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Effect of Installation Conditions on Thermal Deformation and Positioning Accuracy of a Ball Screw in Motion

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Abstract: - Thermal deformation is an important factor affecting the positioning accuracy of a ball screw. Existing studies focus on the influence of the temperature rise of a ball screw on thermal deformation but ignore the impact of installation mode on thermal deformation and positioning accuracy. This paper analyzes the effects of the two modes of high-precision installation: fixing both ends of the screw, and supporting one end while fixing the other. The installation mode is found to have a very strong influence on positioning accuracy. The thermal deformation of the screw with both ends fixed is affected by the temperature rise of the bearings at both ends, and the deformation amount is smaller than that with one end fixed. The screw undergoes thermal expansion on both sides when both ends are fixed, but only on one side when one end is fixed. This has a very significant effect on the precision of the screw and provides a specific basis for devising thermal compensation measures.

Keywords: Ball screw, Thermal deformation, Positioning accuracy, Installation conditions

Introduction

The ball screw pair is a critical rolling element widely used in mechanisms that need positioning or transmission, which plays an essential role in the mechanism's performance. In practical application, the choice of installation mode for the ball screw pair affects the performance of the whole structure. There are many ways of installing a ball screw pair depending on the situation. Two common ways of installing a ball screw pair in high-precision applications are fixing both ends and fixing one end of the set while supporting the other end. The deformation of the screw caused by the temperature rise varies, which affects the positioning accuracy.

Many researchers have analyzed the thermal deformation of a ball screw. For example, Wu[1] experimentally analyzed the thermal deformation caused by the temperature rise of the screw. However, there was no specific classification or analysis of different installation methods in that study. Xia[2] studied the relationship between rising temperature and thermal error under varying operating conditions, but no installation method was mentioned. Hu[3][4] has analyzed the thermal deformation caused by rising temperature of a screw with one end fixed and the other end free and shown that the direction of thermal expansion is in the opposite direction on both ends. This analysis considered chiefly the effect of internal thermal expansion of the screw stroke segments on location accuracy, without considering the impact of the heat transfer of both end bearings

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on the screw. Ramesh[5] has shown that the thermal drift cannot be correlated to a single temperature sensor because different errors are obtained depending on the conditions for the same rise in temperature of a nut. However, the nut temperature rise does not represent the temperature rise of the screw. The nut is in contact with the workbench, and the exposed nut also participates in thermal convection. The loading of the nut affects the nut temperature rise. Xu[6] experimentally analyzed the thermal deformation of hollow and solid ball screws after a temperature rise. Li[7] combined the finite element method and Monte Carlo method to simulate the temperature field and analyze the thermal error of a ball screw with one end fixed and the other end free. Li[8] used the finite difference method to analyze the temperature rise and thermal deformation of ball screws in different working conditions with one fixed and one supported end. However, he did not investigate the actual displacement direction or amount of displacement in detail. Xu[8][10] analyzed the thermal deformation of a screw under different strokes but did not clarify the precise installation method or specify the thermal deformation direction. Li[11] used thermal network analysis to predict the temperature of a bearing and screw by measuring the temperature of the bearing surface and the nut. However, the screw had an internal heat source, whereby the heat was generated by the contact friction between the ball and the raceway surface. The applicability of this method needs further study. Liu[13] studied a ball screw with one end fixed and the other supported. The total thermal error was divided into thermal expansion error in the stroke range and thermal drift error of the origin. That paper proposed that thermal expansion error depends on temperature and location, while thermal drift error only depends on temperature. This viewpoint needs to be further developed because installation conditions are also a significant factor in zero drift.

Although researchers have adopted many methods to analyze the temperature rise of a screw and its relationship to thermal deformation and positioning error, there has been no investigation of the effect of installation on the thermal deformation of the screw. Different methods of installing a screw lead to different thermal errors and different displacement directions, so judging positioning error by temperature alone is considerably one-sided. Therefore, it is necessary to analyze the thermal deformation and positioning error due to different installation methods.

