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Study on Model Predictive Control to Minimize
Movements in Positions Due to Thermal Expansion of
Plate with Varying Generation of Heat

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Abstract: Precise temperature control to decrease movements in positions due to thermal expansion of work pieces is required in the manufacturing processes to achieve nanometer-order accuracy. We analytically examined the effect of a method of minimizing movements in positions on a plate with varying generation of noise-heat. Control by monitoring temperature changes caused larger movements in positions than that without control because maximum change in temperature occurred at non-monitoring positions. The best method of minimizing movements in positions due to thermal expansion of a plate with varying generation of noise-heat was model predictive control by the monitoring movements and distributed temperature changes in the control heater according to the effects of the generation of noise-heat. The maximum movement in positions was 6 nm, which was 1/4 times of that without control.

Key words: Precise temperature control, heat transfer, thermal expansion, process control, model predictive control.

1. Introduction

Recent advances in VLSI (very large scale integrated) circuit technology incorporate high-density devices and nano-engineering, which require very accurate thermal control during the manufacturing process to achieve nanometer-order accuracy. For example, a temperature change of 0.001 °C causes 1 nm-movement in the position due to thermal expansion of a steel plate that is 100 mm in width. However, the local temperature of manufacturing apparatuses changes more than 0.1 °C even in constant-temperature rooms with air-conditioning facilities because noise-heat is generated in the working apparatuses. Therefore, it is necessary to develop precise methods of thermal control to decrease movements in positions due to thermal expansion of work pieces under circumstances where noise-heat is generated.

Some work on precise temperature control has been reported. Experiments on temperature control within 0.0001 °C in a thermally insulated room without the generation of noise-heat have been reported [1]. Kudo et al. [2] developed an inverse problem approach to controlling object temperature by changing the boundary conditions. Diaz et al. [3] reported an adaptive method of neurocontrol to keep air temperature that left heat exchangers constant. Sweetland and Lienhard [4] analyzed active thermal control for IC (integrated circuit) devices. Hoshino et al. [5] developed a precise method of temperature control by improving a PID (proportional-integral-derivative) controller for adiabatic demagnetization refrigerators. Model predictive control was reported to be preferable to process control under circumstances where there was random noise [6, 7]. Future response of the object has been predicted in model predictive control using a dynamic predictive model and the control rate was determined so that the response became an ideal response pattern.
Authors [8-10] have reported analytical and experimental studies to minimize temperature changes at object positions in one-dimensional or two-dimensional vertical plates with varying generation of noise-heat using model predictive control. The temperature change at an object position can be decreased to 0.002 °C, which is 1/1,000 of that without control using model predictive control in analysis [8]. Experimental results have revealed that the minimum temperature change at the object position is 0.04 °C, which is 1/80 of that without control in a surrounding vacuum [9]. The effect of error in a dynamic predictive model on temperature change at the object position has been studied in numerical simulations and experiments [10].

In this work, we studied the effect of a method of minimizing movements in positions due to thermal expansion of a plate with varying generation of noise-heat using model predictive control with numerical simulations. The paper is organized as follows: Section 2 introduces analytical model; Section 3 presents the calculation results without control; Section 4 explains model predictive control; Section 5 presents the calculation results with model predictive control; and Section 6 gives conclusions.

