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# Active Compensation of Thermal Deformation in Machining Process

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**ABSTRACT:-** The biggest factors, which lower the machining accuracy of machine tools, are thermal deformation and chatter vibration. In this article, we introduce the development case of a device and technology that can automatically compensate the errors of thermal deformation of machine during long-time processing on the machine tool's CNC(Computerized Numerical Controller) in real time. In machine processing, the data acquisition of temperature signal in real time and auto-compensation of the machine origin of machine tools depending on thermal deformation have significant influence on improving the machining accuracy and the rate of operation. Thus, we attempts to introduce the related contents of the development we have made in this article : The development of a device that embedded the acquisition part of temperature data, linear regression to get compensation value, compensation model of neural network and a system that compensates the machine origin of machine tool automatically during manufacturing process on the CNC.

**Keywords:-** Active compensation, Thermal deformation, Machining process, machine tools

## I. INTRODUCTION

The analysis result of the parameter that has influence on the processing of machine tools such as common machining center is as follows. First of all, the factors that lower machining accuracy include the geometric error, manufacturing process, driving mechanism, and environmental factor. The causes of geometric error include the inaccurate processing of structure, inaccurate assembly, the inaccuracy of transfer unit and servo system etc. The causes of the error in manufacturing process are the condition of tools and processing specimens. The error in driving mechanism is caused by the principal axis bearing, transfer medium, guiding part, transfer screws and various motors. The above-mentioned causes are the result of dynamic or static deformation, thermal deformation, the error of rectilinear movement or rotary motion, the change of response characteristic, and the damage of tools. Main parameters are thermal deformation, chatter vibration and abrasion of tools, among which thermal deformation occupies 70% and chatter vibration occupies 30% of the total causes of error. Chatter is an abnormal vibration occurring during cutting process, which means an abnormal state and have negative influence on the surface roughness of structure, life span of tools, processing error and the stability during cutting process. That is to say, the biggest factors which lower machining accuracy of machine tools are thermal deformation and chatter vibration.1-2

Machine tools have processing tools for the processing which moves along X, Y, Z axis and the processing tools are sensitive to temperature that thermal deformation happens by temperature change as processing time passes by.3-4 This research concerns a compensation system and embedded device for compensation diagnosis of machine tools' thermal deformation which is equipped with thermal deformation compensation algorithm devised to prevent the decline of the machining accuracy by compensating the machining error in real time which is caused by the sagging of processing axis due to thermal deformation during long-time processing of machine tools. The reason why we considered thermal deformation is that thermal deformation occupies about 70% of the error occurring in machine tools and such an error can have a serious influence on the degree of precision of machine tools. We tested thermal deformation prediction model and the function to compensate machine origin by embedding them in the machine tool controller, CNC, which can bring the effect of improving productivity such as improving processing quality and minimizing defective by enabling automatic machine origin compensation even if thermal deformation occurs.

The solution to reduce thermal deformation error can be divided into improvement through design change of target machine and error compensation technology. The method of design change has limit in its application because it requires a lot of time and money. The method of error compensation consists of thermal deformation prediction and compensation control and the thermal deformation prediction has been applied by interpretative method and by empirical model method. Representative Interpretative methods are finite element method and finite difference method and this method cannot guarantee accuracy because it cannot provide enough information about heat generating rate which changes depending on the boundary condition of machine and various cutting condition and this method cannot be applied to real-time error compensation due to the time required for interpretation.

Thus, there have been researches using empirical model which requires short time for calculation because of real-time compensation of machine tools. Heat error compensation has been done mainly by the method that applies compensation value calculated through heat error model in real time through internet using PC. The application of compensation signal includes real-time NC command correction, analog compensation embedding analog voltage into the location feedback signal of machine servo loop and digital compensation correcting driving signal of machine servo loop by transferring digital value to CNC controller using digital I/O communications port. But NC command correction method can compensate only both end points of transfer command and is a barrier to achieving high-speed processing. In addition, analog and digital compensation work are inapplicable to many machine tools, difficult to achieve, and need to be prevented from crashing against feedback signal of machine.