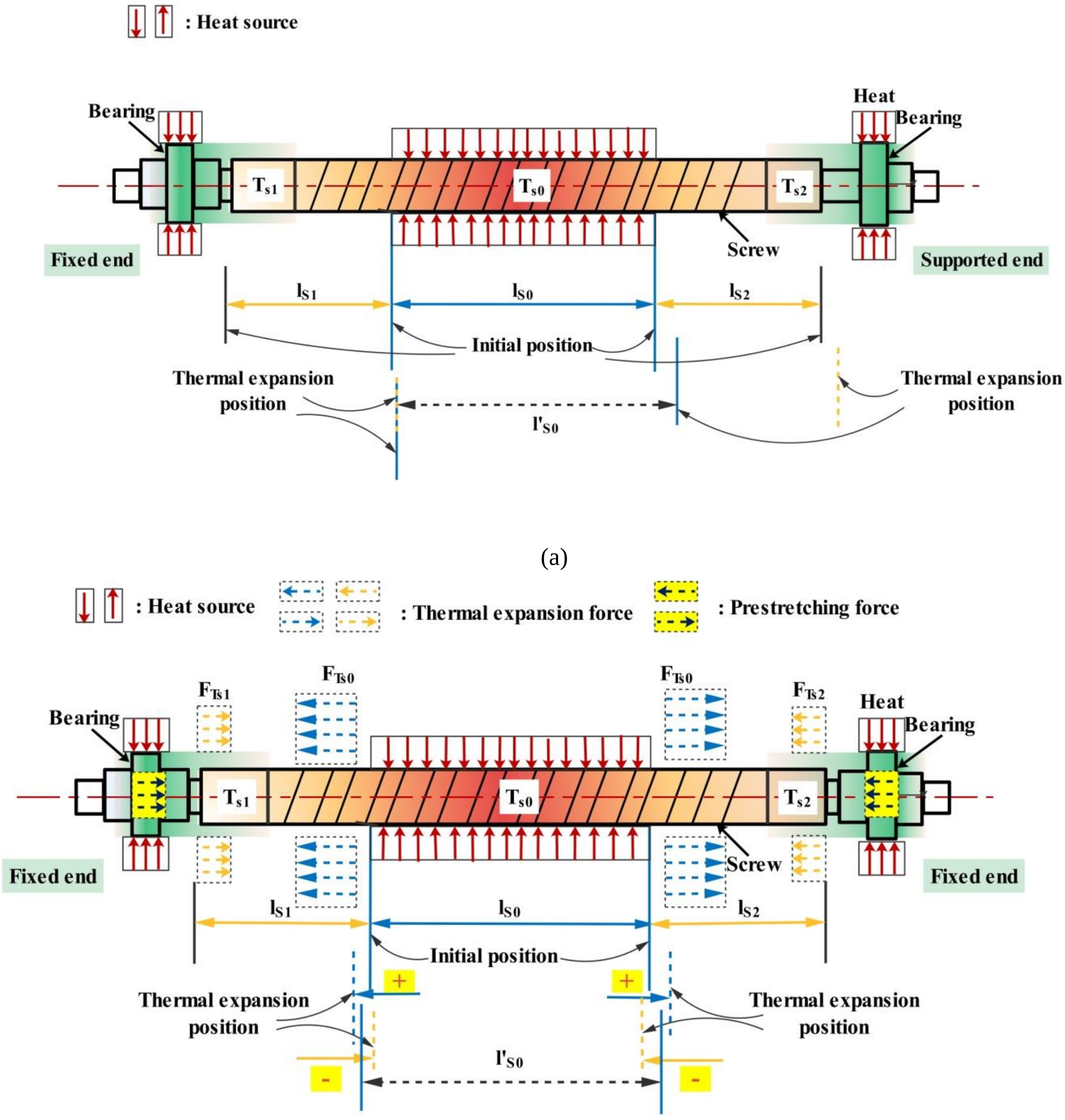
1. Positioning accuracy of a screw

Figure 1(a) shows the temperature field and thermal expansion for a screw installed with one end fixed and the other supported. The thermal expansion of the fixed end is restrained. The screw can still expand freely at the other end. The heat generated by the bearing at the fixed end is passed to the screw to produce thermal expansion, which drives the screw stroke along interval starting points to support directional migration. Meanwhile, the screw stroke section also thermally expands towards the supported end under the temperature rise. Hence, the screw in the figure changes from the initial length l_{s0} to the extended length l'_{s0}.

Figure 1(b) shows the temperature field and thermal expansion for a screw installed with both ends fixed; the red arrows indicate the heat source areas. The nut contact region and bearings on both ends are the main areas that produce heat. The central part of the screw expands toward both sides under a temperature rise caused by friction. The thermal displacement of the screw is represented as “+” in the figure.

