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A Study on Precision Thread Grinding with Numerically Controlled Compensation*

By Akira YAMAMOTO** and Jiro OTSUKA***

For leadscrews used on machine tools or length measuring instruments, requirement of grinding after hardening is increasing. Therefore, ground leadscrews of a higher pitch accuracy are required. Taking into account that one of the causes of pitch error in thread grinding is thermal deformation in the workpiece screw and the grinding machine, it is desirable that the pitch error compensation be performed according to the grinding condition of the workpiece screw. The purpose of this study is to improve the pitch accuracy of ground leadscrews by using the compensation of a numerical control system. The method is as follows: Initially thread grinding without compensation is performed. On the basis of the pitch error obtained in this case, a tape for compensation is punched, and a second thread grinding is performed with the operation of the numerically controlled compensation device. As the result of an experiment, in a ground leadscrew of 1 m in thread length the accumulated pitch error in the whole length was reduced to about $5\ \mu$ by using this device.

1. Introduction

Leadscrews used on machine tools or length measuring instruments have to be hardened and ground, aiming at permanency in their pitch accuracy. Long ball screws being used generally in numerically controlled machine tools must be ground. Therefore, requirement of a higher pitch accuracy for ground leadscrews is increasing.

Causes of pitch error in thread grinding may be classified as follows:

- (1) errors peculiar to the grinding machine, for instance, pitch error of the leadscrew,
- (2) temperature variation of the surroundings,
- (3) thermal deformation of the workpiece due to heat generated during grinding,
- (4) thermal deformation of the machine during running, and others.

Among the above-mentioned causes of pitch error, only (1) can be eliminated by certain devices, for instance, a pitch error compensator using a cam; and (2) can be avoided by installing the machine in a temperature controlled room. Elimination of (3) and (4) is difficult owing to grinding conditions, for instance, workpiece size or rotating speed of workspindle. According to the theoretical and

experimental investigations on (3) carried out by the authors⁽¹⁾, this is recognized as a very complicated problem. Therefore, it is desirable that pitch error in thread grinding be compensated in accordance with the grinding conditions.

It is the purpose of this paper to get a leadscrew of a higher pitch accuracy using a thread grinding machine equipped with a numerically controlled pitch error compensation device. Its process is as follows:

- (i) a thread is ground without operating the error compensation device, (called "test grinding" or "test ground thread" in this paper);
- (ii) pitch error of the "test ground thread" is measured;
- (iii) a tape for numerical controlling is punched so as to compensate the measured pitch error;
- (iv) then, the thread is ground operating the numerically controlled error compensation device (called "compensation controlled grinding" or "compensation ground thread" in this paper).

Y. Fukuda has investigated the error compensation of the index angle in a hobbing machine equipped with a numerically controlled device⁽²⁾, and the present paper is nothing but an application of his idea to thread grinding. But it must be noted that thread grinding has inherent problems, for example, thermal deformation of the workpiece as mentioned above.

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** Professor, Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology.

*** Graduate student, Tokyo Institute of Technology, Meguro-ku, Tokyo.

2. The numerically controlled error compensation system used in this experiment

2.1 Thread grinding machine

An Ex-cell-0 precision thread grinding machine type 50 is used with some modifications for the experiment. This machine can grind thread lengths up to 1270 mm (50"). The operating principle of the machine is shown in Fig. 1. The workspindle, to which the leadscrew is connected by means of a gear train, is rotated by a hydraulic motor mounted in the workspindle head. The thrusting force of the rotating leadscrew shifts the table on which a workpiece is mounted longitudinally, while the nut in which the leadscrew is engaged is fixed to the machine-bed.

2.2 The pitch error compensation device

The error compensation device is shown in the

Fig. 1 Operating principle of the thread grinding machine and the error compensation device

Fig. 2 Mechanical parts of the error compensation device

Fig. 3 The thread grinding machine and the error compensation device

portion enclosed by broken lines in Fig. 1. To the original table movement caused by the rotation of the leadscrew, a small displacement for the pitch error compensation is added. The angle of rotation of a pulse motor is converted to a small displacement by means of a planetary type reduction gear and a differential screw. Their details are shown in Fig. 2. The angle of rotation of the shaft in the pulse motor A is reduced in the ratio 1/150 by the planetary type reduction gear B (360° rotation of the shaft being done in 48 pulses), and the reduced angle is transferred to the differential screw C, the end of which is connected to the shaft of the planetary type reduction gear by a bellows coupling. The differential screw, which consists of two threaded parts having pitches 2.75 mm and 3.00 mm respectively, acts as if it had a pitch of 0.25 mm. After all, one rotation of the pulse motor shaft is converted to a small displacement $5/3 \mu$ of a table

movement. There exists a backlash in the planetary type reduction gear and its amount is converted to a table movement of about 1μ , while it is considered that there is no backlash in the differential screw because the thrusting force of the leadscrew acts in one direction.

