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Geometric Accuracy Measurement of Machined Surface Using the OMM (On the Machine Measurement) System

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ABSTRACT

Machining information such as form accuracy and surface roughness is an important factor for manufacturing precise parts. To this regard, OMM (On the Machine Measurement) has been researched for last several decades to alternate CMM (Coordinate Measurement Machine) process. In this research, the OMM system with a laser displacement sensor was developed for measuring form accuracy and surface roughness of the machined workpiece on the machine tool. The surface roughness was estimated comparing the sensory signal with the reference data measured from master specimen. Also, form accuracy was determined from the moving averaged raw data. In addition, the geometric error map constructed beforehand using the geometric errors of the machine tool was used to compensate the obtained form accuracy. The overall performance was compared with CMM result, and verified the feasibility of the measurement system.

Key Words: On the Machine Measurement (OMM), Form Accuracy, Surface Roughness, Laser Displacement Sensor, Volumetric Error

1. Introduction

Special purpose processes or measuring devices between the production lines for measuring form or dimensional accuracy can be efficient in case of mass production system, whereas they are not efficient for the case of small lot job of a batch. Therefore, CMM is introduced in the machine shop to inspect a part after completing machining. In this case, the investment fund or management of the system may be burden some. Since this system takes some time to balance the temperature difference between a part and the measurement system, there is some loss in the process. In addition, Owen[1] and Kim[3] presented measurement of the large workpieces due to the limited size of the system is not easy in CMM.

In these regards, Keizo[1], Kim[2] and Lee[3] was researched OMM systems that measure the workpiece mounted on the machine tool by changing a cutting tool with a sensing probe after finishing machining processes. Improved accuracy of the machine tool and a variety of precise sensors in contact or non-contact type have made the system practical. Recently, Kim[3] increased measuring speed by replacing the touch trigger probe as scanning probe. Lee[4] applied the OMM technology into the machine tool for realizing complex functions of the machine. In addition, Lee[5], Lee[6] and Kim[7] were analyzes error sources existing in the OMM system. Cho[8] proposed the error modeling scheme using a closed loop system of the OMM for the integration of CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing) /CAI (Computer Aided Inspection). These research efforts aimed at the increase of productivity, giving the complex functions to the machine tool, and the information integration of the machining system.

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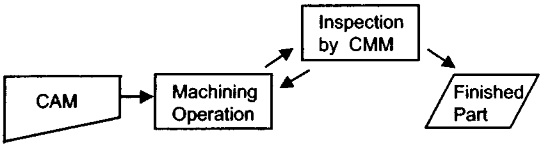
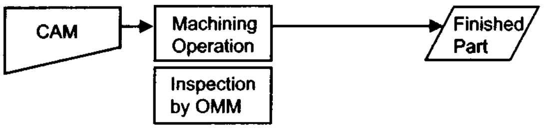


(a) Conventional Order of Manufacturing



(b) On the Machine Measurement Concept

Fig. 1 Concept of OMM system

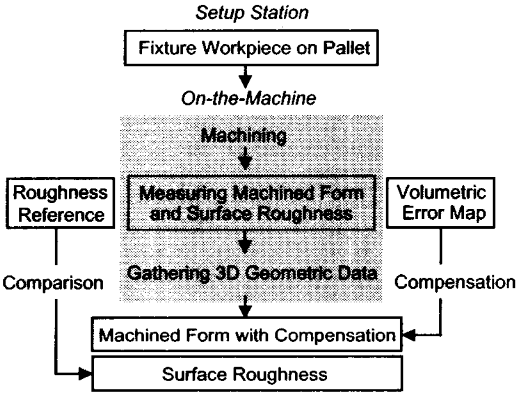


Fig. 2 Measurement information flow

Figure 1 shows how the processes can be improved by adopting the OMM in the machining system to shorten the process. However, it is still restrictive since the measuring system inherently includes the geometric errors of the machine tool, thermal error of the machine tool and workpiece, and tool deflection error, etc. These error sources make the accuracy of the OMM lower than the CMM. Among these errors, thermal and tool deflection errors can be suppressed to some extent relatively to the geometric errors.

In this paper, a new technology for OMM is introduced using a laser displacement sensor for measuring both the surface roughness and the form accuracy as shown in Fig. 2. Firstly, surface roughness is estimated by comparing a measured signal with the reference data taken from a master specimen beforehand. Secondly, form accuracy is calculated by the moving averaged raw sensory signal. Finally, the form accuracy is compensated with previously acquired geometric errors of the machine tool. The performance of the proposed OMM system was evaluated through measuring a part on the OMM and CMM, then comparing the measured values.