However, because both ends are fixed, the thermal expansion in the screw stroke is limited, resulting in a thermal stress F_{Ts0} on both sides. The bearing at each end transfers heat to the screw end, which is at lower temperature. This is reflected in the thermal displacement, which is represented as "-" in the figure.

The thermal stresses F_{Ts1} and F_{Ts2} develop from both ends to the stroke area. Under reverse thermal stress, the length of the screw stroke in this installation mode changes from the original l_{s0} to the extended l'_{s0}, and the thermal deformation in the stroke of the screw is less than the free expansion.



(b)

Figure 1. Thermal expansion for two installation modes: (a) one end fixed and the other supported (state 1), (b) both ends fixed (state 2).

2.1 Screw temperature rise

In the ball screw pair, the friction heat of the ball in the raceway surface causes the temperature of the screw to rise. According to the conservation of energy, the increase in internal energy of the screw is the friction heat minus the heat lost by convection and the heat transmitted out.

The heat balance equation of the screw is

$$\rho cm\Delta T_{s0} = (H_f - H_c - H_d)t \tag{1}$$

where ρ is the density of the screw, c is the specific heat of the screw, m is the mass of the screw segment whose internal energy increases, ΔT_{s0} is the temperature rise of the screw interval, H_f is the friction heat between the ball and screw raceway surface, H_c is the convection with the external environment, H_d is the heat transferred to other low-temperature regions of the screw, and t is the time taken for the temperature of the screw to rise by ΔT_{s0}.

2.1.1 Friction heat of the screw

When analyzing the effect of installation mode on thermal deformation, it is necessary to examine the temperature rise of the screw first. The temperature rise of the screw is mainly caused by the friction of the ball on the raceway surface. According to the structural parameters and friction torque of the screw, the formula of friction heat per unit time is

$$H_f = 2\pi \frac{r_m}{\cos\gamma (r_m - r_b \cdot \cos\alpha)} nM_s \tag{2}$$

where r_m is the radius of the screw, r_b is the radius of the ball, n is the speed of the screw, and M_s is the friction moment generated by the ball on the screw raceway surface.

In engineering practice, the friction torque between the ball and nut surface is typically used to facilitate detection, so the above formula can be expressed in terms of nut friction torque:

$$H_f = 2\pi \frac{r_m}{\cos\gamma (r_m + r_b \cdot \cos\alpha)} nM_n \tag{3}$$

During screw motion, the friction torque is mainly affected by the contact load and viscosity of the lubricating grease. The friction torque formula can be expressed as

$$M_n = M_{nQ} + M_{n\eta} \tag{4}$$

where M_{nQ} is the contact load friction torque, and $M_{n\eta}$ is the viscous friction torque. These two kinds of friction torque at high speed are analyzed in reference [12].

2.1.2 Convection heat of the screw

When the ball screw is in motion, the temperature of the screw rises, and the external environment dissipates convection heat because its temperature is lower than that of the screw. The convection heat dissipation is

$$H_c = hA_c\Delta T' \tag{5}$$

where h is the coefficient of thermal convection, A_c is the area of the screw where thermal convection occurs, and $\Delta T'$ is approximately the difference between the surface temperature of the screw and the ambient temperature[13].

2.1.3 Conduction heat of the screw

During nut motion, the screw section that is not involved in friction heating absorbs the heat from the high-temperature area of the screw. The conduction heat is

$$H_t = \lambda A \frac{\partial T}{\partial z} \tag{6}$$

where λ is the coefficient of thermal conduction of the screw, A is the cross-sectional area of the screw, and $\partial T/\partial z$ is the temperature difference between the screw sections whose distance is z .

2.1.4 Screw temperature rise equation

The temperature rise within the travel range of the screw is given exponentially as

$$T_{s0}(t) = T_\infty + \Delta T \times (1 - e^{-\tau t}) \tag{7}$$

where T_∞ is the initial temperature, ΔT is the increasing temperature in the steady state, τ is the exponential percentage, and t is the time.

2.1.5 Bearing temperature rise

In addition to the friction between the ball and the ball screw raceway surface, there is friction between the ball and the bearing's inner and outer raceway surfaces. The friction heat in the raceway is defined as [14]

$$H_b = 1.047 \times 10^{-4} n M_b \tag{8}$$

where n is the speed of the screw, and M_b is the friction torque of the bearing.