2. Analytical Model

Fig. 1 shows a calculation model of a plate with varying generation of noise-heat. We studied a precise method of temperature control for a simple model. Heat transfer to the plate except for a control heater was neglected. The plate was steel (thermal conductivity of 43 W/m·K, density of 7,850 kg/m³, specific heat of 465 J/kg·K, and a coefficient of thermal expansion of $11.8 \times 10^{-6} \text{K}^{-1}$) that was 270 mm in width and 10 mm in thickness. We calculated the one dimensional temperature distribution in direction $x$. Movement at the centre of the plate was assumed to be zero. Temperature change and thermal expansion were symmetrical to the positive and negative directions of $x$. Noise-heat was generated on both sides of the plate. The noise-heat generated on both sides of the plate was from turning the heat off for 600 s and turning it on at 30 W/m for 600 s repeatedly. A control heater was placed below the plate and controlled heat was transferred to the plate by thermal radiation. We calculated two cases of temperature distribution in the control heater: uniform temperature change, and distributed temperature change, which was a linear distribution of zero change at the centre and large changes on both sides. The main purpose of control was to minimize movements in all positions on the plate in the $x$ direction due to thermal expansion even though there was a change in the generation of noise-heat. The initial temperature distribution of the plate was that from repeatedly turning the heat off and on to generate noise-heat and after turning the heat off for 600 s. In this work, the temperature changes and movements in positions from the initial values were shown.

A one-dimensional temperature distribution in the plate is calculated as

$$
\rho C_p \frac{\partial T_w}{\partial t} = \frac{\partial^2 T_w}{\partial x^2} + q_c + q_n
$$

where, $T_w$ is the temperature of the plate, $t$ is time, $x$ is coordinates ($x = 0$ at the centre of the plate), $\rho$ is density, $C_p$ is specific heat, $\lambda$ is thermal conductivity, $q_c$ is the radiation heat transfer rate from the control heater, and $q_n$ is the rate at which noise-heat is generated per unit volume. The rate at which radiation heat is transferred from control heater $q_c$ is calculated

![Fig. 1 Calculation model.](image-url)
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\[ q_c = \frac{\sigma(T_c^4 - T_w^4)}{1 + \frac{1}{\varepsilon_c} - 1} \]  

where, \( T_c \) is the temperature of the control heater, \( \sigma \) is the Stefan-Boltzmann constant (\( \sigma = 5.67 \times 10^{-8} \) W/m\(^2\)K\(^4\)), and \( \varepsilon_c \) and \( \varepsilon_w \) are the emissivities of the surfaces of the plate and the control heater (we assumed \( \varepsilon_c = \varepsilon_w = 1.0 \)). The movement of position \( \Delta x \) at position \( x \) in the plate due to thermal expansion is calculated as

\[ \Delta x = \int_0^x aT_w dx \]

where, \( a \) is the coefficient of thermal expansion. Eq. (1) was calculated with the implicit finite-difference method. The mesh spacing of numerical calculation was 30 mm and the calculation time step was 60 s.

3. Temperature Change and Thermal Expansion without Control of Heat Generation

First, unsteady temperature change was calculated without control of heat generation, which means that the temperature of the control heater was fixed at \( T_c = 0 \) °C. Figs. 2 and 3 plot the calculated results for temperature changes at positions \( x = 15, 45, 75, 105, \) and 135 mm and temperature distributions at time \( t = 60, 120, 600, 660, \) and 1,200 s when noise-heat was generated by turning the heat on from time \( t = 0 \) s to 600 s and turning heat off from time \( t = 600 \) s to 1,200 s. The maximum temperature change without control of heat generation is 0.039 °C at position \( x = 135 \) mm and time \( t = 600 \) s. Fig. 4 plots the calculated results for the movements in positions and they are similar to the temperature changes (Fig. 2). The maximum movement in position without control of heat-generation is 23 nm.

4. Model Predictive Control

Basic idea of the model predictive control is as following [6]. The future response of the object is predicted using a dynamic predictive model. Further, the control rate is determined so that the response becomes an ideal response pattern. The difference between the predicted response and the actual response is modified simultaneously. We studied two cases where we monitored temperature change in the plate on side \( x = 135 \) mm and monitored movement in the plate on side \( x = 135 \) mm. Change in the
generation of noise-heat was predicted by monitoring temperature changes or movements. The temperature of the control heater was determined using the dynamic predictive model so that the monitored temperature change or movement became zero after 60 s under the predicted generation of noise-heat. The dynamic step responses of the temperature change or movement in position of the plate on side $x = 135$ mm were obtained in advance for a step change of $+3$ W/m in the generation of noise-heat or $+0.1$ °C for a uniform temperature change in the control heater. The obtained step response patterns are plotted in Figs. 5 and 6 and they were used in the dynamic predictive model. Our control time interval was 60 s.

