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Thermal Expansion of a Leadscrew*

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A leadscrew which is used in an up-to-date machine tool, measuring machine and so on requires very high accuracy. In practical use, a leadscrew may thermally expand due to heat sources such as an oil tank or undoubtedly to frictional heat between the leadscrew and the mating nut. Thermal expansion of a leadscrew lowers the working accuracy of the machine, as if the latter has a pitch error. This paper treats experimental and theoretical analysis on the thermal expansion of leadscrews which are used in a thread grinder and a thread cutting lathe.

As the result, the following are clarified. (1) Theoretical analysis of temperature-rise and thermal expansion due to frictional heat shows good agreement with the experimental results. (2) Thermal expansion of a leadscrew mounted on a thread grinding machine is much influenced by the heat sources such as an oil tank as well as the frictional heat. (3) Thermal expansion of a leadscrew mounted on a screw cutting lathe is exclusively influenced by the frictional heat.

1. Introduction

A leadscrew which is used in an up-to-date machine tool, measuring machine and so on requires very high pitch accuracy.

In practical use, a leadscrew may theoretically expand due to heat sources such as an oil tank or undoubtedly to the frictional heat between the leadscrew lowers the working accuracy of the machine, as if the latter has a pitch error.

In this paper thermal expansion of a leadscrew is investigated theoretically and experimentally. The experiments are done on a leadscrew itself, a leadscrew mounted on a thread grinding machine and one on a screw cutting lathe.

2. Theory on temperature-rise and thermal expansion of a leadscrew due to the frictional heat between the leadscrew and the mating nut

2.1 Temperature-rise

Symbols used in this theory are as follows.

J : mechanical equivalent of heat, kg m/kcal

C : heat capacity of a leadscrew, kcal

F_t : tangential force due to friction between a leadscrew and a mating nut, kg

α : surface heat transfer coefficient, kcal/m² hr °C

A : heat radiating area of a leadscrew, m²

γ : coefficient of linear thermal expansion, 1/°C

L : thread length of a leadscrew over which the mating nut travels and reciprocates, m

ω : rotating speed of a leadscrew, rpm

With the rotation of a leadscrew the mating nut travels and reciprocates along it over the distance L under an axial load P . When tangential force F_t due to friction acts between the leadscrew and the mating nut at the circumferential velocity V , the heat generated during the time dt is given by

$$dQ_0 = \frac{1}{J} F_t V dt \dots\dots\dots (1)$$

Supposing the temperature of the leadscrew higher by θ_s than that of the ambient air, heat dQ_r which radiates from its surface during the time dt is given as follows

$$dQ_r = \alpha \theta_s A dt \dots\dots\dots (2)$$

where A is the surface area of a leadscrew

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without the mating nut.

Heat $(dQ_0 - dQ_r)$ gives the temperature-rise $d\theta_s$ of the leadscrew in the following form.

$$d\theta_s = (dQ_0 - dQ_r) / C \quad (3)$$

From Eqs. (1), (2), (3) and by integrating under the initial condition $\theta_s = 0$ at $t = 0$, the following solution is obtained

$$\theta_s = \frac{F_t V}{J \alpha A} \left\{ 1 - \exp \left(-\frac{\alpha A}{C} t \right) \right\} \quad (4)$$

From Eq. (4) it is supposed that the temperature of the leadscrew rises gradually with the time t and finally saturates at the value of $F_t V / (J \alpha A)$.

The word "temperature" shall mean a temperature-rise above the room temperature hereinafter in this paper.

2.2 Temperature distribution of a leadscrew in its longitudinal direction

In the section 2.1 the temperature-rise of the leadscrew has been treated as uniform over all its length. When we notice a temperature gradient, three-dimensional temperature distribution in the leadscrew as a cylinder must be discussed.

Supposing the leadscrew, however, has hardly any temperature gradient in the radial direction because its diameter is small enough

as compared with the length, we analyze the temperature distribution of a leadscrew in its longitudinal direction as a one-dimensional heat conduction problem⁽¹⁾.