The friction torque of the bearing is mainly influenced by the contact load and viscosity of the lubricating grease. The formula of friction torque can be expressed as

$$M_b = M_{bQ} + M_{b\eta} \tag{9}$$

where M_{bQ} is the contact load friction torque, and $M_{b\eta}$ is the viscous friction torque. These two kinds of friction torque at high speed are analyzed in reference [6].

Then the screw temperature caused by bearing friction is[13]

$$T_{sb}(t) = [C_1 \exp(-\chi x) + C_2 \exp(\chi x)][1 - 2\pi^{-0.5} \int_0^\theta \exp(-\delta^2) d\delta] \tag{10}$$

where C_1 and C_2 are parameters to be determined, x is the distance between the detected screw section and the bearing end, $a = \dfrac{\lambda}{\rho c}$, $\chi = \sqrt{\dfrac{4h_s}{\lambda D}}$, t is time, and $\theta = \dfrac{x}{2\sqrt{at}}$.

2.2 Effect of temperature rise on thermal deformation

The installation method affects thermal deformation. When one end is fixed and one end is supported, the screw is free to expand thermally because the supported end is not constrained in the axial direction. However, when both ends are fixed, the screw cannot thermally expand freely because both ends are constrained. Therefore, this section will analyze the positioning accuracy under rising temperature in both installation methods.

Liu[13] analyzed installation with one end fixed and one end supported, and divided the positioning error of the screw into thermal expansion error in the stroke range and thermal drift error of the origin. The zero-point drift affects the thermal expansion of the screw and the thermal compensation direction of the starting point of the screw. Assume that the starting position on the left in **Figure 1** is the initial point of screw motion. In actual working conditions, the position deviates after each temperature rise, which significantly impacts the machining accuracy, so this requires attention. According to Liu's [13] analysis, the zero-point thermal drift is closely related to temperature and can be expressed as

$$\Delta l_{sO} = c_1 \Delta T_{b1} + c_2 \Delta T_{s0} + c_3 \Delta T_{\infty} + c_4 \tag{11}$$

where ΔT_{b1} is the temperature variation of the motor side bearing; ΔT_{s0} is the temperature rise of the screw; ΔT_{∞} is the temperature variation of the environment; and c_1, c_2, c_3, and c_4 are coefficients to be determined.

When the ball screw pair is installed in this mode, the above analysis can be used to compensate the zero-point drift. However, when the installation mode of the ball screw changes, the fitting coefficient needs to be corrected, so this method is not universal. The critical influence of both installation modes on thermal deformation is next investigated theoretically and experimentally.

2.2.1 One end fixed and the other supported

When the screw is fixed at one end and supported at the other end, the screw expands freely at the supported end after its temperature rises. Suppose that the initial length of the screw stroke is l_{s0}, then the thermal expansion error Δl_{s0} of the stroke in **Figure 1** is

$$\Delta l_{s0} = \int_0^{l_{so}} \alpha_T \Delta T_{s0} dl \tag{12}$$

Then the length after thermal elongation is

$$l'_{s0} = l_{s0} + \Delta l_{s0} \tag{13}$$

2.2.2 Both ends fixed

Thermal expansion is produced when the temperature of the screw rises and both ends are fixed. However, the temperature of the bearing also rises with both ends rotating. When the heat of a bearing is passed to the screw, the screw undergoes thermal expansion. However, the thermal expansion on both sides in the stroke of the screw is in opposite directions when both ends of the screw are fixed.

The stroke of the screw after the temperature rise is l'_{s0}, as shown **Figure 1**. This can be obtained as

$$l'_{s0} = l_{s0} + \Delta l_{s0} + \Delta l_{s01} + \Delta l_{s02} \tag{14}$$

where Δl_{s0} is the thermal expansion error in the screw stroke given by formula (12), and Δl_{s01} and Δl_{s02} are the zero-point drifts of the screw near both ends, respectively, and are expressed as

$$\Delta l_{s01} = \int_0^{l_{s01}} -\alpha_T \Delta \overline{T}_{s1} dl \tag{15}$$

$$\Delta l_{s02} = \int_0^{l_{s02}} -\alpha_T \Delta \overline{T}_{s2} dl \tag{16}$$

Under double-fixed installation, the direction of thermal expansion at both ends of the screw is opposite to that in the stroke of the screw, so it is negative in the formula.

The theoretical analysis also shows that the actual displacement of the screw with both ends fixed is less than that with one end fixed and one end supported.