Most of all, all traditional methods have been limited to only calculating and analyzing machine origin compensation value about how much should we increase or decrease the compensation value depending on thermal deformation, the machine origin, by using PC or laptop computer.5-6 These methods lose the merit of real-time characteristic by using PC or laptop computer and especially, cannot perform compensation during machine processing in reality. The reason for this is that the people who research thermal deformation do not know well CNC, the machine tool controller, and even if they know a little bit, they only know how to use it and lack the understanding about internal CNC kernel which is a subordinate area of CNC Vendor, which caused difficulties for approaching internally and was also considered as a different area.

Thus, we need a method to improve processing quality and minimize defective by enabling self-compensation of machine origin in real time even if thermal deformation of processing axis occurs during long-time processing.

## II. ACTIVE COMPENSATION DEVICE OF THERMAL DEFORMATION

We prepared experiment environment for thermal deformation data acquisition as shown in Fig. 1. We equipped the machine tool with processing tool and connected eddy current displacement sensor around processing tool to measure the displacement of X, Y, Z Axis. We also connected thermocouple temperature sensor to measure X, Y, Z Axis and air temperature. The temperature value of X, Y, Z Axis and the air gets entered into A/D conversion device from the thermo-couple temperature sensor and the displacement value of X, Y, Z Axis gets entered into A/D conversion device from the eddy current displacement sensor. PC can measure thermal deformation data from the temperature data and displacement data input from the two A/D conversion devices. We made a look-up table by calculating error compensation value from these thermal deformation data. .

In these cases, the real compensation during processing procedure cannot be performed due to the loss of real-time property by using PC or laptop computer. Thus, in this research, we aimed at developing a device that embedded real-time data acquisition of temperature signal depending on thermal deformation of machine tool, linear regression to get compensation value for self-compensation of machine origin of machine tool during processing, and the data acquisition part equipped with compensation model based on neural network and developing a system that can enable the real self-compensation during processing in connection with the CNC as shown in Fig. 2.

