High-Precision Machining of Aluminum Parts
(As a Countermeasure for the Thermal Displacement of Transmission Cases)

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The thermal displacement of aluminum parts subjected to high-precision machining is a constant cause for concern. An effective method to repress thermal displacement needs to be found. Currently, high-precision machining is performed by keeping workpiece temperature constant, however this requires significant investment in coolant systems and increases production line initial outlay. The workpiece temperature compensation function we have developed is an effective solution to this problem. This function controls workpiece temperature using coolant with a temperature that follows room temperature and compensates workpiece machining coordinates on the machine side to suit changes in room temperature. As a result, coolant system investment can be reduced and a stable machining accuracy can be achieved throughout all four seasons.

Key Words*: high-precision machining, thermal displacement, work temperature compensation, coolant temperature compensation*

1. Introduction

JTEKT has developed high accuracy technologies for the TOP center series of inline machining centers in order to incorporate the finishing process. The adoption of a highly rigid 3-point support bed has made it possible to reassemble machines at our customers' facilities with the same accuracy as prior to shipment and maintain a stable accuracy over an extended period of time. Moreover, the following thermal displacement countermeasures have been implemented, achieving highly accurate positioning.

(1) Reducing heat generation by reducing weight of moving objects
(2) Isolating structural objects from coolant heat
(3) Compensation function for thermal expansion caused by ball screw heat generated by movement of moving objects
(4) Compensation function for the displacement of machine structural objects caused by changes in room temperature

However, the mainstream method to suppress thermal expansion of workpieces resulting from changes in room temperature is to maintain coolant at a constant temperature, without the thermal displacement of the workpiece itself being compensated. As a result, the initial cost of line installation is significantly higher as costly coolant systems capable of maintaining a constant temperature are required. Maintaining a constant temperature throughout all four seasons in a year is difficult, and problems such as the need to frequently correct machining coordinates in summer and winter, remain to be solved.

Consequently, JTEKT has developed a new thermal displacement compensation function that involves coolant temperature following room temperature, estimates thermal expansion of a workpiece due to change in coolant temperature and compensates machining positions accordingly. As a result, stable machining accuracy is possible.

This report describes the newly developed technology and gives machining examples.

2. Conventional Thermal Displacement Compensation Technology

In TOP centers, the concept behind stabilizing accuracy against thermal displacement is "suppress, isolate and compensate heat" and these three approaches are effective in reducing thermal displacement (**Fig. 1**). The ball screw thermal displacement compensation function (**Fig. 2**) works by measuring the ball screw expansion caused by the movement of moving objects with a gap sensor mounted on the ball screw tip and feeding this back to the NC positioning command. The machine thermal compensation function (**Fig. 3**) measures the temperature of structural objects and converts this into expansion amounts, then feeds this back to the NC positioning command. These two functions ensure a positioning accuracy (pitch) within ±10 μm regardless of whether the equipment generates heat or not and irrelevant of changes in room temperature (**Fig. 4**).

Moreover, coolant temperature adjustment maintains coolant temperature at a constant 20℃ thus suppressing thermal expansion of workpieces. However, room temperature in factories throughout the year varies significantly between 10 and 32℃. Building a coolant system capable of maintaining coolant temperature at 20℃ in response to room temperature change is around twice as costly as the commonly used coolant tank system that follows room temperature. Also, depending on the temperature adjustment capacity, the system may not be capable of maintaining 20℃ constantly. In such cases, pitch accuracy is ensured by correcting machining coordinates.

