherical ball artifact and a touch probe unit is proposed. The proposed measurement system can be easily installed on machine tools, and used to measured and compensated the geometric and the thermal errors without any interruption in metal cutting.

2. Thermal Error Modeling

2.1 Error Modeling

Thermal errors are different in the working area of machine tools because of spindle drift error, angularity errors of the column, and axis errors. Therefore, thermal errors are modeled using angularity errors of the column, spindle drift error, and axis errors that are measured by the on-the-machine measurement system with heat sources.

In coordinates x_i, y_i, and z_i on working area of machine tools, if machine tools have angularity errors of the column, i.e., a_{xi}, a_{yi}, and a_{zi} in YZ, XZ, and XY planes, axes errors of the ball screw, i.e., δ_{xi}, δ_{yi}, and δ_{zi} in X, Y, and Z directions, and spindle drift error δ_{sp}, then actual position vector P_{actual} of machine tools is described using the homogeneous transformation matrix, as follows;

$$\begin{aligned} P_{actual} &= A_0^1.A_1^2.\dots.A_{n-1}^n P_{ref} \\ &= A^3(\delta_{sp})A^3(-L)A^6(a_{zi})A^5(a_{yi})A^4(a_{xi})A^2(y_i+\delta_{yi}) \\ &\quad A^3(z_i+\delta_{zi})A^1(x_i+\delta_{xi})P_{ref} \\ &= [T]P_{ref} \end{aligned} \tag{1}$$

where $P_{ref} = \begin{bmatrix} x & y & z-L & 1 \end{bmatrix}^T$ is a position vector without heat sources, A^i is the homogeneous transformation matrix. In case that some heat sources have been generated, volumetric thermal error ΔP is as follows;

$$\begin{aligned} \Delta P = P_{actual} - p_{ref} &= [T]P_{ref} - P_{ref} \\ &= \begin{bmatrix} \delta_{thx} & \delta_{thy} & \delta_{thz} & 1 \end{bmatrix}^T \end{aligned} \tag{2}$$

In formula (2), if angularity errors of the column are very small, second order terms can be negligible, i.e., $\cos\theta \approx 1$ and $\sin\theta \approx \theta$. Therefore, $[T]P_{ref}$ is as follows.

$$[T]P_{ref} = \begin{bmatrix} 1 & -a_{zi} & a_{yi} & x_i+\delta_{xi}+(z_i+\delta_{zi})a_{yi}-(y_i+\delta_{yi})a_{zi} \\ a_{zi} & 1 & -a_{xi} & (x_i+\delta_{xi})a_{zi}+y_i+\delta_{yi}-(z_i+\delta_{zi})a_{xi} \\ -a_{yi} & a_{xi} & 1 & z_i+\delta_{zi}+\delta_{sp}+L-(x_i+\delta_{xi})a_{yi}+(y_i+\delta_{yi})a_{xi} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Therefore, thermal errors δ_{thx}, δ_{thy}, and δ_{thz} of machine tools can be found by relation $\Delta P = [T-I]P_{ref}$, as follows;

$$\delta_{thx} = \delta_{xi} + (z_i + \delta_{zi})a_{yi} - (y_i + \delta_{yi})a_{zi} \tag{4a}$$

$$\delta_{thy} = (x_i + \delta_{xi})a_{zi} + \delta_{yi} - (z_i + \delta_{zi})a_{xi} \tag{4b}$$

$$\delta_{thz} = \delta_{zi} + \delta_{sp} - (x_i + \delta_{xi})a_{yi} + (y_i + \delta_{yi})a_{xi} \tag{4c}$$

where x_i, y_i, and z_i are volumetric coordinates on working area.

2.2 Thermal Errors of Column, Spindle, and Moving Axes

When there are temperature changes in machine tools, the star type probe with five styluses is changed with angularity errors of the column, i.e., a_{xi}, a_{yi}, and a_{zi} in X, Y, and Z axes, respectively. In this case, the changed position vector P_{new} of the star type probe is described using the rigid body homogeneous transformation matrix, as follows;

$$P_{new} = TR.P_{old} \tag{5}$$

where variable TR is multiple of the homogeneous transformation matrices for rotational angles. P_{old}

and P_{new} are position vectors in case of temperature changed, before and after, respectively. These variables are as follows;