3. Experiment

3.1 Test setup

Two groups of screws connected to the worktable in a machining center in service were investigated to effectively analyze the effect of installation mode on the in-stroke accuracy through thermal deformation of the screw. As shown in **Figure 2**, one group of screws was located on the X-axis and the other on the Y-axis. Two sets of screws were installed in the two ways shown in **Figure 1**. Because the screw was rotating, a temperature rise sensor could not be installed directly, so a contact temperature sensor was used for intermittent measurement. Bearing temperature was measured in real time through direct contact with a patch-type temperature sensor. A RENISHAW XL laser system was used to monitor the motion error in the stroke. To accurately analyze the motion error of the screw, each reciprocating motion was tested once. The temperature rise of the screw was detected every four reciprocating motions to reduce the effect of stagnation time on the temperature rise of the screw.

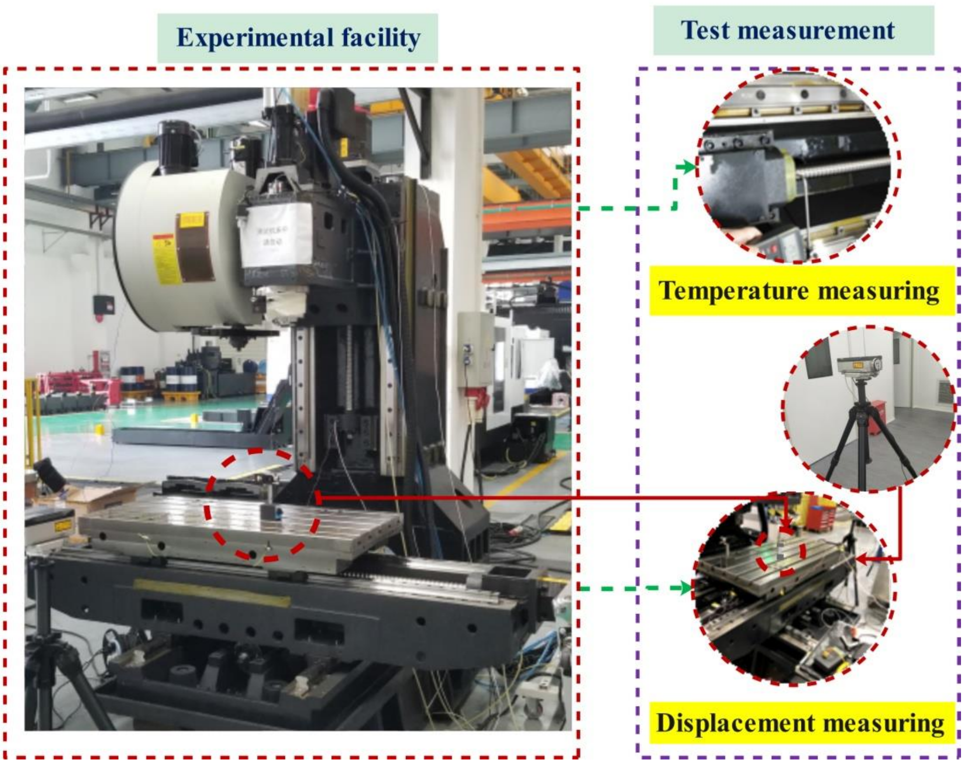


Figure 2. Test device and test diagram.

The structural and motion parameters of the screw used in the test are shown in

Table 1.

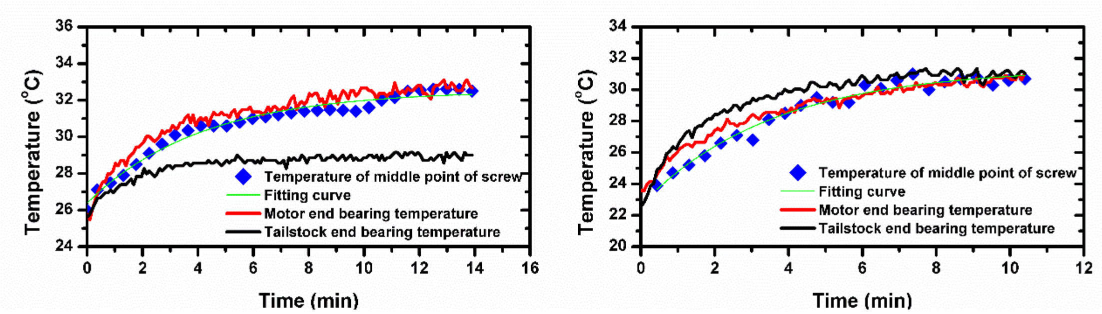
Table 1. Structural parameters and experimental conditions.