The temperature distribution of a leadscrew in its longitudinal direction may be obtained theoretically by the Nakada and other's method⁽²⁾ in three cases that the leadscrew has an infinite length and has different heat sources as shown in Fig. 1.

Let x be the coordinate in the longitudinal direction of the leadscrew and θ be the temperature at x , and the equation of heat conduction in steady state is given in the following form

$$a \frac{\partial^2 \theta}{\partial x^2} - h'(\theta - \Theta) = 0 \quad (5)$$

where

a : temperature conductivity, m^2/hr

h' : relative heat transfer rate, $2\alpha a / (kR)$

R : radius of a leadscrew, m

and Θ : ambient temperature, $^\circ\text{C}$

(1) In case that the part of the length L of the leadscrew is at a constant ambient temperature θ_0 [see Fig. 1 (a)]:

Under the boundary conditions of $\theta = \theta_0$ at $|x| \leq L/2$, $\theta = 0$ at $|x| > L/2$ and $\theta = 0$ at $x = \pm \infty$, the solution of Eq. (5) is given

$$\left. \begin{aligned} \theta(x) &= \theta_0 \left\{ 1 - \frac{1}{2} e^{-(\sqrt{h'/a})(L/2)} \left(e^{(\sqrt{h'/a})x} + e^{-(\sqrt{h'/a})x} \right) \right\} \quad \text{at } |x| \leq L/2 \\ \theta(x) &= \frac{\theta_0}{2} \left(e^{(\sqrt{h'/a})(L/2)} - e^{-(\sqrt{h'/a})(L/2)} \right) e^{-(\sqrt{h'/a})|x|} \quad \text{at } |x| > L/2 \end{aligned} \right\} \quad (6)$$

(2) In case that the temperature of the leadscrew is θ_1 at $x = -x_1$ [see Fig. 1 (b)]:

Under the boundary conditions of $\theta = 0$, $\theta = \theta_1$ at $x = -x_1$ and $\theta = 0$ at $x = \infty$, the solution of Eq. (5) is given as follows.

$$\theta(x) = \theta_1 e^{-(\sqrt{h'/a})(x+x_1)} \quad \text{at } x \geq -x_1 \quad (7)$$

(3) In case that the part of $x \leq x_2$ of the leadscrew is at a constant ambient temperature θ_2 [see Fig. 1 (c)]:

Under the boundary conditions of $\theta = \theta_2$ at $x \leq x_2$, $\theta = 0$ at $x > x_2$, $\theta = \theta_2$ at $x = -\infty$ and $\theta = 0$ at $x = \infty$, the solution of Eq. (5) is given as follows.

$$\left. \begin{aligned} \theta(x) &= \theta_2 \left\{ 1 - \frac{1}{2} e^{(\sqrt{h'/a})(x-x_2)} \right\} \quad \text{at } x \leq x_2 \\ \theta(x) &= \frac{\theta_2}{2} e^{-(\sqrt{h'/a})(x-x_2)} \quad \text{at } x > x_2 \end{aligned} \right\} \quad (8)$$

(a) In case that the part the of length L of the leadscrew is at the constant ambient temperature θ_0

(b) In case that temperature of the lead-screw is θ_1 at $x = -x_1$

(c) In case that the part of $x \leq x_2$ of the leadscrew is at the constant ambient temperature θ_2

Fig. 1 Three cases of heat source for a leadscrew

2.3 Thermal expansion of a leadscrew

When the temperature distribution is denoted by $\theta(x)$ in the longitudinal direction, the thermal expansion δ of a leadscrew is given as follows

$$\delta = \gamma \int_{-L/2}^{L/2} \theta(x) dx \quad (9)$$

where the origin of the x -coordinate is the midcenter of the stroke over which the nut reciprocates.