$$TR = A^4(a_{xi}).A^5(a_{yi}).A^6(a_{zi}) \tag{6}$$

$$P_{new} = \begin{bmatrix} x_{n0} & x_{n1} & x_{n2} \\ y_{n0} & y_{n1} & y_{n2} \\ z_{n0} & z_{n1} & z_{n2} \end{bmatrix}$$

$$P_{old} = \begin{bmatrix} x_{o0} & x_{o1} & x_{o2} \\ y_{o0} & y_{o1} & y_{o2} \\ z_{o0} & z_{o1} & z_{o2} \end{bmatrix}$$

where x_{oi}, y_{oi}, and z_{oi} are values measured by each stylus before temperature changes. x_{ni}, y_{ni}, and z_{ni} are values measured by each stylus after temperature changes. From these relationships, angularity errors of the column, i.e., a_{xi}, a_{yi}, and a_{zi} can be found, as follows;

$$a_{xi} = -\left.\frac{(y_{o2} - y_{n2})x_{o0} - (y_{o0} - y_{n0})x_{o2}}{x_{o2}z_{o0} - x_{o0}z_{o2}}\right|_{i=1\sim4} \tag{7}$$

$$a_{yi} = -\left.\frac{(x_{o0} - x_{n0})y_{o1} - (x_{o1} - x_{n1})y_{o0}}{y_{o1}z_{o0} - y_{o0}z_{o1}}\right|_{i=1\sim4} \tag{8}$$

$$a_{zi} = \left.\frac{x_{o1} - x_{n1}}{y_{o1}} - \frac{[(x_{o1} - x_{n1})y_{o2} - (x_{o2} - x_{n2})y_{o1}]z_{o1}}{y_{o1}(y_{o2}z_{o1} - y_{o1}z_{o2})}\right|_{i=1\sim4} \tag{9}$$

Also, the spindle drift error δ_{sp} is described using the change of the 1st stylus central coordinates, as follows;

$$\begin{aligned} \delta_{sp} &= \left|P_{real} - P_{ref}\right| \\ &= \sqrt{(x_{n0} - x_{o0})^2 + (y_{n0} - y_{o0})^2 + (z_{n0} - z_{o0})^2)} \end{aligned} \tag{10}$$

Thermal errors for the ball screw can be analyzed using mirror image values for some measured angularity errors of column and spindle drift error. Mirror image values can be described as follows;

$$(a_{xi}, a_{yi}, a_{zi}, \delta_{sp}) \Rightarrow (-a_{xi}, -a_{yi}, -a_{zi}, -\delta_{sp})$$

$$\begin{bmatrix} \delta_{thxi} - y_i a_{zi} + z_i a_{yi} \\ \delta_{thyi} + x_i a_{zi} - z_i a_{xi} \\ \delta_{thzi} + \delta_{sp} - x_i a_{yi} + y_i a_{xi} \end{bmatrix} = \begin{bmatrix} 1 & a_{zi} & -a_{yi} \\ -a_{zi} & 1 & a_{xi} \\ a_{yi} & -a_{xi} & 1 \end{bmatrix} \begin{bmatrix} \delta_{xi} \\ \delta_{yi} \\ \delta_{zi} \end{bmatrix} \tag{11}$$

From formula (11), Thermal error matrix d for the ball screw is described as follows;

$$D = A.d \quad \therefore d = A^{-1}.D \tag{12}$$

3. On-Machine Measurement System

In order to measure geometric errors and volumetric thermal errors of machine tools, on-the-machine measurement system has been developed using the touch probe unit and the spherical ball artifact as shown in Fig.1. This system consists of the spherical ball artifact, a temperature data logger, a star type touch probe, a machine interface unit, and the error analysis program for analysis of measured results.

The mean and standard deviation of over travel errors of a touch probe has been calibrated. From measured results, the standard deviations of touch probe are ±2μm in X and Y axes, and ±1μm in Z axis.

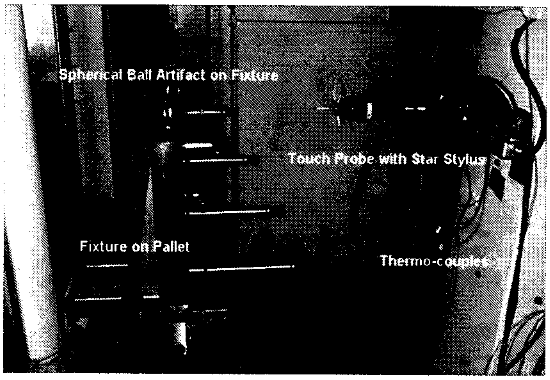


Fig.1 Experimental set-up on the horizontal machining center

In order to measure volumetric thermal errors of machine tools using on-the-machine measurement system, the reference ball artifact is needed. In this paper, the spherical ball artifact has been designed, and used for error measurement as shown in Fig.1. In the designed artifact with four spherical balls, the balls are installed by means of four Super Invar poles (Ni 31%-Co5%, α =1.2e-6) in the diagonal direction of a virtual cube that exists on the modular fixture as shown in Fig.1. Their sphericities are 0.4μm and less, and their nominal diameters are 25.4mm. Distances between the central coordinates of spherical balls are measured by the