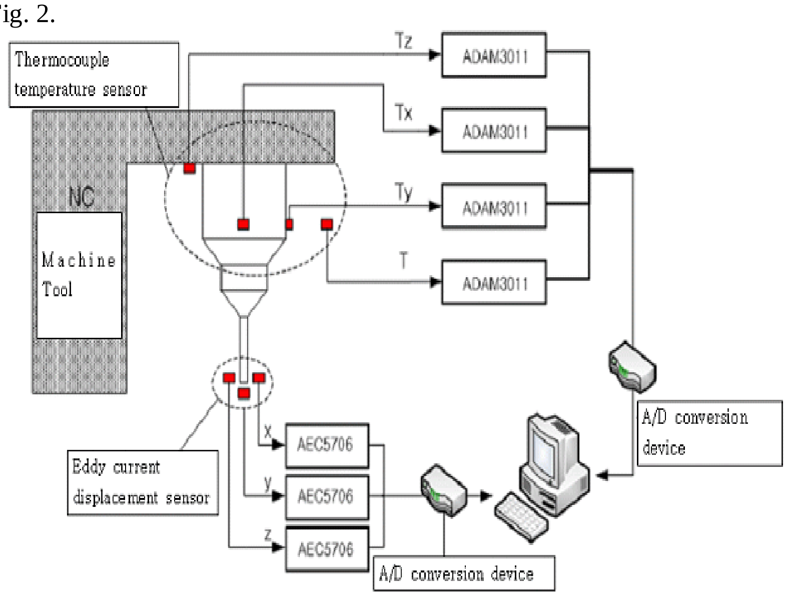


**Fig. 1** Diagram of Basic Thermal deformation Data Acquisition

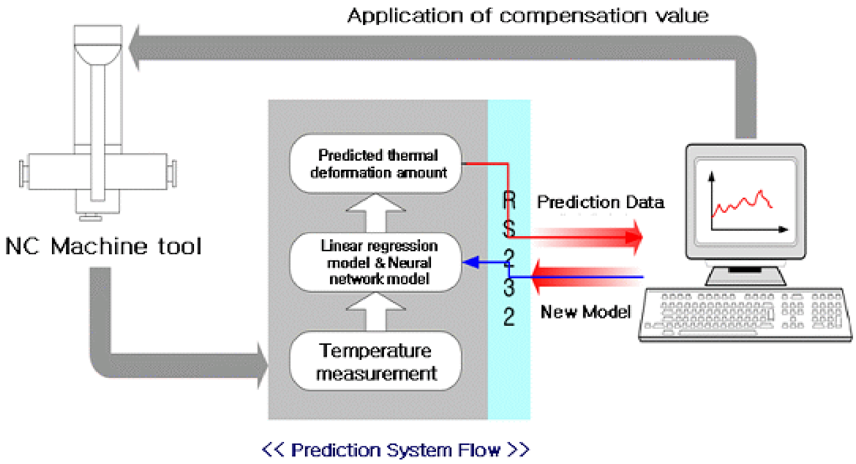


**Fig. 2** Diagram of Thermal Deformation Compensation Experiment Device for Real-Time Compensation during Processing

Figure 2 Diagram of Thermal Deformation Compensation Experiment Device for Real-Time Compensation during Processing. The device equipped with thermal deformation compensation algorithm in this research includes temperature input sensing terminal of X, Y, Z axis, the air temperature input sensing terminal, A/D conversion module, 5V switching power, RS232C communications module, and programmable DSP and the range of this research includes the device equipped with thermal deformation compensation algorithm and the function that enables auto-compensation of machine origin of machine tools depending on thermal deformation during processing on the machine tool controller, CNC. Fig. 3 shows a device for machine tool's thermal deformation diagnosis. We used 16 channel A/D converter to measure the temperature of each axis and the air temperature for thermal deformation prediction inside the device. The input range, sampling cycle, and setting of conversion channel of A/D Converter are algorithmized so that the setting value can be flexibly changed by the setting value input through communication and A/D Converter has built-in RS232 module for communication. We also made the setting of the temperature corresponding to input voltage flexible considering the fact that the output voltage from temperature sensor and the corresponding temperature are changeable according to the applied temperature sensor. The initial input range is set as the voltage value of 0-3.3V and the temperature value of 0~100℃. Firmware Device includes LED Display circuit to alert the user in case that the input temperature exceeds the limit of compensation model. The sampling cycle to measure temperature at DSP(Digital Signal Processor) is implemented using internal interrupter. In addition, an algorithm, which enables the output of thermal deformation prediction value according to the input temperature through RS232 communications module by calling the algorithm of the thermal deformation compensation model embedded inside at each sampling cycle as well as allowing the temperature sampling cycle to be changed by outside user, is embedded. We added JTAG port to change the algorithm embedded inside the DSP and added reset button for the initialization of the developed device.

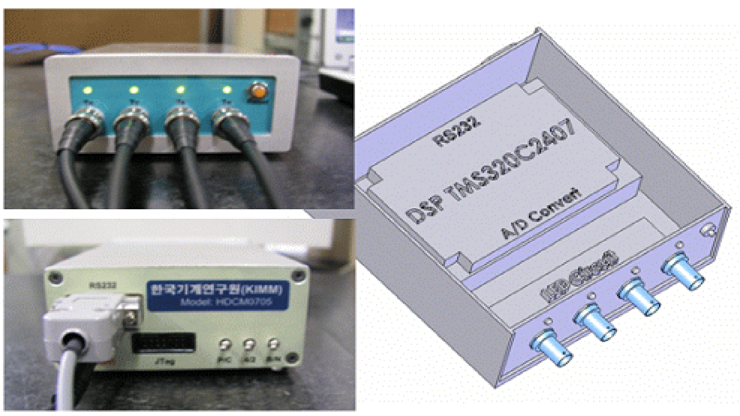


**Fig. 3** Embedded Type Thermal deformation Compensation Device

Figure 4 shows the picture of the Firmware Device for embedding being operated in connection with Labview program for basic simulation. This is to give the advantage of being able to perform simulation before applying the developed device to the thermal compensation of machine tool through the reliability evaluation of thermal compensation model embedded in DSP etc.