As θ_s in Eq. (4) given in the section 2.1 means the average temperature of the leadscrew, θ_s in case that the leadscrew has a temperature gradient in its longitudinal axis is given as follows.

$$\theta_s = \frac{1}{L} \int_{-L/2}^{L/2} \theta(x) dx \quad (10)$$

From Eqs. (4), (9) and (10), δ is given as follows.

$$\delta = \gamma L \frac{F_t V}{J \alpha A} \left\{ 1 - \exp\left(-\frac{\alpha A}{C} t\right) \right\} \quad (11)$$

3. Temperature distribution and thermal expansion in a separated leadscrew

3.1 Experimental apparatus and methods

In order to measure the temperature distribution and thermal expansion of a separated leadscrew due to frictional heat between the leadscrew and the mating nut, the experimental apparatus shown in Fig. 2 (a) and (b) is used. In the apparatus the axial load acting on the nut is given by weights.

The leadscrew, which is designed so as to be mounted on the Ex-Cell-O thread grinding machine, is shown in Fig. 3 (a) and has following specifications:

whole length.....1870 mm,
thread length.....1400 mm,

outer diameter of threaded part.....57 mm ($2\frac{1}{4}$ in), screw thread.....29° trapezoidal, 6 t.p.i., material.....S50C, surface finish.....lathe cut after normalized.

The mating nut, which is designed so as to be mounted on the Ex-Cell-O thread grinding machine, is made of gun metal and the sizes are shown in Fig. 3 (b). The nut travels and reciprocates over the threaded portion of 1 m length of the leadscrew.

The leadscrew has a hole with a diameter of 8 mm along its axis throughout the whole length, and four thermistors are inserted in the hole in order to measure the temperatures at the positions ①, ②, ③ and ④ in Fig. 2 (a). The temperatures at each position are recorded by a pen-ocillo-recorder through a slip-ring and lead wires.

Two measuring microscopes are fixed on the base frame at a distance of about 1 m. Each measuring microscope observes a hair line scratched on the surface of the leadscrew in its field of eye-piece. The thermal expansion of the leadscrew can be measured by a difference

Fig. 3 Sizes of leadscrew and nut

Fig. 2 Experimental apparatus

(b) Photograph

in hair line readings between two microscopes. The apparatus is installed in a temperature controlled room which is kept within the range of $(25 \pm 0.2)^\circ\text{C}^*$ during testing. The base frame of the two microscopes is immersed in an oil with large heat capacitance in order to avoid thermal deformation of the base frame. The apparatus is made carefully to cut off the heat conducting from a thrust bearing or other heat sources to the leadscrew.

The frictional force F_f is measured on the

Fig. 4 Examples of temperature record in case of a separated leadscrew

(a) Temperature distribution in the longitudinal axis of the leadscrew

(b) Average temperature rise

(c) Theoretical expansion

Fig. 5 Temperature distribution, average temperature rise and thermal expansion of the leadscrew in case of $P=20$ kg, $\omega=30$ rpm

arm fixed to the nut by a spring balance during the leadscrew is a rotating one and is converted to a tangential one at the position of an effective diameter of the leadscrew. Since the value F_t differs somewhat by the rotating direction of the leadscrew, the mean values of F_t in the normal and reverse rotation are used for the calculation of Eq. (4). Spindle oil is always dropped to the mating threads at the rate of 0.8cc per minute as lubricant from an oil cup provided on the nut.

The leadscrew is rotated by a powerful electric motor, the rotation of which is reduced by a worm gear reducer (1/40) and a stepless speed reducer.

3.2 Experimental results

Experiments were done by varying the axial load $P=10, 20$ and 30 kg and the rotating speed ω of the leadscrew $\omega=15, 30$ and 45 rpm.

Figure 4 shows two examples of the temperature record under the condition of $P=20$ kg and $\omega=30$ rpm. In the record at the position ② there are two temperature-rises per one longitudinal stroke of the nut as indicated by arrows R_1 , meaning that the nut passes the position ② twice per stroke. On the other hand, in the record at the left end position ④ there is one temperature-rise indicated by an arrow R_2 , meaning that the nut reaches ④ once per stroke. Other records at the positions ① and ③ show similar tendency, too. In spite of complexity in the temperature records, mean curves of these records are adopted for the temperature of the leadscrew.