Coordinate Measuring Machine on the basis of the reference ball (#1). The characteristics of the designed artifact are as follows; 1) set-up errors are negligible because it is configured with four spherical balls of high sphericities, 2) it is easy to set-up and to minimize thermal effect, and 3) geometric and thermal errors can be measured by on-the-machine.

Since the star type probe with three styluses, i.e., p_0, p_1, and p_2 has used for the measurement, three central coordinates are obtained by a measurement for each spherical ball. Therefore, twelve central coordinates, i.e., 3 points per a spherical ball x 4-balls is equal to 12 values are obtained on the spherical ball artifact. From the measured central coordinates by the star type probe and the Coordinate Measuring Machine, some errors on each spherical ball are calculated as follows;

$$\text{Errors on spherical balls} = \left(\text{measured values}\big|_{i+1} - \text{measured values}\big|_{i}\right) - \text{measured values of CMM}\big|_{i} \quad (i = 1..3) \qquad (13)$$

So, from the above-mentioned formulas, volumetric thermal errors of machine tools can be analyzed.

4. Experimental Procedures and Results

The measurement for volumetric thermal errors is accomplished on the horizontal machining center with the spherical ball artifact that is installed on a modular fixture. Measured values have been uploaded to a personal computer for the error analysis, using the RS232 communication. The specifications of experimental equipment are shown in Table 1.

The central coordinates of spherical balls are calculated using the least-square-curve fitting method. The volumetric thermal errors of machine tools are analyzed using the spindle drift error, the angularity errors of the column, the axis errors, and the volumetric thermal error model. These errors are measured for about 5 hours at 20~30 minutes interval at the rotational spindle speeds of 500, 1000, 1500, 2000, 2500, and 3000rpm, respectively.

In order to measure the temperature of the machine tools, thirteen thermocouples have been installed on the machine tools; the spindle head(1 point), the upper part of the spindle unit(3 points), the environment temperature(1 point), the X, Y, and Z axes (3 points), the column part (3 points), and the flange face (2 points).

Table 1 Specifications of the inspection system

Components	Specifications
Machine Tools	Horizontal Machining Center
Laser Interferometer	HP5528A
Temperature Logger	TempScan/1000 32 input channels 8Mbyte memory Pre-trigger / Post-trigger RS-232C / IEEE488
Touch Probe	MP7 (Ranishaw) Optical type MI7 Interface unit Star type Stylus (L=50mm)
CMM	Leitz PMM U1(μm) = 0.5 + L/700 U3(μm) = 0.8 + L/700
Spherical Ball Artifact	Sphericity : 0.1μm ~ 0.4μm Diameter : 25.3998 ~ 25.4mm Super Invar : α =1.2e-6

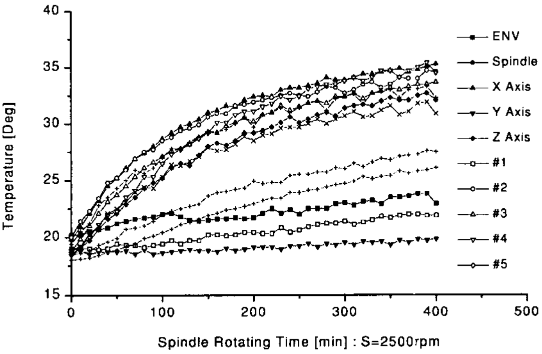


Fig. 2 Trend of temperatures in horizontal machining center (S=2500rpm)

The characteristics of temperature on the machine tools at the rotational spindle speed of 2500rpm are shown in Fig.2. As a result of measured temperature, the characteristics of temperature which occur at each point on the machine tools were divided into three groups according to the degree of temperature changes as shown in Fig.2.