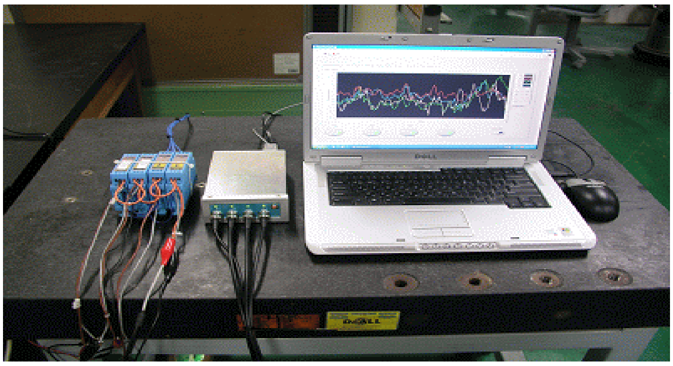

**Fig. 4 Simulation through Labview Programming**

Figure 5 shows the analysis result of the changing value of the temperature of X, Y, Z Axis and the air during long-time processing(e.g. more than 13 hours). Figure 6 shows the calculation of the average error according to thermal deformation based on the difference of the machining precision measurement of before and after temperature change during long-time processing.

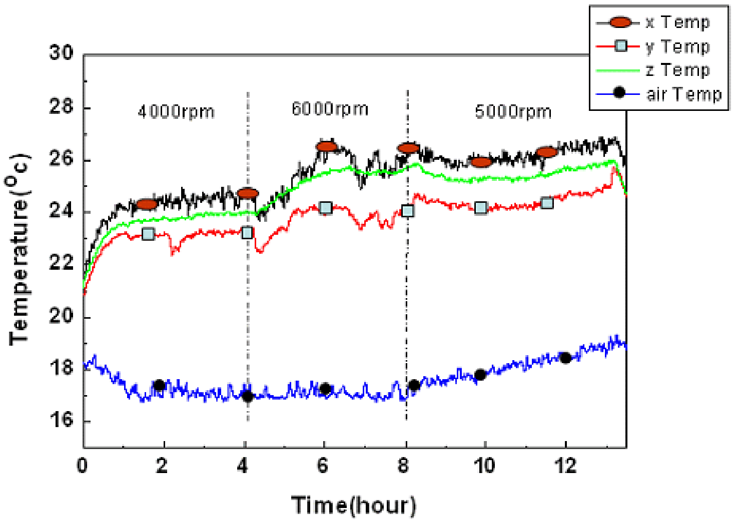


**Fig. 5** Temperature Change of Processing Axis occurring during Long-time Processing

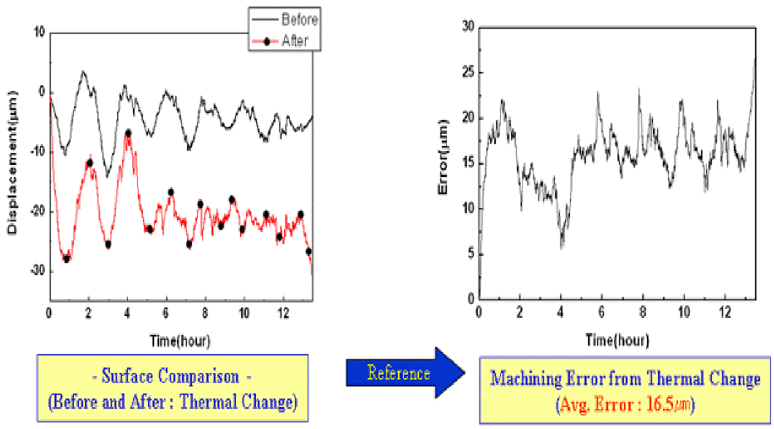


**Fig. 6** Calculation of the Average Error of Thermal Deformation according to Temperature Change during Long-Time Processing.

The compensation algorithm of thermal deformation in this research consists of multiple linear regression model and neural network model. The two models were created based on the measurement data related with the deformation amount of the ends of machine tool due to the temperature change of machine tool. The multiple regression model in the thermal deformation compensation algorithm of this research is a statistical method to explain the relationship mathematically when a phenomenon happens by the causal relationship with variables. We used least squares for the estimation of coefficient of the regression model applied for this research. The numerical formula below shows a general formula of the multiple regression model in this research. Y represents the predicted value and X represents the temperature of each axis and the air.

$$
\begin{aligned}
Y_1 &= \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 \\
Y_2 &= \beta_5 + \beta_6 X_1 + \beta_7 X_2 + \beta_8 X_3 + \beta_9 X_4 \\
Y_3 &= \beta_{10} + \beta_{11} X_1 + \beta_{12} X_2 + \beta_{13} X_3 + \beta_{14} X_4
\end{aligned}
\tag{1}
$$

We selected Multi-Layer Perceptron structure, which uses error back propagation, as a study method for the neural network model applied for this research. Figure 7 shows the structure of multi-layer perceptron applied for this research.  represents the bonding strength between input layer and hidden layer and  represents the bonding strength between hidden layer and output layer. The bonding strength and corelation coefficients of neural network model of this research were determined through more than 10,000 studies(minimum) based on the measured temperature and deformation amount.