2. System configuration

The sensors generally used for OMM are touch trigger probe, scanning probe, and laser displacement sensor. The former two sensors are of contact type, whereas the latter one is of non-contact type. Since touch trigger probe is simple, it is widely used for the inspection. However there is pre-travel error that is the motion of the CMM between the real positions of the part and trigging of the probe. Determining an effective stylus ball radius using a master sphere of known radius can compensate for the average pre-travel error. In addition, there is contact pressure difference along the contact direction sinçe the stylus is attached to a tripod structure whose three cylindrical legs are kinematically located by three pairs of crossed cylinders. This makes direction-dependent pre-travel variation or so called probe lobing. Kreuci[9] and Taylor[10] presented also the low measurement speed is another shortage. On the other hand, the scanning probe has the stylus mounted on the three axes parallel moving mechanism, and positional data can be calculated by summing up the count signals of the elastic mechanism. The scanning probe is adequate for the high-speed measurement due to the high resolution and response. On the other hand, the laser displacement sensor can only measure the position along the direction of the light emitting. However, the accuracy is very high and measurement is fast. Furthermore, it is possible to measure both the surface roughness and the form accuracy. Considering these points, laser displacement sensor was used in this research.

Figure 3 shows the configuration of the OMM system. The three axis CNC milling machine has a minimum resolution has 1μm. The machine tool is installed with a linear encoder scale for closed loop control of each axis. Both of machining and measurement was carried out on this same machine. The CCD (Charge Coupled

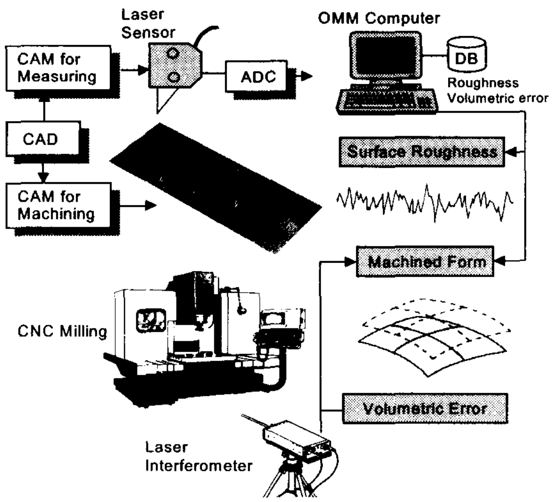


Fig. 3 Configuration of OMM system

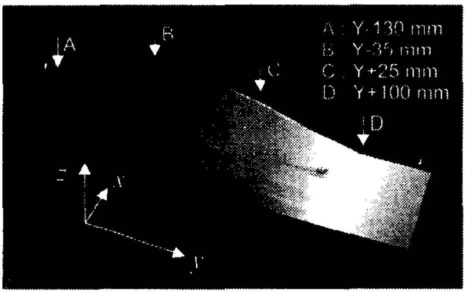


Fig. 4 Machined specimen

Device) type laser displacement sensor for measuring the surface roughness and form accuracy was mounted on the machine tool spindle after completing machining. The resolution of the sensor was 1㎛ and output frequency of the sensor was 1㎑. In order to trace the workpiece with the sensor probe, the sensor path for moving the machine tool was generated from the CAD model considering the spot size of the sensor, which is of the same format as NC code. The NC code for positioning the sensor was transmitted to the NC controller via DNC (Direct Numerical Control). The output of the sensory signal was received through the A/D converter whose sampling frequency was 100*Hz*. This signal was processed for estimating surface roughness and form accuracy. The reference data of surface roughness and geometric error data of the machine tool axes were stored in the computer of the OMM. As shown in Fig. 3, the measured form accuracy was compensated using the geometric error measured at the machine tool in advance, and the surface roughness was evaluated by comparing to the reference data measured from the master specimen.

3. Machining and measurement

3.1 Machining

As shown in Figure 4, the test material was aluminum plate of which the size was 300㎜ long, 20㎜ wide, and 200㎜ high. The shape of the machined part was modeled in the CAD system. The geometry of the machined part consists of the followings: circular interpolation upward direction of 110㎜ (A-B section) circular interpolation downward direction of 60㎜ (B-C section), linear interpolation downward direction of 75㎜ (C-D section), and the last part is horizontal straight. By doing this, we can observe the interpolation characteristic of the control system of the machine tool. The slopes of point A and C were 30 degrees, and 60 degrees, respectively. The ball end mill of diameter of 10㎜ was used, and cutting condition was spindle speed of 1,000rpm, and feedrate of 500㎜/min. To generate NC code using CAM system, the machining tolerance and cusp height was set as 0.001㎜.