Parameters	X axis	Y axis	Unit
(1) The outer diameter of screw d_m	40	40	mm
(2) Helix angle of screw γ	2.75	5.27	degree
(3) The lead of screw p	16	12	mm
(4) Total length of the screw S	1280	800	mm
(5) Detection stroke of the screw l_{s0}	1000	520	mm
(6) Operating speed of the screw v	30	24	m/min

3.2 Analysis of test results

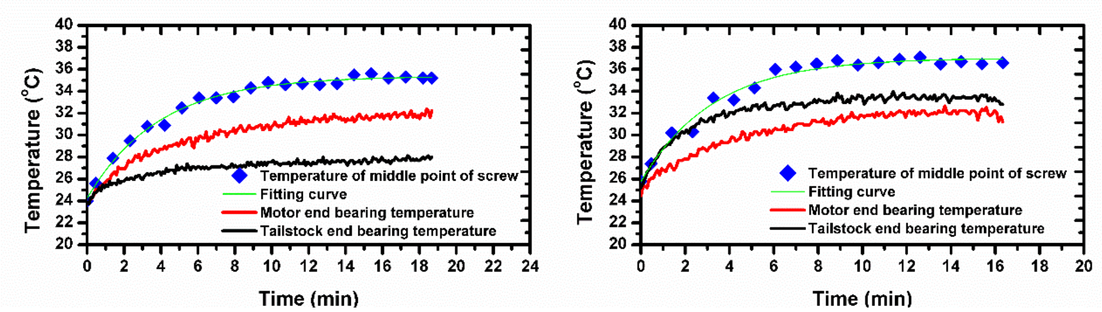
3.2.1 Temperature measurement results

Figure 3 and **4** show the detected temperatures of the screw in the middle stroke and the bearings at both ends of the screw under both installation modes. Because the contact temperature sensor needed to stay in contact with the screw for a specific time for each measurement, the detected temperature fluctuated to a certain extent. However, this fluctuation did not affect the overall trend or the difference in temperature rise between the two installation methods. As can be seen from the figures, the bearing temperature at the tailstock end changes significantly with different installations, and the bearing temperature rise at the tailstock end with both ends fixed is higher than that with one end fixed. It can be inferred from this that when the two ends are fixed, thermal stress is generated at both ends because the thermal expansion of the screw cannot proceed after the temperature rises. This thermal stress increases the resistance of the tailstock bearing, making its temperature rise.



(a) (b)

Figure 3. Temperatures of the middle interval of the X-axis screw stroke and bearings at both ends under different installation methods: (a) state 1, (b) state 2.



(a) (b)

Figure 4. Temperatures of the middle interval of the Y-axis screw stroke and bearings at both ends under different installation methods: (a) state 1, (b) state 2.

3.2.2 Direction of thermal deformation

The screw test points were evenly distributed according to **Figure 5** to investigate the effect of rising temperature on the deformation of the screw.