The force required to move the table is 20 kg, and the power to drive this system is gained only from the electric power of the pulse motor and no hydraulic power is used. A photograph of the thread grinding machine and the error compensation device is shown in Fig. 3.

The tape reader and the pulse motor driving device are manufactured by Fujitsu Co., Ltd., named "FANUC 6050". The punched tape on the tape reader is fed by the command pulse synchronized with the micro-switch sign taken from the workspindle rotation. Maximum amount of the compensation possible from one command pulse is 4.4μ (127 pulses). This system needs an interval of 1.5 sec from a command pulse to another and when the interval is shorter, out-of-balance* takes place in the pulse motor.

2.3 Preliminary test of the control system

Before the mechanical parts of the error compensation device are attached to the grinding machine, it is checked

* Out-of-balance means that, when a command pulse is given while the pulse motor is rotating, the latter cannot move as commanded, due to the inertia of the moving parts.

whether this system can be driven as commanded under the condition that a force of 20 kg is applied to the end of the differential screw as shown in Fig. 4. The result shows that the device satisfies the above requirement.

Next, the mechanical parts are fixed to the grinding machine and it is checked whether the system can be driven with a small feed of the table, corresponding to the number of pulses. The method is shown in Fig. 5 (a). An electric micrometer is fixed on the wheel base and its feeler is made to contact the flank of a thread which was ground beforehand. Then the machine is driven under the same conditions as in thread grinding. When a certain number of pulses corresponding to 10μ of the table displacement is given to the system, the feeler deflection is recorded as shown in Fig. 5 (b). (As mentioned in Section 2.2, the number of pulses that can be given at a time is limited to 127, corresponding to 4.4μ . Therefore, the displacement of 10μ is divided, for instance, into 4.4, 4.4 and 1.2μ , which are given successively.)

As was described in Section 2.2, a backlash of 1μ is observed in Fig. 5 (b). In the same figure a small wave having an amplitude of about 1μ is seen, which may be due to the drunkenness of the leadscrew in the machine.

Fig. 4 Preliminary test on the error compensation device before it was attached to the thread grinding machine

(b) A record of the electric micrometer
Fig. 5 Preliminary test on the error compensation device after it is attached to the thread grinding machine

3. Experimental method

3.1 Temperature and pre-running

3.1.1 Room temperature

The grinding machine is installed in a temperature controlled room of 25°C^* . The room temperature, as shown in Fig. 6, varies periodically at intervals of 20 min. within the range of $\pm 1.4^{\circ}\text{deg}$, and the temperature at the center of the workpiece varies within a very small range. The resulting thermal expansion of a workpiece of 1 m in length may be limited to less than $\pm 0.5\mu$. Therefore the effect of the room temperature variation on the grinding machine may be neglected.

3.1.2 Pre-running

Grinding process is started after 1 hour of pre-running, and finished after the same predetermined number of grinding strokes, in both cases of "test grinding" and "compensation controlled grinding". Prerunning has a great influence on the pitch accuracy owing to thermal deformation of the machine as will be mentioned in Section 5.2.

3.2 Grinding conditions

3.2.1 Grinding fluid

Two kinds of grinding fluids, that is, oil and water soluble oil are generally used in thread grinding. According to the authors' investigation⁽¹⁾ they have opposite effects on pitch accuracy. In the case of grinding with oil, repetition of the grinding stroke causes a temperature-rise of the workpiece due to accumulated grinding heat, and the thermal expansion cannot be neglected. Accordingly pitch error tends to be negative.

In the case of grinding with water soluble oil, evaporation of the fluid has a greater influence on the workpiece than the grinding heat. The fluid remaining on the surface of the workpiece is abruptly evaporated by the wind from the rotating grinding wheel. This lowers the temperature of the

Fig. 6 Recorded temperature of the room and the workpiece

* The selected temperature of 25°C is due to the lack of control capacity of the air-conditioner, though it is proper that the temperature should be set at 20°C .

workpiece beneath the room temperature, and the workpiece contracts. But in the next grinding and thereafter the temperature distribution along the axis of the workpiece becomes very stable. In the case of grinding with oil, temperature control of the fluid is inevitable, but in the case of grinding with water soluble oil it is unnecessary.