The equations to calculate the temperature of control heater $T_{c,i}$ at each time step $i$ by monitoring temperature change $T_{w-mon-i}$ are:

$$T_{c,i} = K_1(T_{w-prev(i+1)} - T_{w-mon,i}) + K_2(T_{w-mon-i} - T_{w-prev,i}) \quad (4)$$

$$T_{w-prev,j} = \text{func}(T_{w-mon-k}, T_{c,k}) \quad (5)$$

where, $T_{w-prev(i+1)}$ is the predicted temperature after 60 s, $T_{w-mon}$ is the initial temperature and $T_{w-prev}$ is the predicted temperature at time $j$. Here, $T_{w-mon,k}$ is the monitoring temperature at time $k$, and $K_1$ and $K_2$ are the control constants. The function in Eq. (5) means to obtain values using the dynamic predictive model.

5. Temperature Change and Thermal Expansion with Model Predictive Control

Figs. 7 and 8 plot the calculated results for the temperature changes and temperature distributions with model predictive control by monitoring temperature change at position $x = 135$ mm and uniform temperature change in the control heater. The temperature change at position $x = 135$ mm and time $t = 660$ s is 0.01 °C, which is 1/4 of that without control. As position $x = 135$ mm is the monitoring position, the temperature change is small. However, the maximum absolute value of change in the temperature is 0.025 °C at position $x = 15$ mm and time $t = 660$ s, which is in a non-monitoring position.

Fig. 9 plots the calculated results for the movement in position. The maximum movement in position is 31 nm at position $x = 135$ mm and time $t = 660$ s, which is larger than that without control because the maximum change in temperature occurred at non-monitoring positions.
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Fig. 8  Temperature distribution with control by monitoring temperature.

Fig. 9  Movement in position with control by monitoring temperature.

Fig. 10  Temperature change with control by monitoring movement and uniform temperature change in control heater.

Fig. 11  Movement in position with control by monitoring movement and uniform temperature change in control heater.

Fig. 12 and 13 plot the calculated results for temperature changes with model predictive control by monitoring movements at position $x = 135$ mm and distributed temperature change in the control heater, which was a linear distribution of zero change at the centre and large changes on both sides. The temperature change at position $x = 135$ mm and time $t = 600$ s is 0.009 °C, which is 1/4 of that without control.

Fig. 11 plots the calculated results for the movements in position. The movement in position is 8 nm at position $x = 135$ mm and time $t = 660$ s and the maximum movement in position is 9 nm at position $x = 120$ mm in the non-monitoring position. The reason for the larger movement in position at the non-monitoring position than that at position $x = 135$ mm is that the uniform temperature change in the control heater was not suitable for generating noise-heat on both sides.

As the maximum movement in position occurred at time $t = 660$ s, which is after one control time interval from the change in the generation of noise-heat, the movement in position can be reduced by monitoring the change in the generation of noise-heat earlier with other information.
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6. Conclusions

We analytically examined the effect of the method of minimizing movements in position due to thermal expansion of a plate with varying generation of noise-heat with model predictive control, and following results were obtained:

(1) Control by monitoring temperature changes caused larger movements in positions than that without control because maximum change in the temperature occurred at non-monitoring positions;

(2) Control by monitoring movements and uniform temperature change in the control heater decreased the maximum movement in position to 9 nm. However, larger movements in position occurred at non-monitoring positions because uniform temperature change in the control heater was not suitable for the generating of noise-heat on both sides;

(3) Control by monitoring movements and distributed temperature change in the control heater decreased maximum movement in position to 6 nm, which was 1/4 of that without control (23 nm). Therefore, the best method of minimizing movements in position due to thermal expansion of the plate with varying generation of noise-heat was model predictive control by monitoring movements and distributed temperature changes in the control heater according to the effect of the generation of noise-heat.

References


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