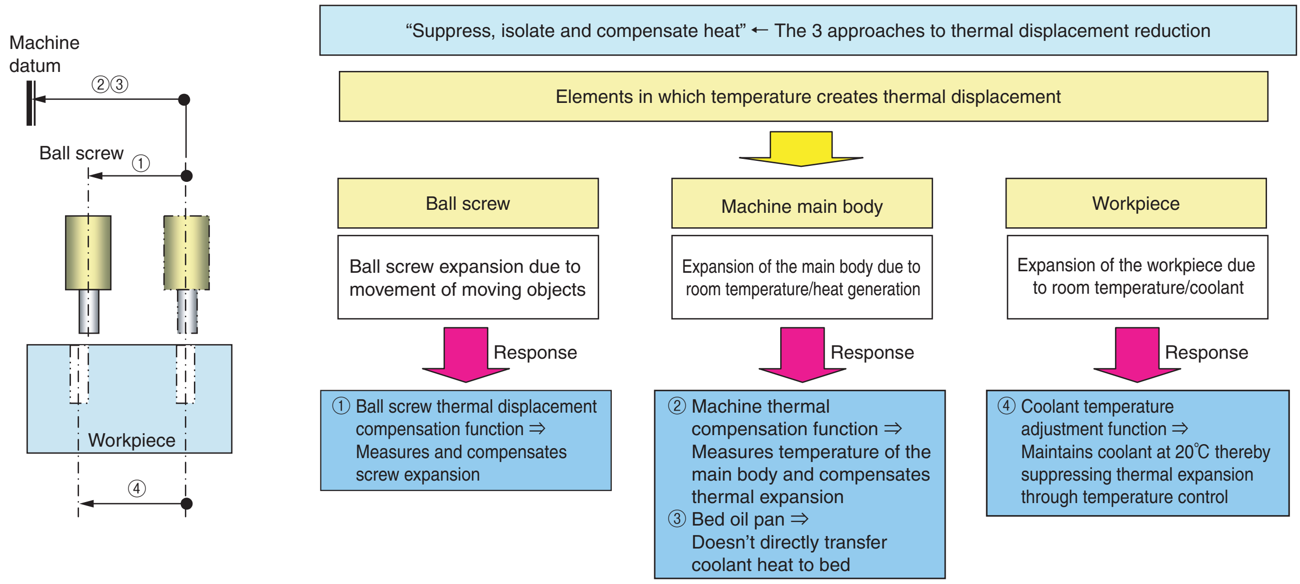
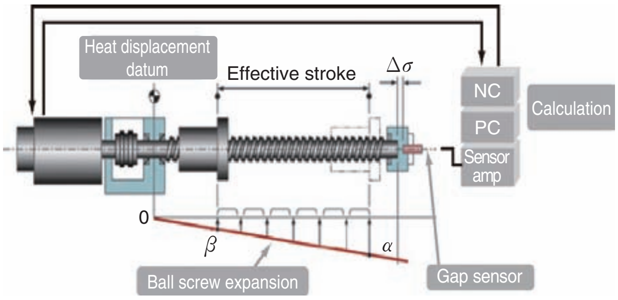


Fig. 1 Concept of thermal displacement compensation for TOP centers



JTEKT's original ball screw thermal displacement compensation function maintains stable positioning accuracy from a cold start

Fig. 2 Thermal displacement compensation function for ball screws

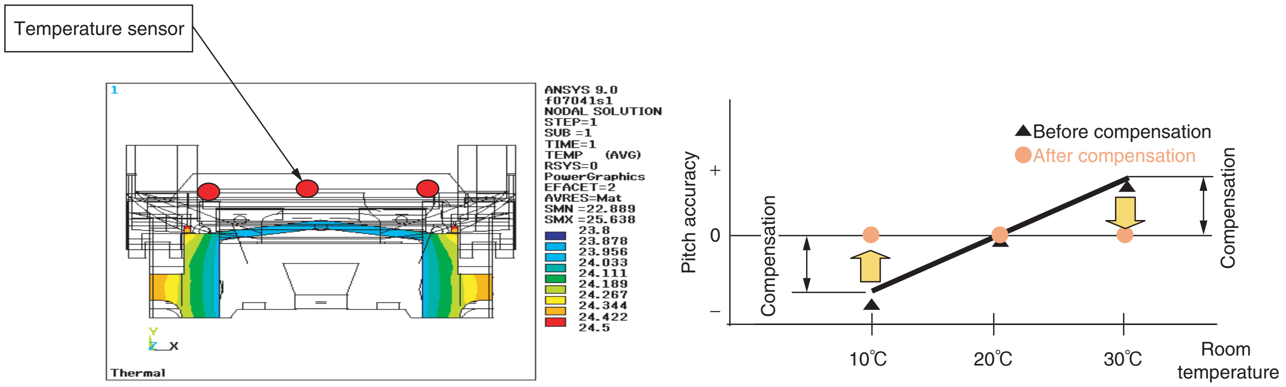


Fig. 3 Thermal compensation function for machines

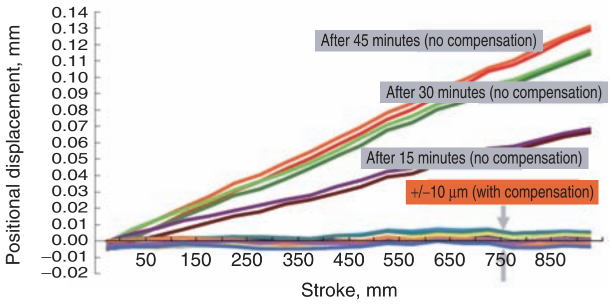


Fig. 4 Repeated positioning accuracy results

3. New Thermal Displacement Compensation Technology

The new thermal displacement compensation function shown in **Fig. 5** was devised to overcome this issue of cost. This method measures the temperature of coolant that has been made to follow room temperature, and compensates machining positions to suit the thermal expansion of the workpiece which has adapted to coolant temperature. To do this, the positional change caused by temperature change of each machined hole must be measured on the actual workpiece and the linear expansion coefficient then calculated. Each workpiece machining position is compensated according to the obtained linear expansion coefficient and coolant temperature.