By this means, a temperature distribution is obtained along the longitudinal axis of the leadscrew, changing as shown in Fig. 5 (a).

In this figure it is seen that the temperature drops gradually toward both ends of the leadscrew.

An average temperature of the leadscrew θ_s was calculated each time using Eq. (10) and the results of Fig. 5 (a).

The relation of θ_s obtained by such a way to the running time t is shown in Fig. 5 (b) with mark $\circ$ and full line, and the relation of the thermal expansion δ measured by the two microscopes to the running time is shown in Fig. 5 (c) likewise.

Consequently it is seen that in case of $P=20$ kg and $\omega=30$ rpm the leadscrew reaches steady state attaining a temperature-rise by 0.9°C and thermal expansion by $10\mu\text{m}$ per 1 meter after about 3 hours' running.

* As the experiment was done in summer, the temperature was set at 25°C by a temperature control device.

Moreover, Fig. 6 (a) is a case that the rotating speed ω varies 15, 30 and 45 rpm under the constant load P of 20 kg and Fig. 6 (b) one that the load P varies 10, 20 and 30 kg under the constant rotating speed ω of 30 rpm.

In a similar way the relations of the temperature-rise θ_s and thermal expansion δ of the leadscrew to the running time t are illustrated in Fig. 6 (a) and (b).

3.3 Discussion

In order to calculate the temperature distribution of the leadscrew in steady state, Eq. (6) was used under the following assumption. That is, it is assumed that the heat source, so called the mating nut, heats the leadscrew uniformly over all the range of length L over which the nut travels.

According to this assumption, the nut

(a) In case of load $P=20$ kg

(b) In case of revolution $\omega=30$ rpm

Fig. 6 Average temperature rise θ_s and thermal expansion of a leadscrew under various conditions of revolutions and loads

temperature θ_0^* (here, $\theta_0=0.85$ °C) is measured in steady state and the result calculated from Eq. (6) is shown by a broken line in Fig. 5 (a).

As the result, the difference between the theoretical and experimental values at 3.3 hours' running enlarges increasingly toward both ends of the leadscrew. The main reason may be that Eq. (6) is derived by regarding the leadscrew as having an infinite length.

In calculating Eqs. (4) and (11) it must be considered that the rotation of the leadscrew is intermittent in order to measure the thermal expansion with the two microscopes.

Let ΔT be this interruption time and T be the time necessary for one stroke of the nut, and these equations are rewritten in the following form.

$$\theta_s = \frac{F_t V}{J \alpha A} \frac{T}{T + \Delta T} \left\{ 1 - \exp\left(-\frac{\alpha A}{C} t\right) \right\} \quad \dots\dots (12)$$

$$\delta = \gamma L \frac{F_t V}{J \alpha A} \frac{T}{T + \Delta T} \left\{ 1 - \exp\left(-\frac{\alpha A}{C} t\right) \right\} \quad \dots (13)$$

In Eqs. (12) and (13) the following values are used for each coefficient, that is,

$$C^{**} = 1.96 \text{ kcal/}^\circ\text{C}$$

$$\alpha^{(1)} = 13.5 \text{ kcal/m}^2 \text{ hr } ^\circ\text{C}$$

$$A = 0.164 \text{ m}^2$$

$$\gamma = 11.0 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$$

$$L = 1 \text{ m}$$

$$\Delta T = 2 \text{ min}$$

$$T = 31 \text{ min } (\omega = 15 \text{ rpm}), 16 \text{ min } (\omega = 30 \text{ rpm}), 10 \text{ min } (\omega = 45 \text{ rpm})$$

and F_t = see Table 1.

Calculating Eqs. (12) and (13) with these values, θ_s and δ are given by a broken line as shown in Fig. 5 (b) and (c).