3.2 Alignment of the sensor axis

After machining, a cutting tool was replaced with a laser displacement sensor probe of the OMM system. In this case, there exists center difference between the center of cutting tool and measuring sensor. The center shifts of sensor probe make the measurement inaccurate. In case of ball type probe, Lee[3] presented effectiveness to use a known reference hole to calibrate the center difference. However, in case of laser displacement sensor, measurable direction is only along the light emitting. Therefore, as shown in Figure 5, a master sphere was used to calibrate the center shift, which was mounted on the known reference hole, where the measured sphere center of P_2 was translated with respect to the center point of P1 that was cut by the machine tool. The P_2 point could be determined by searching the maximum value of the X, Y coordinate respectively. As shown in Fig. 5, the reference hole was machined off the primary machining zone. The master ball was made of zirconium,

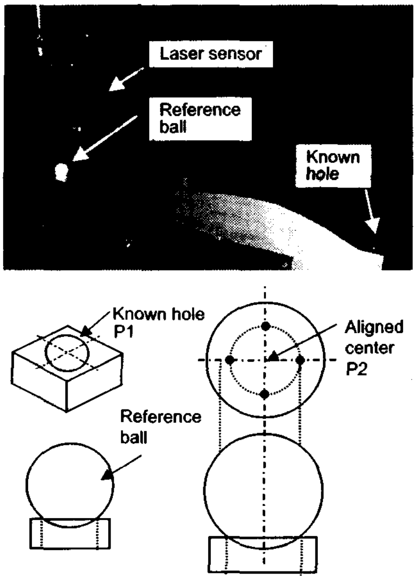


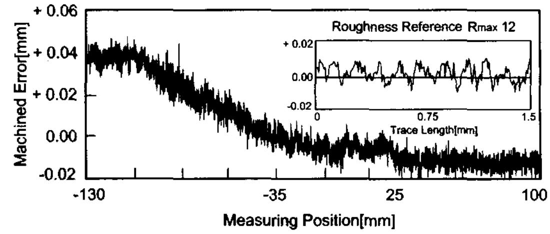
Fig. 5 Center alignment method between cutting tool and measuring sensor

and has a diameter of 12.7mm. Form accuracy of the ball was less than 1μm. The reason for two reference holes was to give the reference coordinate in the CMM.

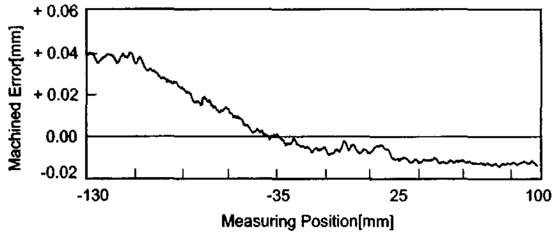
3.3 Measurement of surface roughness and form accuracy

After calibrating the center shift, measurement was executed. NC code for measurement was generated from the CAD/CAM system considering the spot size of light of 30μm. Tolerance for making NC program of measurement was set less 10 times than NC program of machining. The measurement principle was based on the fact that the output of the sensory signal is zero if the workpiece was machined exactly as the geometry of CAD model. In this case, form accuracy is zero. Therefore, the sensor was initially moved to the reference position, and set the height of Z axis zero.

Figure 6 shows the measured data with the probe tracing speed of 500mm/min. In Figure 6(a), horizontal and vertical axes represent measuring position, and measured raw data, respectively. In this figure, positive value represent under cut, and negative value does overcut. Small graph in Figure 6(a) is the measurement reference data of the master specimen for estimating machined surface roughness. The surface roughness of the master specimen was 12μm R_{max}, which was for milling and prepared based on the JIS B0659. By comparing these two data, the surface roughness was estimated to be approximately 10μm R_{max}.