Figure 6 shows measurement results. The actual workpiece has a dowel hole (K1) which is the datum for positioning with the jig. The machine must use this K1 as the datum and compensate each machined hole (H1, H2, O1, O2, etc.) position to suit the coolant temperature. As such the change in position of each machining hole from the K1 datum due to temperature is measured. To explain using the H1 hole, if the linear expansion coefficient obtained from measurement and the measured angle that the linear expansion coefficient is heading towards in substituted in the compensation equation (**Fig. 7**), the linear expansion coefficients for the X and Y directions of each machining hole position can be obtained.

Figure 8 shows the compensation logic of the new thermal displacement compensation function. The new thermal displacement compensation equation consists of conventional machine thermal compensation and ball screw thermal displacement compensation with the addition of workpiece temperature compensation. The special feature of this new technology is that by only measuring the workpiece linear expansion coefficient and the measured angle that the linear expansion coefficient is heading towards on the actual workpiece itself, the amount by which each machined hole be compensated can be obtained. By separating compensation on the machine side (machine thermal compensation, ball screw thermal displacement compensation) and workpiece temperature compensation, applying this compensation equation to other models is easier.

4. Machining Examples

To confirm it was possible to maintain machining accuracy throughout the year, the equipment was placed in a climate-controlled room and evaluated. Winter temperatures were set between 10 and 17℃, spring/autumn 20 and 25℃ and summer 25 and 32℃, and the equipment was exposed to each of these for 8 hours.

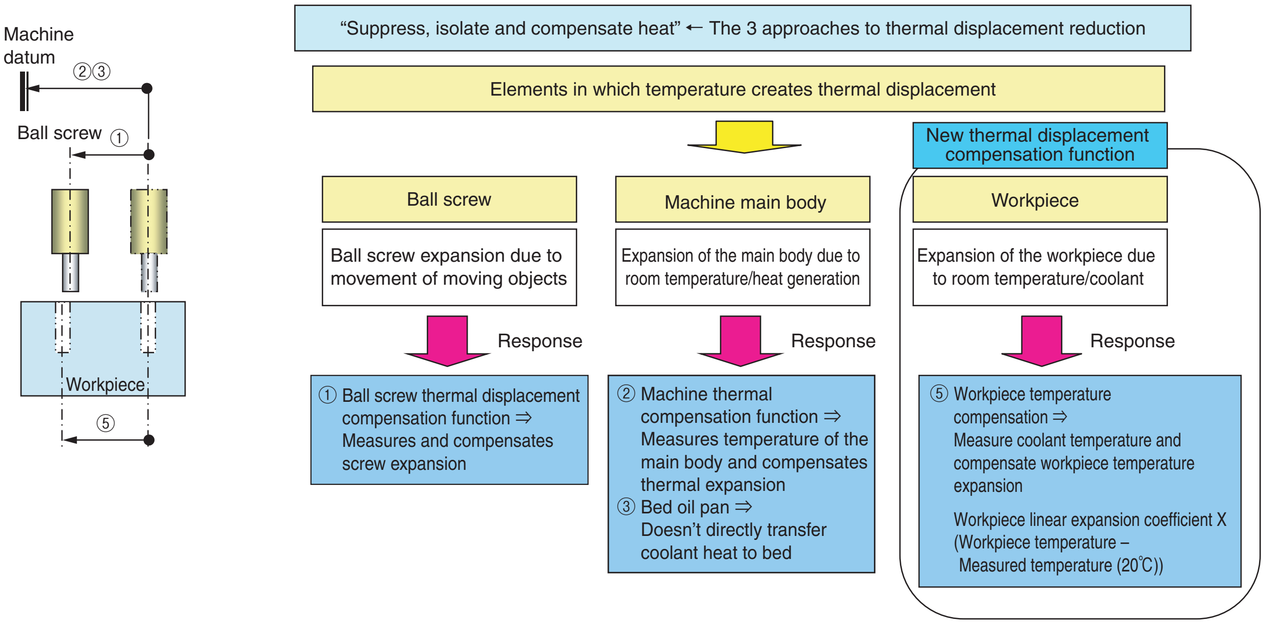


Fig. 5 Concept of thermal displacement compensation based on workpiece temperature compensation on TOP centers

