Extreme High Precision Machining Center with New Effective Thermal Displacement Countermeasures

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By the application of combined simple and effective technologies to minimize variations in the machine body temperature and meet optimum specifications based on numerical analysis of the effects of the technologies to be applied, Mitsubishi Heavy Industries, Ltd. (MHI) has newly developed a vertical type machining center capable of keeping the relative thermal displacement between work piece and tool under the world’s smallest level of $\pm 5 \mu m$, even at a world fastest main spindle rotating speed for this spindle diameter, at a low manufacturing cost roughly equivalent to those of popular models now available in the market. New technologies to minimize thermal displacement are exploited in this machining center. They include, for example, heat insulation covering the entire machine body, so as to make the rate of temperature change uniform; circulation and stirring of the air inside the machine body; cooling with temperature controlled oil used on heat sources; and compensation for thermal displacement considering delay in conduction of heat. These technologies are applied effectively where they have been proved effective by preliminary analyses. This paper describes the main specifications of the newly developed machining center, the principle of the technologies applied to minimize the thermal displacement and the results of the verification tests.

1. Introduction

A new machine tool is always expected to help to reduce the machining process and increase the machining accuracy. Such demands have been increasing, mainly among metallic mold manufacturers, with the intention of differentiating their products from others, as well as reduction of machining cost. To meet such needs, MHI has developed the high precision vertical type machining centers, M-V 50 and M-V 50 FM. They are capable of largely reducing the thermal displacement during operation to $\pm 5 \mu m$ from the $\pm 20 \mu m$ normal in conventional models, despite that both types have a main spindle rotating at a high speed of 30 000 min$^{-1}$, the world’s top speed (Fig. 1). This machining center has a 30 000 min$^{-1}$ high-speed main spindle capable of keeping amplitude to $3 \mu m$ or less over the entire range of its rotational speeds (FM type), a simple, efficient means to minimize thermal displacement, and a fine mold (FM) control system to offset any error from the pass line of the command value.

This machining center features high-speed, high-accuracy and high-quality surface finishing which has
not been achieved by any conventional model. This report describes the details of the features of this newly developed machining center, in particular the technologies implemented to minimize the thermal displacement.

2. Features

The main specifications of this machining center are shown in Table 1, and its features are summarized as follows: where (1) to (3) are related to the high machining accuracy, (4) and (5) to high productivity, and (6) and (7) to maneuverability.

(1) Structurally optimized machine design using FEM rigidity analysis reduces deformation, bending and vibration arising from traverse of headstock and table,

(2) Uniform distribution of local temperature changes and compensation for displacement minimizes the thermal displacement to $\pm 5 \mu m$ or less per day,

(3) Use of feed guide for the table as a static-pressure guide way prevents changes in machining accuracy due to weight of work,

(4) Provision for a 14 000 min$^{-1}$ high-rigidity main spindle and a 30 000 min$^{-1}$ high-speed main spindle expands the range of machining applications,

(5) Employment of high-speed automatic tool changer (ATC) reduces machining cycle time,

(6) Availability of footing space under the machine allows workers to stand closer to the machine for clamping and unclamping of tools and checking the machining condition, and improving work efficiency, and

(7) Chip disposal and sealing structure designed by reviewing the accumulated data improve the reliability of the machine.

In particular, thermal displacement is the most serious hindrance to high-speed machining. It is necessary to take countermeasures not only against changes in ambient temperature but also against the temperature rise in the spindle bearing, of which the temperature rises directly as a cube of the rotational speed of the main spindle. Hence, four new technologies were applied in this machining center for the reduction of thermal displacement. Their principles and effects are described in the next chapter, together with the results of the verification tests.

3. System composition

3.1 Cause of thermal displacement

The problem of thermal displacement in machine tools is the relative displacement between work and tool. In this new machining center, thermal displacement on X axis (widthwise) is suppressed by the employment of symmetrical structure. As regards thermal displacement on Y (forward and backward) and Z axes (upward and downward), Fig. 2 shows the mechanical relation between work and tool, and such members as table, bed, column, saddle, headstock and main spindle are involved. When the temperature level among these members varies, the aggregate of the thermal deformation resulting from bending and expansion and contraction of these members constitutes the thermal displacement. The main heat sources that cause the temperature differences are also shown in Fig. 2. When taking the variation in temperature simply as a temperature fluctuation rate, it can be expressed by the equation given below, where conductance of heat transferred from heat source $i$ to member $j$ is $C_{ij}$, its heat capacity is $C_{ai}$ and temperature difference from heat source $i$ is $\Delta T_i$.
From this equation, it is seen that the temperature fluctuation rate between members; that is thermal displacement, increases with $C_i$ to $Cap$ ratio or variation in $C_i$.