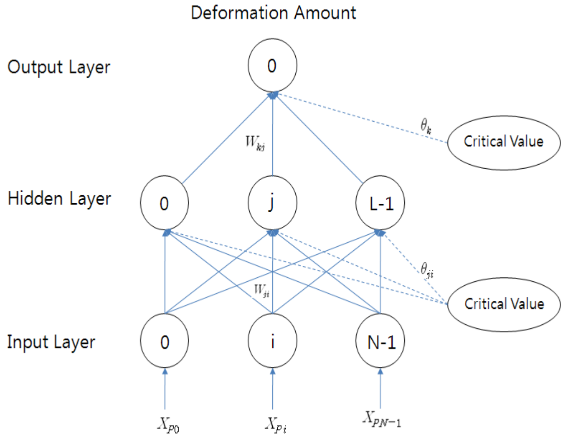


**Fig. 7 The Structure of Neural Network**

In case of the compensation model based on the linear regression model and neural network model of DSP, we algorithmized it to minimize the calculation time and we set it to be ramified into selected model by the user if interrupter occurs.

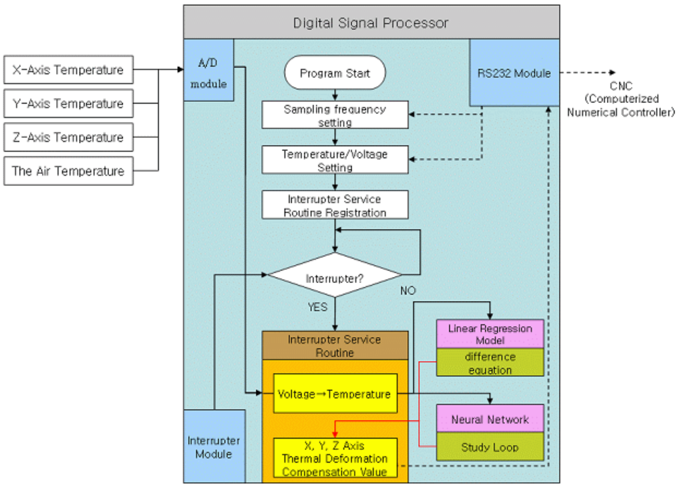


**Fig. 8 Internal Diagram of Thermal Deformation Compensation Device equipped with Compensation Model(Linear Regression Model and Neural Network Model).**

The thermal deformation result predicted by linear regression model and neural network showed similar result with the thermal deformation result of real experiment for a long time. Thus, it was concluded that the predicted result of compensation model of the simulation was reliable as shown in Fig. 9.

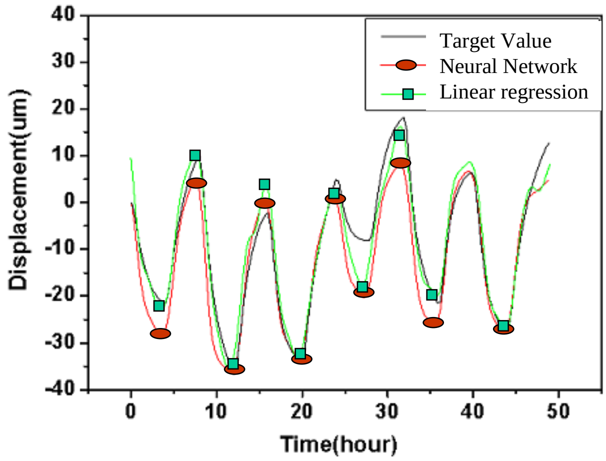


**Fig. 9. Confirmation of the reliability of the predicted thermal deformation value of the Compensation Model**

## III. ACTIVE COMPENSATION IN MACHINING PROCESS

Active and automatic compensation of the machine origin value of 3 Axis(X, Y, Z) through the machine tool controller, CNC, is needed for real-time auto-compensation during machine processing. Figure 10 shows the diagram of connection between embedded compensation device and CNC for this goal. We equipped it in CNC by making user code(VC++) accessible to NC kernel variable, the machine tool controller kernel[example:$P_UIFR(…)] and to Link variable[example: /Channel/UserFrame/LinShift(…)] and by embedding the function as a OEM sub-module in HMI(Human Man Interface, CNC screen area).