The full lines in Fig. 6, which show the relation of the thermal expansion δ to the running time t , are theoretical values calculated by Eq. (13). The temperatures at the surface and center of the leadscrew are measured under the condition of $P=20$ kg and $\omega=45$ rpm in order to make sure that the temperature gradient in the radial direction is negligible as supposed in the section 2.2.

As the result, both measured values show

Table 1 The values of F_t

Unit: kg

Load P kg		Revolution of the leadscrew rpm		
		15	30	45
10		—	1.88	—
20		3.44	3.30	3.36
30		—	4.74	—

* The measuring position is indicated with N_1 in Fig. 3 (b).

** $C = 0.1125 \text{ cal/g } ^\circ\text{C} \times \pi d^2 L \gamma' / 4$; d : effective diameter of a leadscrew, γ' : specific gravity

good agreement under the measuring accuracy of about $\pm 0.05^\circ\text{C}$.

4. Temperature distribution and thermal expansion in a lead-screw mounted on a machine tool

The same experiment is done for a leadscrew mounted on machine tools, that is, a thread grinding machine and a screw cutting lathe. These machines have other heat sources than the frictional heat between the leadscrew and the mating nut.

4.1 In case of the leadscrew being mounted on a thread grinding machine

In this experiment an Ex-Cell-O Model 50 thread grinding machine, made in U S A about 1935, was used. The outline of the machine is illustrated in Fig. 7. The leadscrew is rotated by the change gears which are driven by a hydraulic motor built in the head stock of the table, on the other hand the nut is fixed to the bed.

By the rotation of the leadscrew, the table which carries the work piece on it is fed by longitudinally acting a thrust at the right end as shown in Fig. 7. The thread grinder is installed in a temperature controlled room ($20 \pm 0.8^\circ\text{C}$).

4.1.1 Method of experiment

The leadscrew used in the experiment of section 3.1 is mounted on the Ex-Cell-O thread grinding machine. The table is reciprocated over a length of 1 m, the force to thrust the table is 20 kg and the rotating speed of the leadscrew is kept at 15 rpm, corresponding to a work spindle speed of 10 rpm.

Then, the temperature-rise from beginning of the test is measured by thermistors at four positions of the leadscrew axis. The same measurement is done under the state of the table not being moved, that is, the leadscrew not being rotated.

Fig. 7 Schematic diagram of the thread grinding machine used in this experiment

Moreover, the thermal expansion of the leadscrew is measured as follows. A screw, which was previously ground by this machine, was set between both centers of the table and rotated by the headstock spindle as a master screw, that is, a standard yielding no thermal expansion during the table reciprocating.

Here, the thermal expansion may be measured by recording the relative displacement between the leadscrew and the master screw by means of an electric micrometer, the feeler of which is touched to a flank of the master screw.

4.1.2 Results of experiment

Figure 8 (a) shows the temperature distribution of the leadscrew along the axis with the running time t as a parameter. From the figure it is seen that the temperature distribution reaches steady state after 13.5 hours' running.

The same experiment was done under the condition that the table was stationary and the result is shown in Fig. 8 (b). This temperature-rise is due to heats from the hydraulic motor oil, the oil tank and so on as well as the frictional heat generated between the leadscrew and the nut.

Consequently the frictional heat causes a difference in temperature distribution between

(a) In case that the table is traversing.

(b) In case that the table is being stationary
Fig. 8 Temperature distribution of a leadscrew mounted on the thread grinding machine

(a) and (b) in Fig. 8. Thermal expansion of the leadscrew of 1 m in length is calculated by Eq. (9) at various running times. The calculated results of δ_1 and δ_2 are shown in Fig. 9, where,

δ_1 is thermal expansion calculated from Fig. 8 (a)

δ_2 is thermal expansion calculated from Fig. 8 (b).

