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Development of a new lapping method for high precision ball screw (2nd report) Design and experimental study of an automatic lapping machine with in-process torque monitoring system

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Abstract

This paper presents a new approach in lapping process in making appropriate condition to improve the manufacturing operations for ball screw. After grinding, high precision ball screw is lapped by highly skilled operators. These operators have the ability to control and maintain the lapping conditions by sensing the lapping torque manually. Prior to lapping process, the effective diameter must be measured to find out the effective threaded profile along the screw shaft. The section which has a large effective diameter will be primarily lapped wherein the lapping torque is high. The aim of this study is to establish a control scheme on the automatic lapping machine for high precision ball screw in both measuring and finishing process. A prototyped horizontal lapping machine with in-process torque monitoring system has been designed, built, and tested. This is to determine the relationship among lapping torque, effective diameter, and error on travel to establish the measurement system to control the finishing operations efficiently and eventually improve and eliminate the various sorts of error components in a ball screw. The experimental results showed that the new lapping method could adequately predict the effective diameter and error on travel by observing the lapping torque.

Keywords: Ball screw; Lapping; Effective diameter; Drunkenness; Lapping torque; Automatic lapping machine; Error on travel

1. Introduction

Ball screw is a precision screw mechanism, which is designed for rolling contact that uses steel balls between a screw shaft and a nut to transfer the force and motion for accurate positioning and higher speed in linear movement. Unlike any conventional power transmission screw, which needs to overcome sliding friction between the screw and the nut threads, ball screw which operates similar to bearing components could achieve high mechanical efficiency since it eliminates relative contact motion between the threaded surfaces [1–3]. This makes the device a highly efficient low friction linear driving mechanism. Likewise, the rolling contact also cuts back on wear, so this efficiency lasts for extended life in high and low load applications. Fig. 1 illustrates the typical ball screw design mechanism.

In recent years, precision ball screws are widely used in various manufacturing industry for advanced technologies. They are heavily utilized in the field of mechatronics for semiconductors, PCBs, robotics, and other motion control applications. The demand has grown almost equal to that used in machine tools. Considering this increasing demand and broadening range of applications together with end-users need to design better products and processes, the need for improving ball screw quality and performance should be continuous [4].

High precision ball screws are lapped as a finishing method after grinding by a highly skilled machine operator to improve the threaded surface profile and lead accuracy. The existing method of manufacturing is labor intensive

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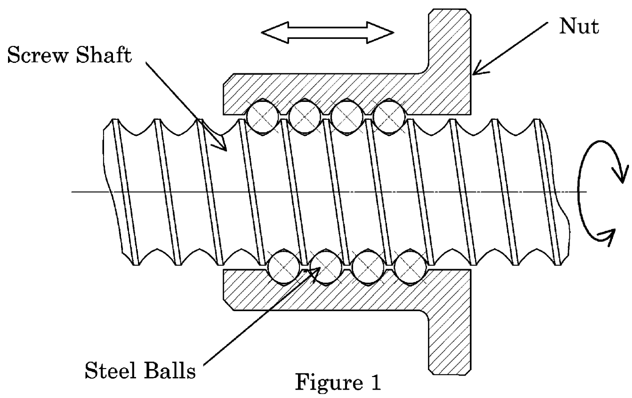

Fig. 1. Typical design of precision ball screw.

and requires specialized skilled to perform the manual lapping operations that needs both measuring and finishing processes. The skilled operator has the ability to control and maintain the lapping condition, which relies entirely on his feel particularly the high lapping torque. Thus, it will be difficult for only a semi-skilled operator to produce the high precision ball screw.

In addition, despite of the ever growing demand for ball screws, there are few research works about the process of enhancing its performance and product quality that can be found concerning the lapping method itself [5–7]. Important contributions to the understanding of lapping performance are given through theoretical and experimental investigations by Kyusojin et al. [8] and Kyusojin and Inada [9]. Therefore, this paper deals on prototype development of an automatic lapping machine to evaluate the suitability and feasibility with in-process torque monitoring system as a new approach of manufacturing technique for ball screw. It aims to control the operational system that could perform both finishing and measuring process to improve the special component of drunkenness, travel variation, and effective diameter. In this regard, a prototype automatic lapping machine for ball screw was designed, manufactured, and tested. The outcome of this work can be useful in identifying the areas of cost-effective measures and improvement to meet the much needed demands of today's emerging advanced technologies in the industry and academy as well.

