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Effect of expansion coefficient difference between machine tool and workpiece to the thermal deformation induced by room temperature change

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Abstract

In the precision machining process, ambient temperature is maintained to 20 °C to minimize the thermal deformations. Much energy is consumed to maintain ambient temperature. The use of thermal compensation systems can minimize the energy consumption of room cooling systems. However, the influence of thermal deformation induced by room temperature upon workpieces is not clear. This paper investigates the effect of the linear expansion coefficient difference between a machine tool and workpieces to the thermal deformation induced by room temperature change. Machining experiments are conducted for steel and aluminum workpieces. The results agree with the calculation.

Keywords: Thermal error; Machine tool; Environment; Ambient temperature;

1. Introduction

In precision machining, machining is often performed with the room temperature kept at 20 °C to ignore the effect of thermal displacement caused by changes in room temperature. Because, the standard temperature is determined to 20 °C in ISO-1 [1]. However, air conditioning in an installation environment requires much energy. Jedrzejewski et al. report that air conditioning consumes 15% of the energy of the entire manufacturing process [2]. By changing the room temperature and reducing thermal load, there is a possibility that energy consumption can be significantly reduced. Though changing room temperature causes thermal displacement, it requires compensation in the machining process.

Many papers studied the thermal displacement induced by environmental temperature change. Mayr et al. investigated ambient temperature influences on displacement at the tool center point (TCP) in the frequency domain [3]. Fujishima et al. proposed a deep-learning model using body temperature information to estimate the TCP displacement induced by ambient temperature change on lathes [4]. A method for a 5-axis machine tool to estimate error parameters change induced by thermal displacement is also proposed [5].

However, these conventional studies investigate errors of the coordinate space of the machine tool itself [6], and do not consider the difference of thermal expansion between the workpiece and the machine tool. In order to adjust the environmental temperature in precision machining to minimize the energy consumption of the production system, it is necessary to consider the effect of thermal expansion of the workpiece.

Therefore, this paper investigates the machining error caused by the difference in the thermal expansion coefficient between the machine and the workpiece, when the machining was performed at a temperature different from the standard temperature. Based on the thermal error equations, the machining error caused by the difference in the thermal expansion coefficient between the machine and the workpiece was investigated. The calculation was verified by cutting experiments using a machining center.

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2. Thermal displacement by ambient temperature change

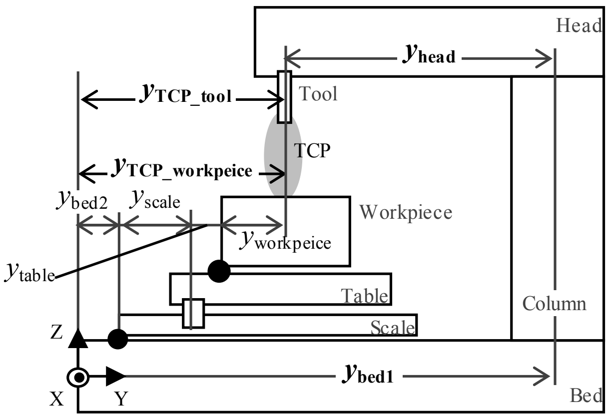


Fig. 1. One dimensional thermal displacement model.

Figure 1 shows the one-directional (y-axis direction) thermal displacement model for a vertical machining center. The tool center point (TCP) is expressed by the stacks of the thermal deformation of machine components from the origin.

The coordinate of the tool side TCP point $y_{\mathrm{TCP\_tool}}$ at the standard temperature is as follows:

$$y_{TCP\_tool} = y_{bed1} - y_{head} \tag{1}$$

where, y_{A} represents the length of component A. When the machine is controlled by a full closed-loop control system, the coordinate of the workpiece side TCP point $y_{\mathrm{TCP\_workpeice}}$ is as follows:

$$y_{TCP\_workpeice} = y_{bed2} + y_{scale} + y_{table} + y_{workpeice} \tag{2}$$