① a group which has large temperature change (spindle head, upper part of spindle unit, Y axis, and flange face)

② a group which has medium temperature change (column)

③ a group which has little temperature change (X axis, Z axis, and surrounding temperature)

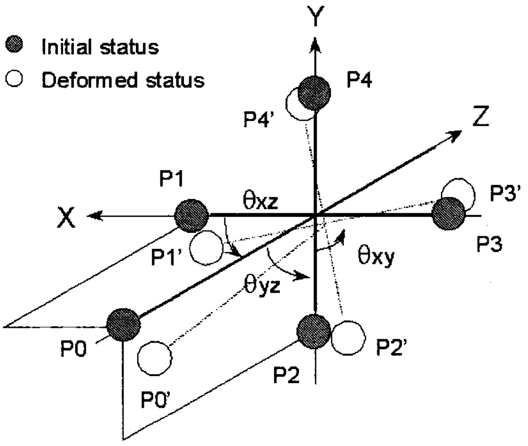
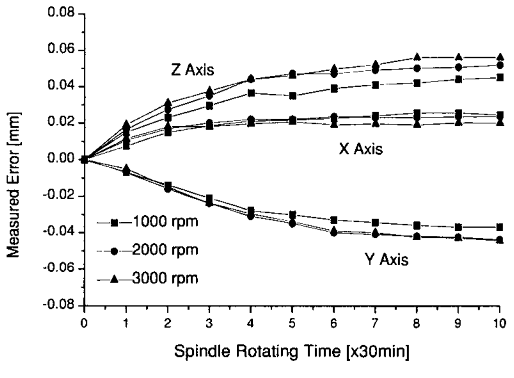
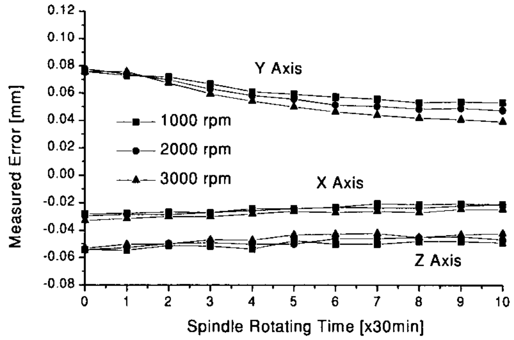


Fig. 3 Configuration of the star type probe

The configuration of star type probe is shown in Fig.3, before and after thermal deformation. The measured scalar thermal error for the reference ball (#1) are shown in Fig.4, with the rotational spindle speeds of 1000, 2000, and 3000rpm.



(a) Measured scalar thermal errors by the 1st stylus in the reference ball



(b) Difference scalar thermal errors between the 1st and the 4th balls

Fig. 4 Measured scalar thermal errors with respect to rotational spindle speeds

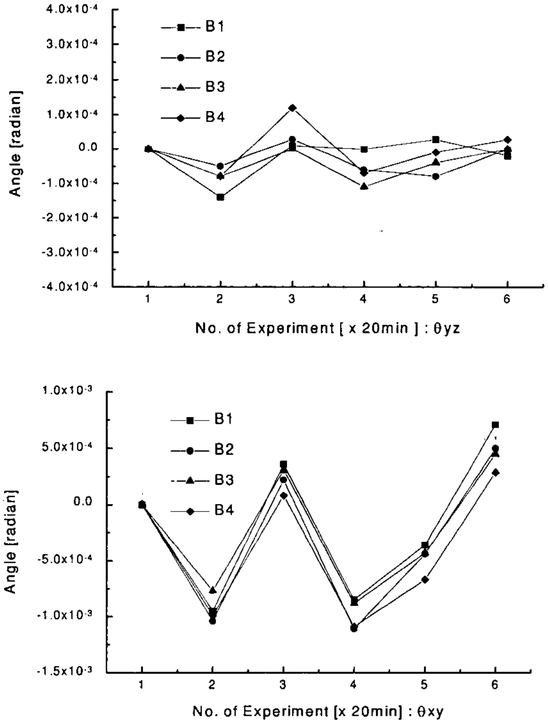
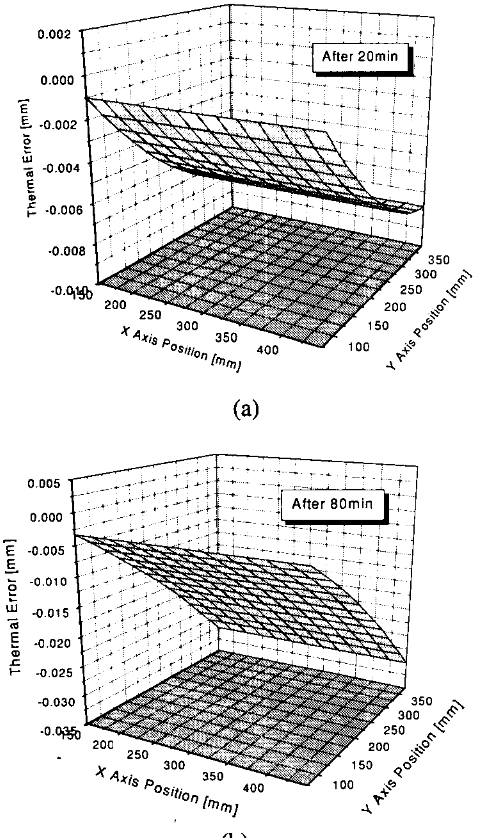