Taking the above mentioned properties into account, water soluble oil* is used for the experiment. The fluid is splashed on the workpiece in the neighbourhood of the grinding wheel during grinding stroke but not during backward stroke.

3.2.2 Workpiece and grinding wheel

The workpiece used in the experiment is shown in Fig. 7. Its specifications are as follows: thread length-1 m, outer diameter-50 mm, thread profile-29° trapezoidal thread, threads per inch-4, material -0.5% carbon steel, heat treatment (after thread cutting)-induction quenched and tempered ($H_{RC}=50\sim55$).

The specifications of the grinding wheel are as follows: material-WA, grain size-80, grade-L, outer diameter-420 mm, circumferential speed-24 m/sec, dressing speed-30 mm/sec.

The grinding starts on the tailstock side and ends on the headstock side, and is performed on one side flank of the thread. The workspindle speed is 10 rpm and it takes about 16 min for a grinding stroke.

3.3 Measurement of the workpiece temperature

The workpiece has a hole with a diameter of 6 mm and a depth of 150 mm as shown in Fig. 7 and a thermistor element is inserted in it to measure the temperature of the workpiece at its axis during

Fig. 7 Design of the workpiece used in the experiment

Fig. 8 Pitch measurement of the ground thread

grinding. By the recorded temperature, thermal expansion or contraction of the workpiece can be estimated⁽¹⁾.

3.4 Measurement of pitch error

For pitch measurement, a SIP screw cutting lathe is used with some modifications. Both the grinding machine and the pitch measuring machine are installed in the same room. Two gauge heads are made to contact the common helix of the thread at an angle of 180° to each other as shown in Fig. 8. Measuring accuracy in 1 m in length is 5 μ *, and repeated accuracy is 3.5 μ as will be described in Section 4.3. Measurement should be carried out after a duration of more than 5 hours after grinding, because it takes about 5 hours for the workpiece temperature to coincide with the room temperature.

4. Experimental results

4.1 Repeatability of positioning accuracy in the grinding machine

After the ground thread is kept for one day in the room the repeatability of positioning accuracy is investigated by the same method as shown in Fig. 5 (a). An electric micrometer is fixed on the wheel base and its feeler is made to contact the flank of the ground thread. While the grinding machine is running under the same conditions as in thread grinding, the feeler deflection is recorded. This is done once a day and repeated three times. The result is shown in Fig. 9. From this figure, it is seen that the repeatability of positioning accuracy in this machine is within 3.5 μ throughout the table movement of 1 m.

4.2 Temperature variation in the workpiece during grinding

Figure 10 shows the temperature variation in

Fig. 9 Repeatability of positioning accuracy in the thread grinding machine

Fig. 10 Temperature variations of the workpiece and the grinding fluid during grinding

* It contains an inorganic salt and amin, and is dissolved in water of 50 times in volume.

* Calibration was done by a SIP standard scale of 1 m in length.

the workpiece during grinding. As mentioned in 3.2.1, the temperature variations during the 2nd grinding stroke and thereafter are almost identical. Under such a temperature distribution, the workpiece contracts by about $20\ \mu$ in the longitudinal direction⁽¹⁾.

4.3 Pitch errors of the ground thread before and after error compensation

4.3.1 Compensation controlled grinding

Pitch error measurement of the "test ground thread" is repeated three times at several hours interval. From the average of these results, the number of pulses is calculated and a tape is punched for compensation.

The tape is fed when the command pulse synchronized with the workspindle is given. In case the amount of compensation per rotation of the spindle is too large, this is properly distributed to the neighbouring threads.

4.3.2 Result of error compensation

Accumulated pitch errors at the following flank of the ground thread before and after compensation are shown in Fig. 11. Figure 12 shows the result of repeated measurements on "compensation controlled ground thread". From this figure it is seen that the accuracy in repeating the pitch measurement is about 3.5. Accumulated pitch errors in the

leading flank of the thread are shown in Fig. 13. Initial "compensation controlled grinding" (shown by A in the figure) shows an accumulated pitch error of $10\ \mu$. Both results of "compensation controlled grinding" in Figs. 11 and 13 have the same tendency, representing the fact that the expected amount of grinding is not being performed in the portion where the compensation is made comparatively large. The second "compensation controlled grinding" (shown by B in the figure) is repeated, using the same tape for compensation as before and under the same grinding conditions as the initial "compensation controlled grinding". As a result, the accumulated pitch error is reduced to about $5\ \mu$ in the thread length of 1 m. The reasons will be described in Chapter 5.