When the temperature of the airframe rises uniformly by 1 K, thermal displacement changes the coordinates of TCP as follows:

$$dy_{tool} = \alpha_{bed} \cdot y_{bed1} - \alpha_{head} \cdot y_{head} \tag{3}$$

$$dy_{workpeice} = \alpha_{bed} \cdot y_{bed2} + \alpha_{scale} \cdot y_{scale} + \alpha_{table} \cdot y_{table} + \alpha_{workpiece} \cdot y_{workpeice} \tag{4}$$

where α_{X} represents the linear expansion coefficient of component X. For simplicity, the thermal expansion coefficient of the machine components is set to a common value: $\alpha_{\mathrm{machine}}$.

$$dy_{tool} = \alpha_{machine} \cdot y_{tool} \tag{5}$$

$$dy_{workpeice} = \alpha_{machine} \cdot \left(y_{TCP\_workpeice} - y_{workpeice}\right) + \alpha_{workpiece} \cdot y_{workpeice} \tag{6}$$

The positioning error is expressed as follows:

$$dy = dy_{tool} - dy_{workpeice} = \alpha_{machine}\left(y_{tool} - \left(y_{TCP\_workpeice} - y_{workpeice}\right)\right) - \alpha_{workpiece} \cdot y_{workpeice} = \left(\alpha_{machine} - \alpha_{workpiece}\right) \cdot y_{workpeice} \tag{7}$$

Equation 7 shows that the machining error is determined by the difference between the thermal expansion coefficient of the machine and the workpiece, and the machining position.

Next, the thermal displacement that appears as a machining error on the workpiece at this time is investigated. Figure 2 shows the machining error transferred to the workpiece during the cutting of block workpiece at position L. Figure 2a shows the nominal cutting position. Figure 2b shows the thermal displacement during cutting at ambient temperature 20+dT °C.

In order to cut out the nominal length L (at the standard temperature), machining must be performed at the position of $L \cdot (1 + \alpha_{\mathrm{workpiece}} \cdot \mathrm{d}T)$. However, it is machined at position $L \cdot (1 + \alpha_{\mathrm{machine}} \cdot \mathrm{d}T)$ due to the difference in the thermal expansion coefficient between the machine and the workpiece. Thus, the machined workpiece length (cut-out length) at 20+dT °C, $L_{\mathrm{cut}}(\mathrm{d}T)$ is as follows:

$$L_{cut}(dT) = L \cdot (1 + \alpha_{machine} \cdot dT) \tag{8}$$

Figure 2c shows the workpiece shape when after acclimated to the standard temperature (20 °C). In this accumulation, the cut-out length changes according to the temperature distribution in the workpiece due to the thermal expansion of the workpiece. After sufficient accumulation, the cut-out length measured at standard temperature $L_{\mathrm{cut}}(0)$ is as follows:

$$L_{\mathrm{cut}}(0) = \frac{L_{\mathrm{cut}}(\mathrm{d}T)}{1 + \alpha_{\mathrm{workpiece}} \cdot \mathrm{d}T} \tag{9}$$

From equations 8 and 9, the cut-out length at the standard temperature 20 °C is summarized as follows:

$$L_{\mathrm{cut}}(0) = L \cdot \left(\frac{1 + \alpha_{\mathrm{machine}} \cdot \mathrm{d}T}{1 + \alpha_{\mathrm{workpiece}} \cdot \mathrm{d}T}\right) \tag{10}$$

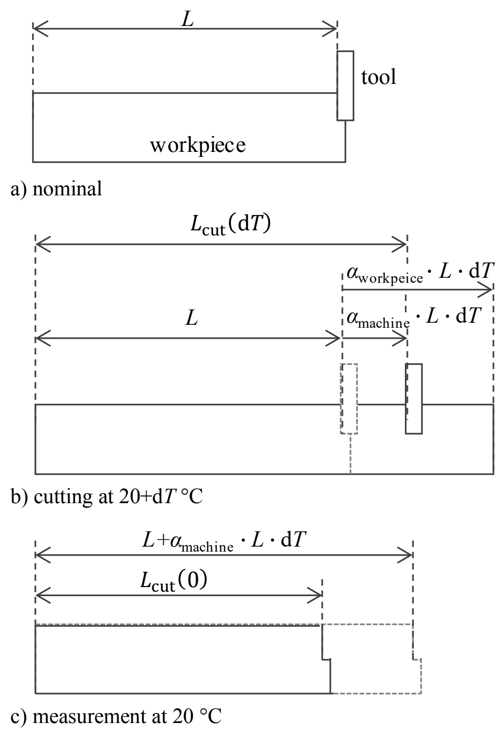


Fig. 2. Schematics of workpiece deformation around cutting at 20+dT °C.