In the curve, $[\delta_1 - \delta_2]$ in Fig. 9, which shows good agreement with the result at $P=20$ kg and $\omega=15$ rpm in Fig. 6 (a), is due to the heat generated by the frictional heat between the leadscrew and the mating nut.

Fig. 9 Thermal expansion of the leadscrew calculated from Eq. (9) by using the temperature distribution of Fig. 8

(a) Heat sources A and B

(b) Theoretical temperature distribution due to heat sources A and B

Fig. 10 Theoretical analysis of heat sources and temperature distribution in a thread grinding machine

4.1.3 Discussion

The leadscrew mounted on the thread grinder has two heat sources A and B, as shown in Fig. 10 (a), in addition to the frictional heat generated between the leadscrew and the mating nut, where

A: heat source from hydraulic motor oil used for lubrication of change gears, heating the left end of the leadscrew.

B: heat source from an oil tank under the bed, heating the leadscrew by convection and radiation.

(i) On the heat source A; Assuming that the leadscrew is long enough and negligible in the radius, and a part of it is at the temperature θ_1 , the temperature distribution of the leadscrew calculated under steady state by using Eq. (7) of the section 2.2 (2) is shown as θ_A in Fig. 10 (b). The temperature θ_1 measured at the heat source A was 14 °C.

(ii) On the heat source B; The temperature distribution calculated under steady state by using Eq. (8) of the section 2.2 (3) is shown as θ_B in Fig. 10 (b). The temperature θ_2 measured at the heat source B was 6 °C.

The value $\theta_A + \theta_B$ which is calculated from these θ_A and θ_B is shown as a curve A+B in Fig. 10 (b). This curve A+B shows good agreement with the experimental result which is shown by the broken line in the same figure.

Records of the temperature variations at two positions ① and ④ in the axis of leadscrew are shown in Fig. 11.

The temperature of the leadscrew rises every time the nut passes the position ① as indicated by an arrow R_3 [see Fig. 10 (a)].

On the other hand, the temperature falls every time the nut just passes the position ④ as indicated by an arrow R_4 . That is to say, the temperature of the leadscrew is higher at the

Fig. 11 Records of temperature rise in case of a leadscrew mounted on the thread grinding machine

left end than that of the nut under the influence of other heat sources than the frictional heat and it is inverse at the right end. It also means that the nut carries heat of heat source A from the left end to the right end during the reciprocation.

Hence, it may be supposed that the nut plays a role in making uniform the temperature distribution of the leadscrew, and in raising the temperature of the leadscrew gradually by the frictional heat.

The temperature-rise must be discussed over all the length of the leadscrew. However, the measurement at the range of $|x| > L/2$ was not done in this experiment, because of the lack of thermistors. But it is supposed from Eq. (6) that the temperature at $|x| > L/2$ goes down gradually with an exponential function. It was impossible for the reason of structure of the thread grinding machine to measure the temperature of the nut.

4.2 In case of the leadscrew being mounted on a screw cutting lathe

In this experiment a screw cutting lathe Model TF-6 made by SIP Co. Ltd. was used. This machine had been reconstructed as a leadscrew measuring machine with automatic recording equipment⁽³⁾⁽⁴⁾. Fig. 12 shows an outline of its main construction in case of being used as a measuring machine.

The leadscrew mounted on this machine is a trapezoidal screw thread having a pitch of 5.08 mm (5 thread per inch), the outer diameter of 44.20 mm ϕ and a total thread length of 1350 mm (53.1 inch).

4.2.1 Method of experiment

In this screw cutting lathe, the following heat sources are considered other than the frictional heat generated between the leadscrew and the nut: that is, frictional heat from bearings, frictional heat from change gears which drive the leadscrew and the master screw, and Joule's heat generated from the change gears by mixing a lubricant oil in the gear box. Heat from an electric motor which drives the lathe

can be ignored, because the motor is far enough from the leadscrew.

These heat sources are shown by shaded portions in Fig. 12.

Moreover positions where temperature was measured are indicated by signs from ① to ⑫ in Fig. 12.