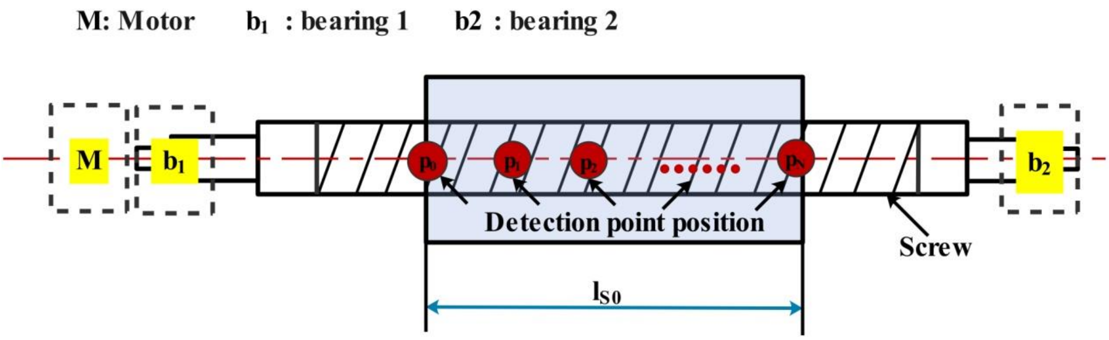


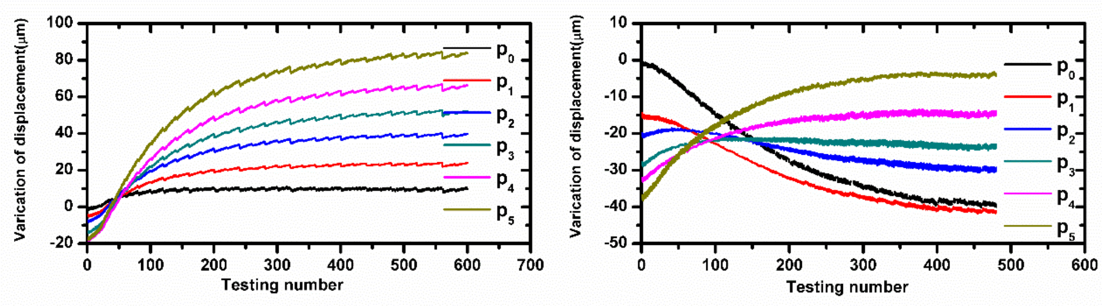
Figure 5. Distribution of detection points.

When sampling the X-axis, the screw detection interval was divided into five sub-intervals on average with six sampling points. The Y-axis was divided into four intervals on average with five sampling points when testing. The displacement of each sampling point was measured through the reciprocating motion of the screw, and the results are shown in **Figure 6** and **Figure 7**. For installation with one end supported and the other fixed, the thermal expansion of the screw proceeds freely. However, when both ends are fixed, the middle interval and both ends of the screw are all heated. The central travelling area of the screw can only undergo limited thermal expansion. Therefore, the thermal deformation direction at each detection point in **Figure 6**(a) and **Figure 7**(a) is consistent, extending towards the support direction. In **Figure 6**(b), points p_0, p_1, and p_2 extend oppositely to the support direction, while points p_3, p_4, and p_5 extend in the supporting direction. In **Figure 7**(b), points p_0 and p_1 extend first in the opposite direction to the support and then in the same direction, while points p_2, p_3, and p_4 extend in the same direction as the support.

The test results for total thermal displacement with the two different installation methods are consistent with the theoretical analysis. The thermal displacement of the traveling screw segment with both ends fixed is less than that with one fixed and one supported.

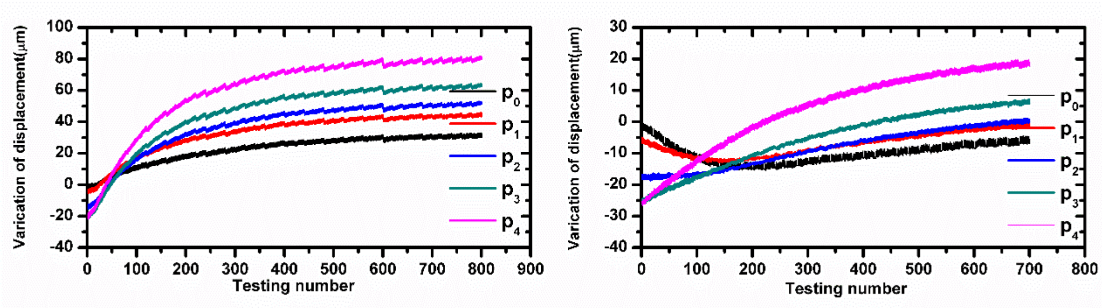
The test results also show that the location precision of the screw is negative for both installations. For a screw in machine tool processing, the deviation in position is caused by thermal expansion. Then, when the screw is used, the rise in temperature of the screw in operation is released after a certain period, resulting in compression and continued elongation.

However, the thermal displacement changes of the two installation modes are different, as judged according to the temperature rise. As shown in **Figure 3** and **4**, the temperature rise of the screw along the Y-axis is always greater than that of the bearings at both ends, while that of the screw along the X-axis is close to that of the bearings at both ends. Therefore, the thermal resistances of the bearings at both ends and the middle of the screw are similar, so the displacement change of the X-axis is asymmetric. Along the Y-axis, the thermal resistance is more extensive because of the higher temperature of the screw, so the screw has a one-way displacement change in the later period. This asymmetry may be caused by the unequal lengths of the screws on both sides beyond the detection area when the detection area is not entirely centered.



(a) (b)

Figure 6. Thermal displacement of the X-axis stroke: (a) state 1, (b) state 2.