3. Experimental verification

3.1. Experimental environment and conditions

Cutting experiments are conducted for the verification of section 2. A fixed distance (299.120 mm) was cut out by side milling with an end mill. Then, the length error from the command value was evaluated at the position shown in Figure 3. The cutting test was repeated at two different ambient temperature conditions 18 °C and 23 °C for two different material workpieces (300 mm × 100 mm × 25 mm), Steel (ISO C50) and Aluminum (ISO AlMg2.5). Table 1 shows the specifications of the machine tool used for the experiment.

Cutting conditions are summarized in table 2. In order to minimize the deformation caused by the process force, the very light cutting condition is chosen. The cutting time for one side is approximately 30 seconds for each material. Cutting was repeated for two times (0.5 mm×2) per side. Although different processing conditions are set for steel and aluminum, the focus of this paper is the effect of room temperature changes on thermal displacement. The cutting conditions are the same in the same material, and by performing the warm-up operation to bring the machine into a thermal equilibrium state, the effect of thermal displacement caused by machine heat generation can be eliminated, and it is not necessary to consider it.

The cutting tests are conducted from the cold start condition after 3 hours of warm-up. The ambient temperature is controlled between ±1 K of the target temperature.

It is expected that the clamping conditions will have a large effect on thermal expansion. In this paper, in order to minimize the impact, after confirming that both the workpiece and the jig are acclimated to the ambient temperature, the workpiece was set immediately before the warm-up.

After accommodating the workpiece to 20 °C for more than a day, the cut-out length was measured by a coordinate measurement machine. The measurement was performed at the three locations, as shown in figure 3, and the average was taken as the actual cut-out length.

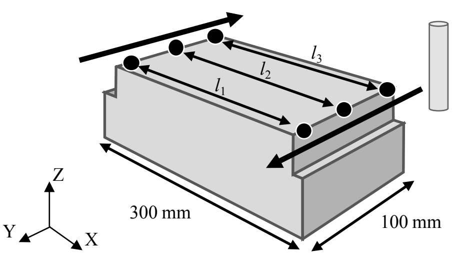


Fig. 3. Workpiece schematics and tool path.

Table 1. Specifications of the machine tool.

Machine type	Vertical machining center
Workspace	X: 800 mm Y 530 mm Z 510 mm
Spindle	Max power: 18.5 kW [100%ED] Max speed: 20,000 min^{-1}
Y-axis	Guideway: Sliding Control: Full closed loop Encoder: Steal scale Positioning Resolution: 1μm

Table 2. Cutting conditions.

	Steel	Aluminum
Tool	Solid Carbide end mill φ12 mm 4 tooth	
Cutting speed	1,300 min^{-1}	900 min^{-1}
Depth of cut ap/ae	10 mm / 0.5 mm	10 mm / 0.5 mm
Feed per tooth	0.05 mm	0.07 mm
Cutting fluid	wet (oil)	dry

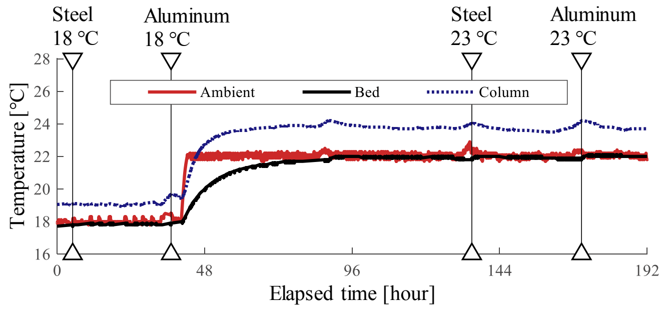
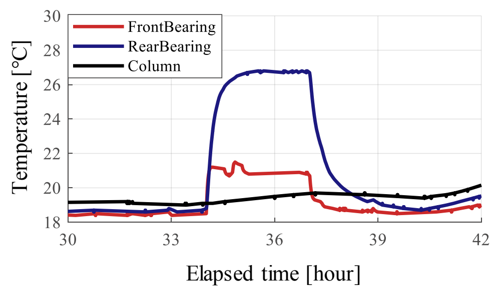
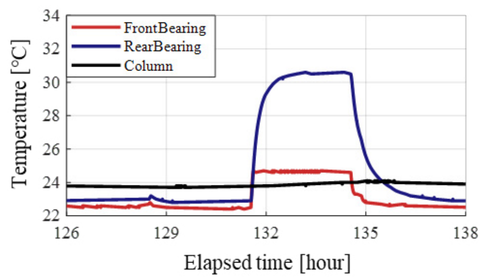