### 3.2 Concepts for thermal displacement minimizing measures

From the above equation, it is obvious that (1) increase of heat capacity of the members large enough to diminish the temperature variation in themselves, (2) increase of conductance in any one of the heat sources to be dominant over others so as to align the temperature variation phase, and (3) reduction of the temperature variation in the heat sources, may be theoretically effective to reduce the variation in temperature difference. However, of the above solutions, (1) to increase the heat capacity of the members is not realistic, because heat capacity depends on the section thickness of the member and any change of thickness is generally restricted by the requirements of mechanical strength and rigidity. As a practical method for (2), there is the possibility of circulating temperature-regulated liquid. But there is a limitation to the heat transmission area of intricate structures and also to the liquid temperature control accuracy. Then, there is also a possibility of utilizing air in such a way as to cause the body temperature to follow the air temperature. More specifically, this involves a method of blowing air to circulate inside the machine on the surface of members. Furthermore, to reduce the variation in the thermal load applied on the surface of the machine from outside as ambient disturbance, a heat insulation cover is used to enclose the machine. This heat insulation cover is designed to form a smooth air circulation channel inside the machine and limit the entry of ambient air in order to minimize the influence on the stability of the internal temperature. For solution (3), cooling oil is circulated to keep cool the important heat sources, including the spindles. Cooling oil is kept at the same temperature as that on the bottom surface of the bed, because the bed is the basic reference member showing the temperature inside the machine. The above-mentioned solutions restrict the bending deformation resulting from the difference in temperature between top and bottom faces of the members. As to the thermal displacement caused simply by expansion and contraction of members, the temperatures of the members are measured in real time to calculate the amount of expansion and contraction, and the calculated result is used to shift zero point for correction. As for the main spindle, of which the temperature cannot be measured directly, correction is made by applying a corrective equation which has been established by taking into account the delay in heat conduction, in addition to the conventional correction due to heat transfer delay to housing.

### 3.3 Prediction of the effects of the measures provided by analysis

In order to confirm the effects of the proposed measures for the minimization of thermal displacement, and to optimize the specifications for the machining center, simulation studies of temperature distribution and thermal displacement occurring in the machine body were performed by numerical analysis. The FEM used for analysis takes into account the diurnal temperature changes, heat generated from spindle and feed motors, cutting heat and friction heat as the causes of heat flux. **Fig. 3** shows the FEM model. The boundary conditions are defined by taking into account, in addition to the conduction of heat, heat transfer to/from the air and each wall surface of the members, which are independently separated by ribs, and also radiant heat transfer in open environments and between wall surfaces, convection heat transfer resulting from replacement of internal air with external air and heat transfer in cooling oil channels. The analyses are carried out with this model by solving simultaneously the temperature and the thermal displacement equations. The optimum solutions are obtained by varying the parameters such as thickness of heat insulation cover, covering area, volume of internal air, main dimensions of ventilation duct and flow rate of cooling oil circulation. **Fig. 4** shows the result of analysis of $Y$ axis thermal displacement due to bending of a column by diurnal temperature changes when different measures are taken for internal air flow. It is seen that the application of circulation air blow and heat insulation cover result in reduction of thermal displacement even if they are used independently, but a joint use of them shows a multiplication of the effect. The analysis results for $Y$ and $Z$ axes thermal displacement on all members of the machine body are shown in **Fig. 5** and **Fig. 6**, respectively. The results
indicate that the Z axis thermal displacement is $\pm 20 \mu m$ when no countermeasures are taken, which corresponds to the average value shown by the popular models now available in the market, while it is reduced to $\pm 5 \mu m$ or less by taking the said countermeasures.

4. Verification tests

Based on the analytical data obtained, heat insulation cover, internal air stirring, heat source cooling and compensation for thermal displacement by measuring the temperatures of main members were applied to the operation of a vertical type machining center M-V 50FM, and thermal displacement was measured in a practical situation. Fig. 7 shows the temperatures measured on the column surface at different points: top, middle and bottom of front and rear face plates, as the outside air temperature changes. The change in outside air temperature used here is based on the standard data for outdoor temperature on fine days in Japan. A severe wide temperature range was purposely applied for this measurement, though the actual change in temperature inside a workshop is generally smaller, even if it is not airconditioned. Although there is slight difference in the body temperature depending on the height of the measuring points, no remarkable difference is seen between the front and rear faces of the machine body even after the elapse of some time. From this fact, it is understood that hardly any forward/backward bending deformation occurs, and that the measurements of machine body expansion and contraction at any one point can precisely represent others. Fig. 8 shows a comparison of the theoretical temperature of the rear face of the column calculated by applying the outside temperature at that time with that actually measured. As they agree with each other, the analysis model used in the preliminary studies seems to be reliable. Fig. 9 shows the measured results of thermal displacement with change in outside temperature. They show that the thermal displacement occurring in a 24-hour period is under $\pm 5 \mu m$ on all X, Y and Z axes. Fig. 10 shows the thermal displacement that...
occurs while the main spindle is rotating. The rotating speed of spindle is increased in steps up to 30 000 min⁻¹. It is seen that the thermal displacement stays under $\pm 5 \mu m$ irrespective of spindle rotating speed.

5. Conclusion

With the aim of minimizing the thermal displacement occurring in the operation of a vertical type machining center to one fourth of that shown by conventional models, MHI has newly employed, as simple, effective measures, (1) heat insulation cover, (2) stirring of air inside machine, (3) cooling of heat source, and (4) heat conduction delay model for thermal displacement compensation. The machine specifications were optimized using the results of preliminary analyses, and were applied to the newly developed vertical type machining center, M-V 50 FM. As a result, thermal displacement due to the change in outside air temperature and also that caused by the rotation of the main spindle operating at the world's fastest speed were both reduced to the design target of $\pm 5 \mu m$. MHI will apply these effective means to other models of machining centers in the future and increase its product line of high-speed, high-precision machine tools.