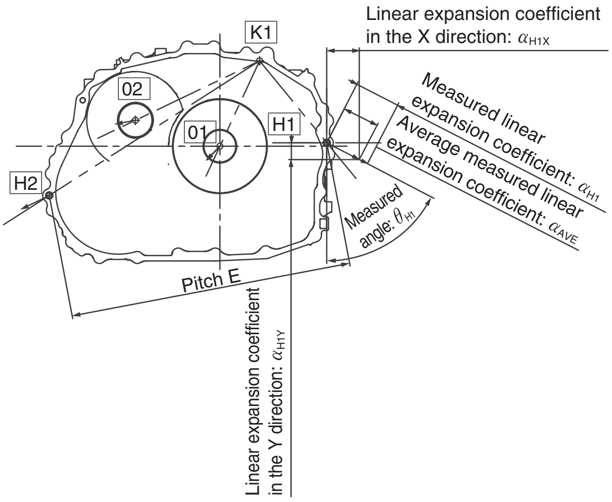


Fig. 6 Linear expansion coefficient and measured angle of actual workpiece

X direction $\alpha_{AX}=\alpha_{ave}\sin\theta_A$

Y direction $\alpha_{AY}=\alpha_{ave}\cos\theta_A$

A : Each machining position (H1, H2, O1, O2, O3, O4, O5, O6)

α_A : Measured linear expansion coefficient of each machining position

α_{ave} : Average measured linear expansion coefficient of each machining position

θ_A : Angle that measured linear expansion coefficient of each machining position is heading towards

α_{AX} : Linear expansion coefficient in X direction for each machining position

α_{AY} : Linear expansion coefficient in Y direction for each machining position

Fig. 7 Compensation equations for linear expansion coefficients in X and Y directions at each machining position

Workpiece coordinates datum — New technology — Workpiece temperature compensation

Machine zero datum — Conventional technology — Machine thermal compensation — Ball screw thermal displacement compensation

X direction = |{α_{AX}×(Coolant temperature*−Measured room temperature)×P_A/1 000}| + |{Linear expansion coefficient of iron×(Bed datum temperature−Bed temperature)×Mounting length/1 000} + (Δδ)|

(Coolant temperature ≒Workpiece temperature)

Y direction = |{α_{AY}×(Coolant temperature*−Measured room temperature)×P_A/1 000}| + |{Linear expansion coefficient of iron×(Column datum temperature−Column temperature)×Mounting length/1 000} + (Δδ)|

(Coolant temperature ≒Workpiece temperature)

* Have confirmed that spraying coolant on workpiece for 3 minutes will make the workpiece the same temperature as the coolant

α_{AX} : Linear expansion coefficient in X direction for each machining position

α_{AY} : Linear expansion coefficient in Y direction for each machining position

P_A : Distance from workpiece coordinates of each machining position

Fig. 8 New compensation equations for thermal displacement

In this evaluation, the process capability Cm (8σ) for the spring/autumn period (the longest period of the year at 20 to 25℃) and the process capability Cm (8σ) for winter, summer (10 to 32℃) was evaluated. The aluminum transmission case shown in **Fig. 9** was the target workpiece for machining used in this evaluation. The target machining accuracies were Cm≧1 (8σ) with relative positions (H1–O1, H1–O2) of ϕ0.05 mm and Cm ≧1 (8σ) with a machined hole-to-hole pitch (H1–H2) of ±0.05 mm.

Relative position (H1–O1) gave a process capability Cm of 1.615 in spring/autumn (**Fig. 10**). The year-long process capability taking into account winter and summer gave a Cm of 1.264 (**Fig. 11**). Next, relative position (H1–O2) gave a process capability Cm of 2.230 in spring/autumn (**Fig. 12**), while the year-long process capability taking into account winter and summer gave a Cm of 1.431 (**Fig. 13**).

Pitch A gave a process capability Cm of 3.222 in spring/autumn, while the year-long process capability taking into account winter and summer gave a Cm of 2.593 (**Fig. 14**).

The above results satisfactorily meet the targets, showing that machining which takes thermal displacement of the workpiece into consideration is achievable.