Fig. 4. Temperature history during measurement and experiment timings.



a) Aluminum 18 °C



b) Aluminum 23 °C

Fig. 5. Temperature history during warm-up.

3.2. Results and discussions

Figure 4 shows the temperature history during the experiments. The machining test was performed under each condition at the times shown in the figure. From the figure, the bed temperature is the same at room temperature during each cutting. The column temperature is always about 1 °C higher than the bed temperature. It is considered that this is because the room temperature has a gradient and that the higher the temperature.

Figure 5 shows the temperature change of the airframe under the condition of aluminum workpieces. From the figure, it can be said that the temperature of the spindle is saturated in about 2 hours, and the machine is in a sufficiently thermal equilibrium state after warming up for 3 hours. It can also be seen that the temperature distribution of the machine is offset by the offset of the environmental temperature. Similar results were obtained under steel conditions.

Table 3. Measured workpiece length.

		Cut-out length	Length difference	
Material	Temperature	Measured	Measured	Calculated
Steel	18 °C	299120.5	2.1	1.4
	23 °C	299118.4		
Aluminum	18 °C	299123.8	19.7	19.5
	23 °C	299104.1		

Unit: μm

Table 3 summarizes the measured and calculated results. Calculated differences of cut-out lengths are obtained from Eq. 10 as follows:

Steel: 1.4 μm =

$$299120\,[\mu\text{m}] \cdot \left(\left(1 - \frac{1 + 10.8\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 3[\text{K}]}{1 + 11.7\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 3[\text{K}]} \right) + \left(1 - \frac{1 + 10.8\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 2[\text{K}]}{1 + 11.7\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 2[\text{K}]} \right) \right) \quad (9)$$

Aluminum: 19.5 μm =

$$299120\,[\mu\text{m}] \cdot \left(\left(1 - \frac{1 + 10.8\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 3[\text{K}]}{1 + 23.8\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 3[\text{K}]} \right) + \left(1 - \frac{1 + 10.8\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 2[\text{K}]}{1 + 23.8\left[\frac{\mu\text{m}}{\text{K}}\right] \cdot 2[\text{K}]} \right) \right) \quad (10)$$

Where, the thermal expansion coefficient of the machine tool was set to that of gray casting iron (ISO 300), 10.8 μm/K. 11.7 μm/K and 23.8 μm/K were used for the coefficients of steel and aluminum workpieces.

The measured difference of cut-out lengths between 18 °C and 23 °C are 2.1 μm in steel workpiece while 19.7 μm in aluminum. The difference between measured and calculated results is less than 1 μm, while still 33% error exists for steel results, which is smaller than the positioning resolution of the axis (1 μm) and unavoidable. Thus, it can be said that, for both steel and aluminum, the calculated results quantitatively agree with measured results.

4. Conclusion and Outlook

The effect of the expansion coefficient difference between a machine tool and workpieces to the thermal deformation induced by room temperature change is investigated. According to the model, when the machine and the workpiece have different coefficients of thermal expansion, a dimensional error occurs in the workpiece while the workpiece is machined with the environmental temperature offset. Machining experiments are conducted for steel and aluminum workpieces to verify this model. As a result, an error of 19.5 μm occurred in aluminum, while it was 2.1 μm in steel. These results agree with simulation results. Although the number of samples and the number of experimental levels are limited and further verification is required, the proposed model is likely to hold.

The results show that when the difference in the coefficient of thermal expansion is significant as in the case of the aluminum workpieces, the effect of the machining error caused by the difference in the coefficient of thermal expansion cannot be ignored. Consideration for transient condition and three-dimensional workpieces will be our next step.

Acknowledgments

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