Thus, we connected the compensation value formulation module, through the acquisition of temperature data and compensation model, manufactured as an embedded device to the 3 Axis thermal deformation spot of the machine tool. We enabled real-time auto-compensation by embedding compensation action function, which can automatically change the parameter inside the CNC during processing, in the CNC of machine tool, the processor which manages real processing.

Figure 11 shows the result of achieving auto-compensation function inside the CNC of machine tool to enable real-time auto-compensation during machine processing.

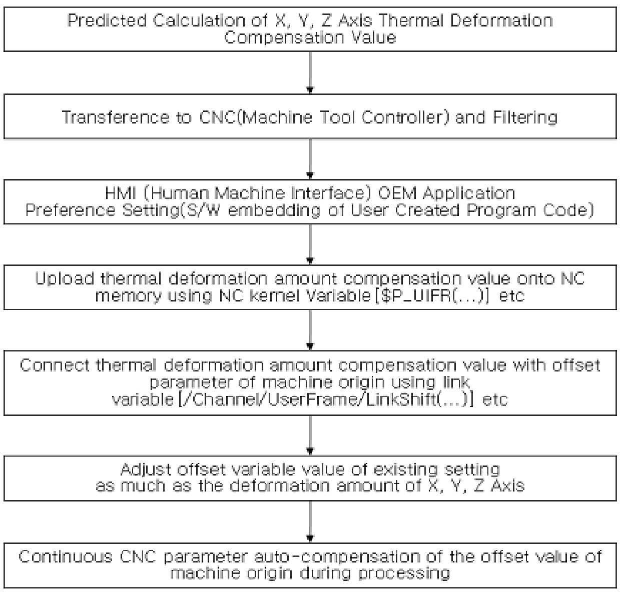


**Fig. 10. Diagram of connection between embedded compensation device for real-time thermal deformation compensation and the CNC**