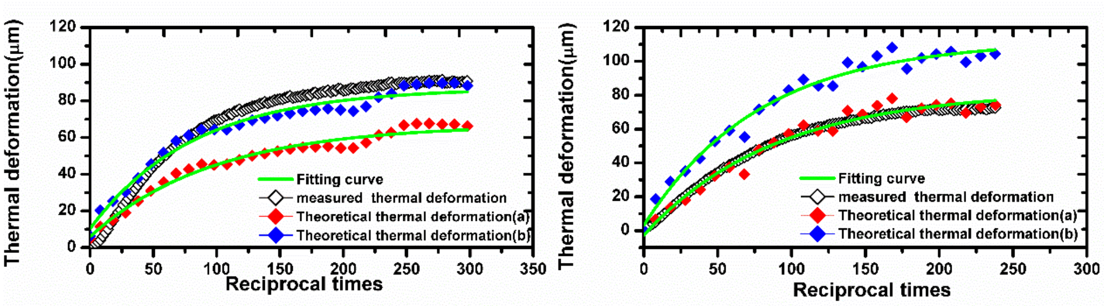


(a) (b)

Figure 7. Thermal displacement of the Y-axis stroke: (a) state 1, (b) state 2.

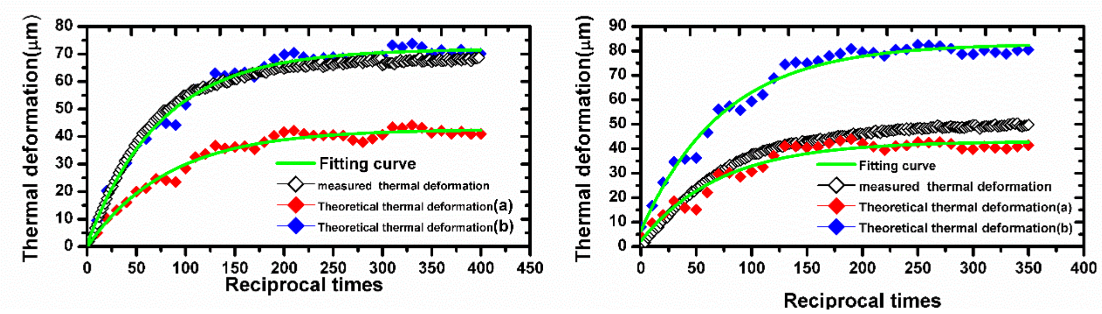
3.2.3 Thermal deformation

Figure 8 and **Figure 9**, compare the theoretical and experimental thermal deformations of the X-axis and Y-axis screw strokes under the two installation modes, respectively. The black markers represent the total thermal deformation between the starting point p_0 and endpoint p_5 (X-axis) or p_4 (Y-axis) measured with the laser interferometer. The red markers are the theoretical thermal deformation values considering the heat transfer from each bearing to the screw. The blue markers represent the theoretical screw temperature rise caused by free elongation. The green curves are the fits to the theoretical data. Overall, the test values agree with the theoretical analysis. Furthermore, the thermal expansion with both ends fixed is lower than the free elongation. This shows that the installation mode has a significant impact on the position accuracy in engineering applications.



(a) (b)

Figure 8. Thermal deformation in the X-axis stroke section: (a) state 1, (b) state 2.



(a) (b)

Figure 9. Thermal deformation in the Y-axis stroke section: (a) state 1, (b) state 2.

4. Conclusions

Installation mode is an essential factor for ball screw positioning accuracy. Most studies thus far have mainly analyzed the thermal deformation and thermal compensation of the screw but not specifically the influence of the installation mode on the thermal deformation of the lead screw. Different installation modes lead to thermal deformation in different directions, thus affecting the positioning accuracy and thermal compensation direction. The following conclusions are drawn from the study:

1) Different methods of installing a ball screw pair have different effects on position accuracy.

2) The temperature rise of the bearing end differs according to the installation mode of the ball screw pair. When the ball screw is fixed at both ends, the temperature rise of the tailstock bearing is higher than when one end is fixed and the other end is supported.

3) The thermal expansion direction of the traveling section of the ball screw differs between installation modes. The thermal expansion of the ball screw is on both sides when both ends are fixed. When one end is fixed, the extension is toward the other end.

4) Different installation modes have different influences on the thermal deformation of the traveling section of the screw. The thermal deformation of a ball screw fixed at both ends is smaller than that of one fixed at one end and supported at the other end.

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