Figure 14 shows an example of registered lead error (accumulated pitch error), and Fig. 15 shows the drunkenness error of the ground thread⁽³⁾.

5. Considerations

5.1 Unequalness between the actual amount of grinding and the expected amount of compensation

As mentioned in Section 4.4, a tendency for unequalness between the actual amount grinding and the expected amount of compensation is observed. This is caused by the poor rigidity of certain parts, the grinding wheel, workpiece, tailstock, headstock and so on. By checking the elastic deformation of these parts, it is found that the rigidity of the wheel spindle is the poorest of all.

Fig. 11 Accumulated pitch errors at the following flank of the "test ground" and "compensation controlled ground thread"

Fig. 12 Repeatability of pitch measurement

Fig. 13 Accumulated pitch errors at the leading flank of the "test ground" and "compensation controlled ground threads"

Fig. 14 An example of registered lead error

The relation between the actual depth of grinding τ and the grinding force F_n is expressed experimentally as follows⁽¹⁾ [see Fig. 16 (a)],

$$\left. \begin{aligned} F_n &= k_1 \tau \\ k_1 &= 0.055 \text{ kg}/\mu \end{aligned} \right\} \dots\dots\dots (1)$$

On the other hand, the relation between the elastic displacement δ_n' of the grinding wheel and the force F_n (applied and measured by a spring-balance) is expressed experimentally as follows [see

Fig. 15 Drunkenness of the ground thread

Fig. 16 Illustration for elastic displacement of the grinding wheel

Fig. 16 (b)],

$$\left. \begin{aligned} F_n &= k_2 \delta_n' \\ k_2 &= 0.20 \text{ kg}/\mu \end{aligned} \right\} \dots\dots\dots (2)$$

Assuming that Eq. (2) is valid even during grinding, eliminating F_n in Eq. (1) and Eq. (2), the relation between τ and δ_n' is expressed as

$$\left. \begin{aligned} \delta_n' &= (k_1/k_2) \tau \\ k_1/k_2 &= 0.275 \end{aligned} \right\} \dots\dots\dots (3)$$

In order to ascertain the above relation, the following experiment is performed. The thread is ground with the operation of the numerically controlled device so as to get a ground thread having a pitch error against the table movement as shown by the full line in Fig. 17. In the next place, the thread is ground without the operation of the controlling device and its pitch error δ_n against the table movement is measured and shown by the broken line in Fig. 17.

In the third place, the thread is ground under the same conditions and its measured pitch error is almost zero. The value δ_n' calculated by Eq. (3) is shown by the chain lines in the same figure. δ_n and δ_n' show good agreement.

In order to prevent the displacement of the grinding wheel at the initial grinding, the tape should be punched, taking elastic displacement of the wheel, for instance by Eq. (3), into consideration.

According to the authors' investigation⁽¹⁾ the grinding force in case of grinding with oil is about one fourth of that with water soluble oil, and therefore, in grinding with oil the above mentioned consideration may almost be unnecessary.

It is supposed that wear of grinding wheel may influence pitch accuracy^{(4) (5)}. However, an estimation using the Ono's experiment shows that it is negligibly small after grinding a thread of 1 m in length.

5.2 Influence of thermal deformation of the grinding machine on pitch accuracy

The grinding machine used in the experiment has many heat sources which may cause thermal

Fig. 17 Experiment about elastic displacement of the grinding wheel during grinding process

deformation of the machine. Observation of the electric micrometer in the same arrangement as shown in Fig. 5 (a) during continuous reciprocal movement of the machine table, shows that it takes about 13.5 hours till the thermal deformation of the machine reaches a steady state and the accumulated pitch error varies $65\ \mu$ per meter from the commencement of operation of the machine. Most of this pitch error variation seems to be caused by the thermal expansion of the leadscrew.

In order to avoid the influence of thermal deformation of the machine, both "testing grinding" and "compensation controlled grinding" should be carried out after the thermal deformation reaches a steady state. But in this study, both grinding operations are carried out after the same duration of prerunning for saving time. If this is impossible, a punched tape should be designed so that the amount of error compensation may include the influence of the thermal deformation of the grinding machine.

6. Conclusion

A numerically controlled pitch error compensation is applied to an ordinary thread grinding

machine, and its effect is studied. As the result, a ground leadscrew having an accumulated pitch error of about $5\ \mu$ throughout the thread length of 1 m is finally obtained.

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