Number ① is the measuring position of the nut temperature, numbers from ② to ⑦ the measuring positions of the leadscrew temperature and numbers from ⑧ to ⑩ the measuring positions of the master screw temperature. The temperature of the leadscrew or the master screw can be, as described in the section 2.2, measured on their surfaces in place of their axial lines. Then the temperature measurement is done by applying thermistors on the surface for about two minutes while stopping the carriage traverse. Number ⑪ is the measuring position of air temperature around the leadscrew just beneath the gear box, and number ⑫ the measuring position of the gear box temperature being measured by applying a thermistor on it.

Measurement of thermal expansion of the leadscrew may be done by using the fact that the screw cutting lathe is reconstructed as a leadscrew measuring machine.

That is, the thermal expansion may be obtained by the change of readings in electric micrometers at the same position of the master screw [see section 4.1.1] at every reciprocation of the carriage.

4.2.2 Results of experiment

From the results of the temperature measurement, the temperature distribution $\theta(x)$ of the leadscrew in the longitudinal direction with the lapse of time over the range over which the nut reciprocates, corresponding to the master screw from 0 to 157th thread (1 m), is shown in Fig. 13 (a).

Here, it is seen that the distribution becomes steady after about 4 hours. From these results, average temperature-rise θ_s to time is obtained over 1 m of the leadscrew by Eq. (10) and it is shown by a full line in Fig. 13 (b).

Measured results of thermal expansion in the leadscrew are indicated with signs $\triangle$ and a full line in Fig. 13 (c).

It is seen from this result that the leadscrew expands thermally by 8.8 $\mu\text{m}/0.76\text{ m}$ after about 4 hours. A full line and signs $\circ$ in Fig. 14 show temperature distribution in the longitudinal direction in steady state over all the length of the leadscrew.

Fig. 12 Heat sources and temperature measuring positions in the screw cutting lathe "SIP"

4.2.3 Discussion

A broken line in Fig. 13 (b) is a temperature-rise of the leadscrew due to the frictional heat calculated by Eq. (12).

The following values are used for the calculation of Eq. (12), that is,

$$F_t = 3.9 \text{ kg},$$

$$\alpha = 11 \text{ kg/m}^2 \text{ hr } ^\circ\text{C}^*,$$

$$V = 2.34 \text{ m/min (forward)}$$

$$V = 7.80 \text{ m/min (backward)}$$

A broken line in Fig. 13 (c) is the theoretical value of the thermal expansion calculated by Eq. (13). These theoretical values show good agreement with the experimental values.

Temperature distribution along the axis of the leadscrew in steady state may be obtained by Eq. (6) from the same consideration as described in the section 3.3. The calculated results are shown by a broken line ① in Fig. 14. In the left end in Fig. 14, the difference between the line ① and experimental value (a full line) may be explained by the heating from the gear box. The calculation of Eq. (8) in the section 2.2 (3) is done by measuring the air temperature around the leadscrew just beneath the gear box, and the calculated result is shown by a broken line ② in Fig. 14. It is seen that a broken line ①+②, superposed by ① and ②, shows good agreement with the experimental values (a full line).

6. Conclusions

In this study the thermal expansion and the temperature distribution in a leadscrew have been researched in three cases that a leadscrew is separated, mounted on a thread grinding machine and mounted on a screw cutting lathe.

The results obtained are as follows.

(1) The theoretical equations on the temperature-rise, the thermal expansion and the temperature distribution along the axis of a leadscrew due to frictional heat generated between the leadscrew and the mating nut are obtained.

(2) The temperature distribution and thermal expansion of a separated leadscrew due to friction generated between the leadscrew and the mating nut are measured, showing good agreements with the theories.

(3) In the case of a leadscrew being mounted on a thread grinding machine, the temperature-rise and the thermal expansion change are considerably influenced by the other heat sources than frictional heat generated between the leadscrew and the mating nut. The experimental values show good agreements with the theories derived in this study.