(a) Roughness topography



(b) Machined error

Fig. 6 Measured machined error using OMM

In order to extract form accuracy from the measurement data, the raw data was moving averaged. Every thirty data points were moving averaged considering tracing speed, output rate of sensory signal, and sampling frequency. Figure 6(b) shows the moving averaged data. Some characteristics can be seen due to the under cut and over cut. In this figure, under cut was generated at the region where the direction of the cutting resistance is opposite to the cutting direction. Over cut is vice versa. In addition, form error is seen to be large where the geometric slope is large. In case of flat surface as in C-D region, the form error becomes relatively small and constant. This error can be surmised to be induced from tool deflection.

4. Geometric error compensation

If one axis translates along its axis in the three axes of X, Y, and Z, the total errors of the machine tool can be represented by three translational (δ_x, δ_y, δ_z) and rotational error components (ε_x, ε_y, ε_z) of each axes, and squareness error of each axis. Firstly, the motion of the three axes machine tool can be represented by HTM (homogeneous transformation matrix) as follows:

$$A^1=\begin{bmatrix}1&0&0&x\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\quad A^2=\begin{bmatrix}1&0&0&0\\0&1&0&y\\0&0&1&0\\0&0&0&1\end{bmatrix}$$
$$A^3=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&z\\0&0&0&1\end{bmatrix}\qquad(1)$$

Then, the tool trajectory of the machine tool can be written as

$$r=A^1(x)\,A^2(y)\,A^3(z)\,r_t\qquad(2)$$

Where r_t is form vector of the cutting tool and set to a unit vector e. Secondly, if the three axis machine tool has three rotational and three translational error components associated with their motion and the angular rotations are minimal as is the case with angular errors on a machine, then the following approximation for the error matrix can be made by considering only the first order errors to their ideal position

$$En=\begin{bmatrix}0&-\varepsilon_{zn}&-\varepsilon_{yn}&\delta_{xn}\\-\varepsilon_{zn}&0&-\varepsilon_{xn}&\delta_{yn}\\-\varepsilon_{yn}&-\varepsilon_{xn}&0&\delta_{zn}\\0&0&0&0\end{bmatrix}\qquad(3)$$

The subscript n represents the each axis carriage motion. When a three-axis machine tool is considered, there are two squareness error components encountered. If Z is the reference axis, one is the squareness error component between the X and Z axes, and the other is between Y and Z axes. If the squareness errors are small, the following approximation for the error matrix can be made

$$Exz=\begin{bmatrix}1&-\varepsilon_z(XZ)&-\varepsilon_y(XZ)&0\\-\varepsilon_z(XZ)&0&0&0\\-\varepsilon_y(XZ)&1&0&0\\0&0&0&0\end{bmatrix}\qquad(4)$$

Similarly, the squareness errors between the Y and Z axis are represented in [12]. Then, the final error matrix of X axis can be described summing Equations (3) and (4):

$$E=E_X+E_{XZ}\qquad(5)$$

Finally, the errors of the machine tool with X axis motion can be represented as follows:

$$\Delta r=Er\qquad(6)$$

The errors associated with the other axes can be calculated by the same process. Errors induced from geometric error components can be obtained from Equation (6) and these are used in the form accuracy compensation. To do this, each error component for constructing error database was measured with the laser interferometer (Renishaw ML10) after completing machining. Figure 7 shows the volumetric error map using position errors of each axis.

5. Results

In order to evaluate the performance of the OMM system, the part used in the OMM was moved to the CMM (MERLIN 1100). In the CMM, the part was measured using two reference holes, a reference face, and CAD data. The accuracy characteristics of the CMM where $U_{1,2}=2.5+L/300\mu m$, $U_3=2.8+L/250\mu m$, where is the positional accuracy, d 1, 2, 3 represents X, Y, Z-axis, respectively. And L is the stroke of the axis. The probe diameter was 1mm and total of 47 points were measured, along the surface with the measurement interval of