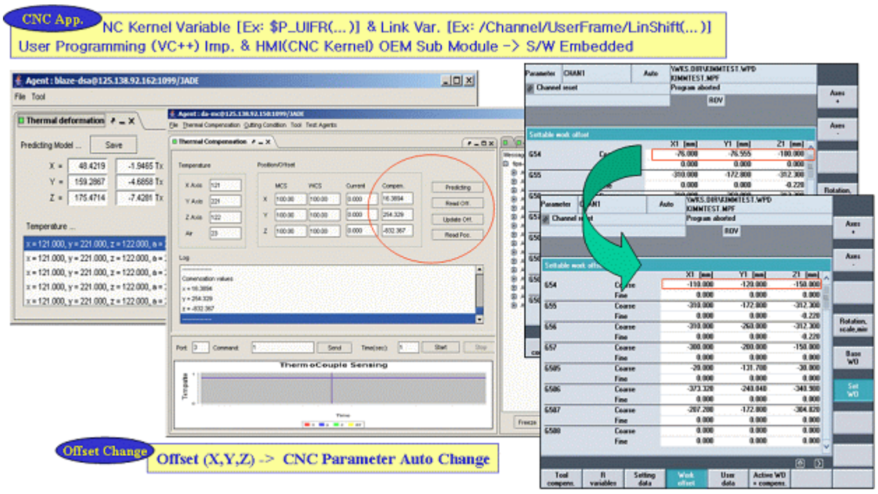


**Fig. 11. Auto-Compensation of Machine Origin in CNC for Real-Time Thermal Deformation Compensation.**

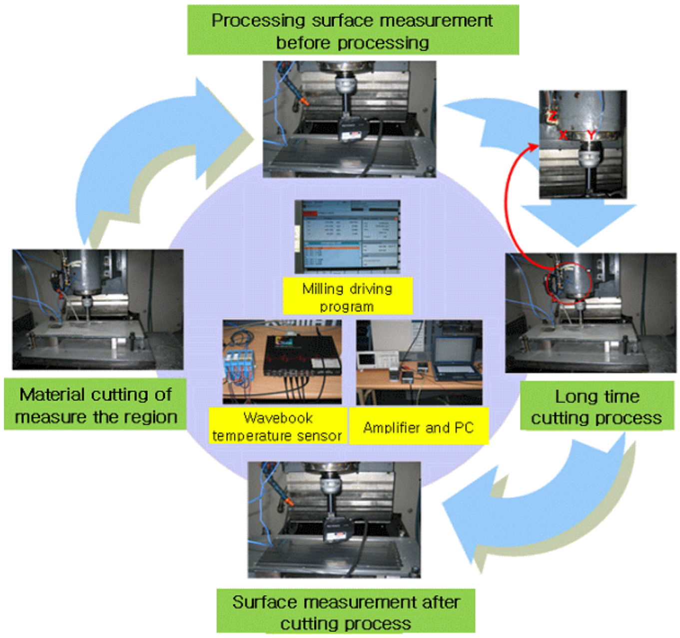


**Fig. 12. Real Experiment of Processing and Compensation**

We implemented real long-time experiment for processing and compensation(longer than 13 hours) to confirm if the thermal deformation compensation during processing was effective through CNC auto-compensation as shown in Fig. 12. We analyzed and compared the processing error in case of processing only without compensation function, the machining error in case of manual compensation through the intervention of worker, and the machining error in case of auto-compensation on the CNC of machine tool during processing together with the processing time. Figure 13 shows the degree of machining accuracy and machining time which are the result of real experiment of machining and compensation in comparison. As a result, the degree of precision dropped significantly showing machining error of 16.5 ㎛ during long-time processing in case of no compensation function but the degree of precision during long-time processing in case of auto-compensation improved more than 70% compared with the case of no compensation function showing machining error of 3.9 ㎛. In case of manual compensation by worker through CNC control without connecting CNC with the embedded compensation device, machining error was reduced compared with the case of no compensation function but showed more machining error than the case of auto-compensation by a margin of 1.9 ㎛ and the machining time was 9.1% longer than the case of auto-compensation. The reason is that the degree of machining precision is lowered due to the errors such as mechanical backlash in the process of processing again after stopping the machine and applying compensation value and the machining time took longer due to worker intervention time.

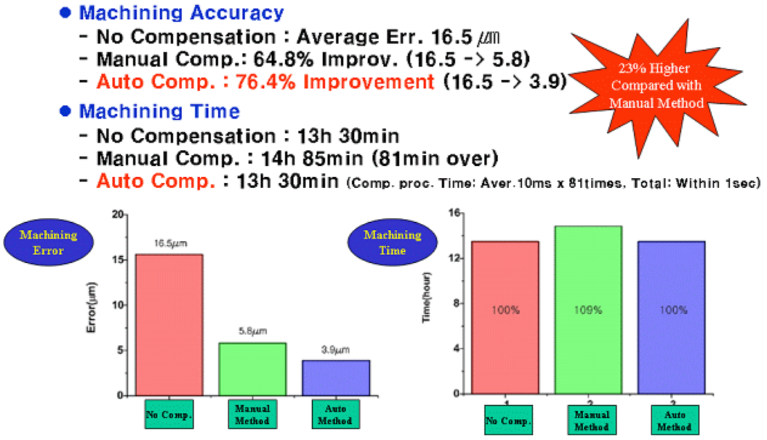


**Fig. 13.** Real Experiment of Processing and Compensation

## IV. CONCLUSION

The embedded device equipped with thermal deformation compensation algorithm of this research has the advantages that we can acquire signal such as the temperature of 3 axis of machine tool and the air in real time because the compensation model for data acquisition part is embedded as hardware instead of being based on PC. We can get machine origin compensation value in real time and the application of new compensation model is convenient in case of changing target machine tool. In addition, it has the advantage that auto-compensation during real processing is done in real time on the machine tool controller. Also it has advantage in terms of time and expense compared with the existing method of design improvement of machine tool applied for thermal compensation. And it has the effect that we can improve productivity and gain economic profit because the application is very convenient and the real time property is excellent compared with existing analog and digital compensation method which changes the driving signal of servo loop.

In the actual machine application, work-offset compensation from thermal change and recommendation of cutting condition are performed on-line performed for real time compensation by CNC.

## ACKNOWLEDGEMENTS

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