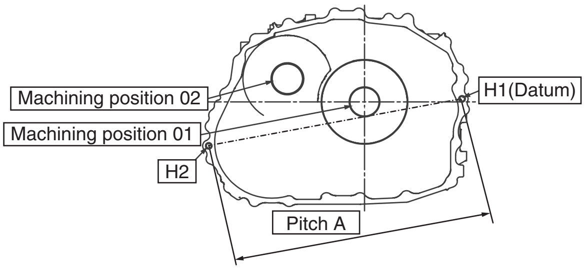


Fig. 9 Machined workpiece

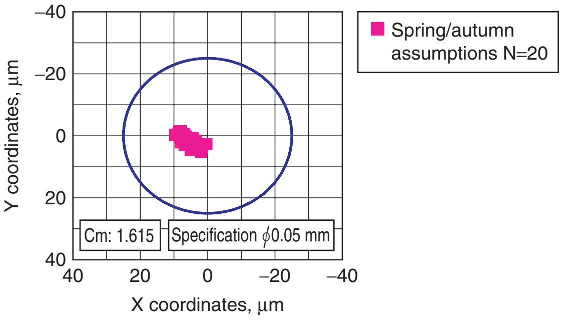


Fig. 10 Relative position 01
Spring/Autumn assumptions (20 ～ 25℃)

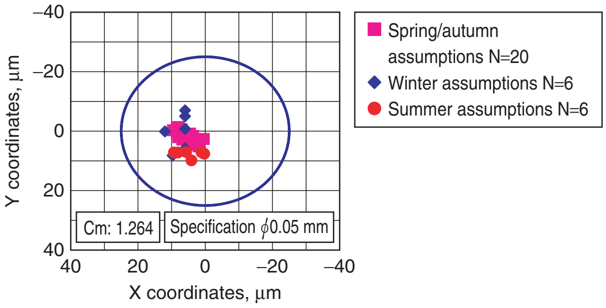


Fig. 11 Relative position 01 Year-long (10 ～ 32℃)

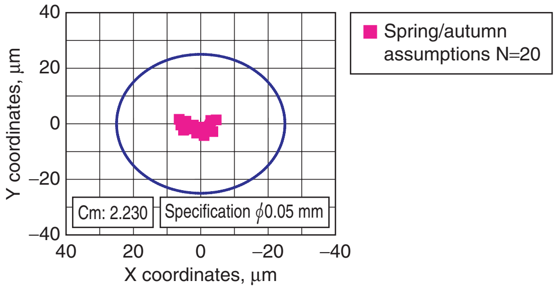


Fig. 12 Relative position 02
Spring/Autumn assumptions (20 ～ 25℃)

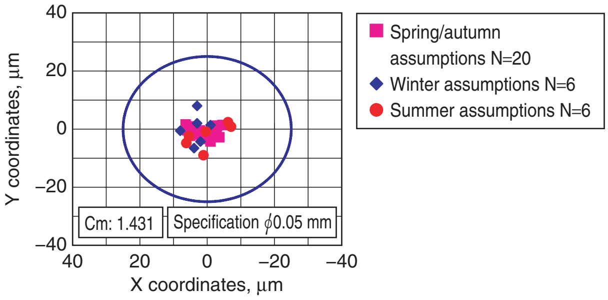


Fig. 13 Relative position 02 Year-long (10 ～ 32℃)

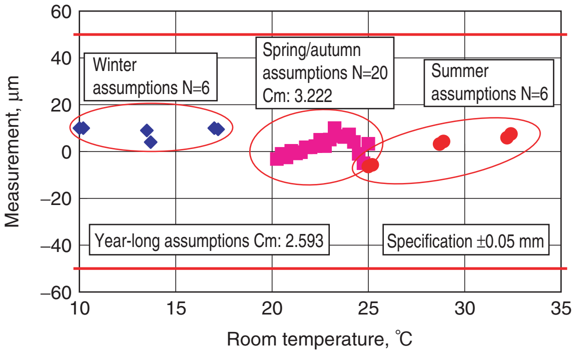


Fig. 14 Pitch A Year-long assumption

5. Conclusion

The workpiece temperature compensation function described in this report was developed specifically for the high-precision machining of aluminum die cast transmission cases. As part of this activity, machining macro programs have been standardized and incorporation of other models and other workpieces has been made easier. From here on, JTEKT will exert efforts to expand this technology to a wider range of models, engine components and other high-precision machined workpieces.

We will continue to stay ahead of market needs in order to develop equipment able to offer our customers the ultimate in user-satisfaction.

＊1 TOP center is a registered trademark of JTEKT Corporation.

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