Fig. 5 Measured rotational angles θyz and θxy with respect to the spindle rotating time

The figure shows that the trends of measured central value for the reference ball (#1) are increased with respect to spindle rotating time for the X and Z axes, and decreased for the Y axis. Also, thermal errors in the directions of the Y and Z axes are changed due to heat expansion of the spindle unit and the ball screw of the Y axis. The thermal error in the direction of the Y axis is caused by the horizontal machining center whose spindle unit is supported by the Y axis ball screw. Heat sources of the spindle unit directly affected accuracy of the Y axis ball screw.



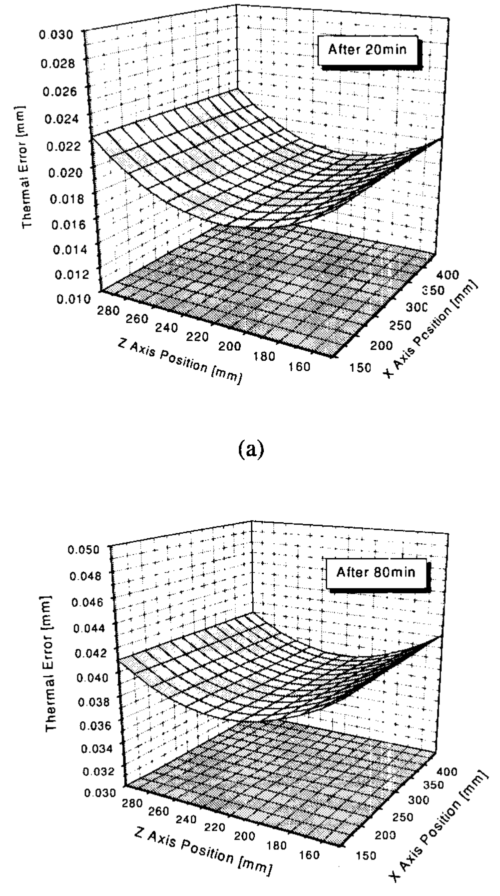
(a)

(b)

Fig. 6 Measured volumetric thermal errors in Y axis after (a) 20min and (b) 80min

The angularity errors of the column are measured at 20 minutes interval under the random rotational spindle speed using the star type probe as shown in Fig.5. From these results, angularity errors of the column are changed in a small amount in the XZ, YZ planes, but in a large amount in the XY plane.

The volumetric thermal errors are analyzed using the spindle drift error, the angularity errors of the column, and the axes errors. The volumetric thermal errors of horizontal machining center measured at 20 and 80minutes after the experiment start are shown in Fig.6 and Fig.7.



(a)

(b)

Fig. 7 Measured volumetric thermal errors in Z axisafter (a) 20min and (b) 80min

5. Conclusions

In this paper, the on-machine measurement system with the spherical ball artifact was proposed, which can measure volumetric thermal errors in the direction of X, Y, and Z axes for a CNC machining center. Using proposed thermal error model, the volumetric thermal error of machine tools can be easily analyzed by means of measured spindle drift error, angularity errors of the column, and axis errors which are measured by means of the on-the-machine measuring system.

The designed spherical ball artifact is installed by Super Invar poles to minimize thermal effect as temperature changes. The proposed measurement system can be easily installed on machine tools, and used to measure and compensate the volumetric errors without any interruption in metal cutting. It is also used for minimization of measuring time and idle time, and productivity improvement. The proposed measurement system can be applied to monitor thermal error changes of machine tools.

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