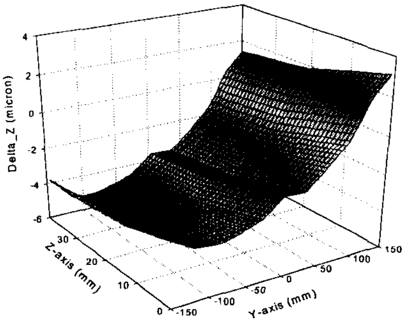


Fig. 7 Volumetric error

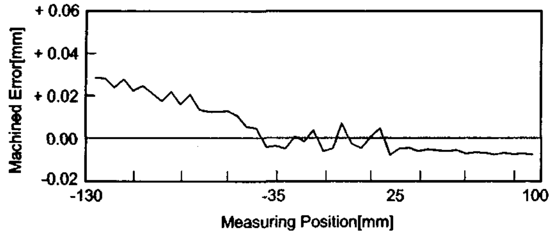


Fig. 8 Volumetric error concerned with cutter position

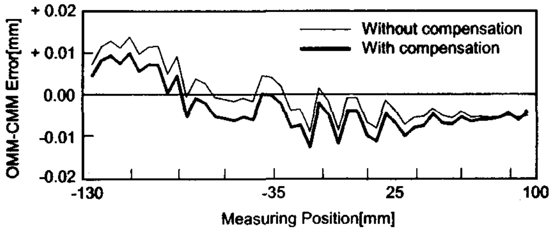


Fig. 9 Error between OMM and CMM

5㎜ between Y-135㎜ and Y+100㎜. After 24 hours to make the part thermal equilibrium on the CMM, the part was measured three times repeatedly. As shown in Figure 8, the trend of the measurement results with the CMM is similar to the OMM results. Then , the geometric errors of the machine tool were incorporated into the OMM results. The relative errors between the OMM and the CMM while considering with and without the geometric errors are shown in Figure 9. After compensating the geometric error, the relative error turned out to be within 10㎛. The difference was larger around the region of slope variation (A-B region), and becomes smaller to constant level at the flat region (C-D region). The reason was the influence of the light intensity at the outside of the laser spot. The error less then 10㎛ after compensation implies that the OMM system can be applied to for measuring the high precision three-dimensional parts.

6. Conclusion

In this research, the OMM system for measuring surface roughness and form accuracy was developed. The system uses the laser displacement sensor, and generates the path for the sensor probe from CAD model. The surface roughness was evaluated comparing the measured data with the reference data obtained from the master specimen. The form accuracy was also obtained from the moving averaged raw data of sensory signal. This data were then compensated for by considering the geometric errors of the machine tool. The accuracy of the system for estimating form accuracy was less than 10㎛. Further research efforts are expected to deal with the tool deflection, thermal expansion of the workpiece and machine tool, and minor errors induced from machine tools.

References

1. Owen, J. V., "CMMs on the Shop Floor," Manufacturing Engineering, pp. 66-70, April 1991.
2. Keizo, U., "Die & Mold 3-DimensionalMeasuring on the Machine," Conf. on Die and Mold Technology, pp. 208-209, 1994.
3. Kim, S. H. and Kim, I. H., "The Development and Evaluation of OMM(On-the-Machine Measuring) System using Scanning Probe," J. of the Korean Society of Precision Engineers, Vol. 13, No.10, pp. 71-77, 1996.
4. Lee, S. W. and Kim, S. H., "Development of On-the-Machine Measurement(OMM) System," J. of Industrial Engineering Interface, Vol. 11, No. 1, pp. 199-205, 1998.
5. Lee, S. J., Kim, S. H., Kim, O. H., "The Analysis of Measuring Error in OMM System," J. of the Korean Society of Precision Engineers, Vol. 15, No. 5, pp. 34-42, 1998.
6. Lee, S. J., Kim, S. H., Kim, O. H., "The OMM system for machined form and surface roughness measurement concerned with volumetric error," J. of the Korean Society of Precision Engineers, Vol. 17, No. 7, pp. 232-240, 2000.
7. Kim, S, H., Ko, T. J., Ahn, J. H., "Elimination of settling error due to clamping forces in on machine measurement," Int'l J. of Advanced Manufacturing Technology, Vol, 19, pp. 573-578, 2002.
8. Cho, M. W., Lee, S. H. and Seo, T. I., "On-Machine Measurement of Sculptured Surface Based on CAD/CAM/CAI Integration," J. of the Korean Society of Precision Engineers, Vol. 16, No. 10, pp. 172-181, 1999.

9. Kreuci, J. V., "CMM Measurement Enhancement Using Probe Compensation Algorithms," SME Technical Paper MS90-09, 1990.
10. Taylor, A., "Performance Characteristics of Touch Trigger Probes," SME Technical Paper MS90-266, 1990.
11. Reshetov, D. N. and Portman, V. T., "Accuracy of Machine Tools," ASME Press, 1988.
12. Cho, J. H., Cho, M. W., Kim, K., Volumetric Error Analysis of a Multi-axis Machine Tool Machining a Sculptured Surface Workpiece, Int. J. Prod. Res., Vol. 32, No. 2, pp. 345-363, 1994.