(4) In the case of a leadscrew being mounted on a screw cutting lathe the difference

Fig. 13 Temperature distribution of a leadscrew mounted on the screw cutting lathe

Fig. 14 Temperature distribution of a leadscrew mounted on the SIP screw cutting lathe

* This value is obtained from surface heat transfer coefficient α in the section 3.3, for α is in proportion to the square of form size.

between the experimental and theoretical values is seen hardly from the experiments of the temperature-rise and thermal expansion due to friction with the mating nut. Moreover the temperature-rise of leadscrew mounted on the screw cutting lathe used in this study is almost due to the influence of frictional heat generated between the leadscrew and the nut and a little influenced by the other heat sources.

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Discussion

R. ICHIMIYA (Niigata University):

(1) The discussor thinks that it will be more practical if in the screw cutting the surface of the leadscrew is heated by a moving heat source rather than heated by a uniform heat source along the whole length of the leadscrew, and moreover if the temperature rise shown in Fig. 4 is obtained theoretically and the pitch error on each part of the leadscrew is to be calculated.

(2) Leadscrew used on a screw cutting lathe or a thread grinder has considerable height of thread compared with its diameter. And the distribution of frictional heat is not uniform on the surface of the leadscrew and the nut, and also is related to the moving direction of the nut. Therefore the temperature distribution of heat sources is complicated just after the driving starts.

Is it allowed to neglect the influence of the height of thread even in transient state of the temperature distribution?

(3) The authors describe in the section 3.3 that the temperature of the leadscrew on its axial line agrees with the surface temperature. However, the discussor thinks that it is very difficult to measure a temperature of the moving surface exactly. In such a case where the temperature rise is small, the measuring error is comparatively large. The discussor wishes to know how the surface temperature of the leadscrew was measured exactly.

M. SAKAMOTO (Kyushu Institute of Technology):

(4) Is it necessary to fill a hollow hole which is used to measure the axis temperature at its axial line with certain materials?

(5) It seems that in case of $\omega = 45$ rpm in Fig. 6 (a) there are some differences between

the experimental and the theoretical values. How do the authors think about it?

Authors' closure

(1) The authors agree with the discussor's opinion, and such a strict analysis is thought to be possible. But the authors think that an approximation treated in this paper is good enough in the present study. Though it seems academically interesting to get the pitch error variance at each part of the leadscrew in transient state, it is considered an outside problem.

(2) In the authors' study, the height of thread can not be neglected so the coefficient of surface conductance α of the leadscrew is calculated, considering the height of thread⁽¹⁾.

As you point out, the temperature distribution is not uniform along the moving direction of the nut. For simplification, the temperature of the heat source which gives rise to a thermal expansion of the leadscrew is substituted by measuring the temperature on its axial line.

(3) After the rotation of the leadscrew was stopped for a while, that is, during the measurement of the temperature a thermistor-head was laid in the thread groove, contacting to both flanks of the thread, and was covered and fixed by rubber clay.

The temperature was measured after about 1 minute by the recorder, because the temperature saturated after about 1 minute. It must be noted that the rubber clay is not warmed by the heat of fingers. The authors' experience showed that the use of rubber clay was not necessarily indispensable.

Thermistor is sealed in the stainless steel

tube (diameter of 2.5 mm ϕ , length of 150 mm and sensitivity of 0.05 °C) and its time constant is small enough for the measurement.

(4) The hole was not filled with anything. However, both sides of the hole are plugged so that a lubricant oil might not enter. The thermistor was fixed to the inner wall of the hole by an M6 headless screw. The authors consider that the effect of the existence of the center

hole is negligible, because the hole diameter of 8 mm is considerably smaller than the thread diameter of 60 mm.

(5) The experimental and theoretical results do not show good agreement in case of $\omega=15$ rpm or 30 rpm, cause of disagreement seems to be carelessness in the experiment, for instance, a slight displacement of the microscopes during the measurement.