2. Conventional lapping technique

In normal lapping method, after grinding, a high precision ball screw is being lapped by a highly skilled operator using a lathe-type lapping machine. A two-slit lap or commonly called as adjustable ring lap usually made of cast iron (FC 20) is used with a fixture as holding device to enable the operator to control the fine adjustment of lapping pressure. But before the lapping process takes place, the operator must measure the workpiece to determine the tapered profile of screw shaft and the difference in effective diameter using ball-point micrometer. An adequate amount of lapping compound is charged on the larger effective diameter. This section will be primarily lapped wherein the high lapping torque can be detected.

Table 1
Manual lapping operational conditions

Machine used	Lathe-type
Speed of rotation	200 rpm
Abrasive grains	FO#400, FO#600
Lapping oil	Rape oil
Lapping time	40 min

Any size of ball screw is held in the universal chuck of the conventional lapping machine. This machine has rotational speed of about 200 rpm and it has a lever that manually shifts the movement of lapping tool from left to right and vise versa. For instance, if the effective threaded length of a workpiece is less than 150 mm, it should be held only in the chuck, while in the case of a long workpiece it should be supported by the tailstock with live center to hold the work in center-to-center position and provide rigidity during operations. However, as indicated in Table 1, it takes about 40 min lapping time for a workpiece with 300 mm effective length of thread. Thus, this conventional process is very complex, time consuming, and low production efficiency.

3. Description of the new type automatic lapping machine

This section describes the design consideration and technical features of the new type lapping machine.

3.1. Design concept

The new type automatic lapping machine, as illustrated in Fig. 2, is horizontal in structure and especially designed and manufactured to function like a highly skilled operator who handle the typical lapping method. Developing such control scheme requires a method for sensing the shape and lead errors of the ball screw through lapping torque, to enable the implementation of an effective finishing process for optimization of the system. Unlike the lapping machine that was stated in the previous report [10], the basic concept applied in the new lapping machine is to incorporate the process of sensing the lapping torque directly through servomotor and drive system which has high resolution feedback device. The signals from the sensor can make the control decisions to maintain the operational parameters within critical constraints and evaluate the screw shaft profile or deflection and proceed to the optimum location for appropriate lapping range. Furthermore, the machine was developed to be more simple and compact in size but complete with all important machine elements.

This new type lapping machine is composed of highly reliable machine components for linear motion application and it is built with close tolerances to conform with the standard

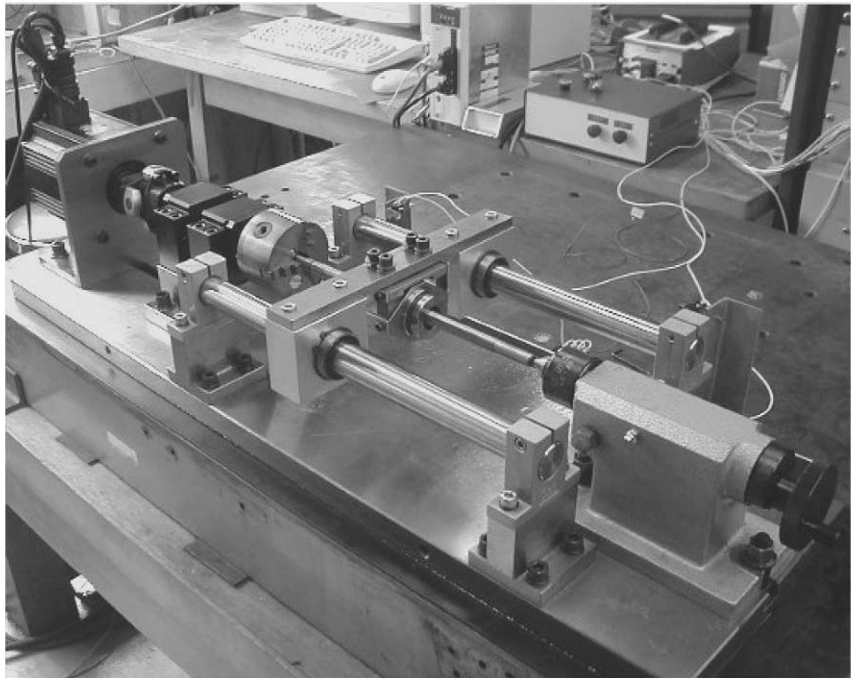

Fig. 2. Photograph of the prototyped automatic lapping machine.

requirements for such machine tool. The drive-train includes an AC servomotor with the drive controller connected through a flexible coupling to a spindle shaft that is built with high stiffness wherein the universal scroll chuck is securely fasten. The ball-type linear motion guide mechanisms with low frictional resistance and high performance are selected for high precision requirement.

3.2. Mechanism of the lapping tool assembly

The essential feature of the new lapping method is the uniquely designed lapping tool assembly which is composed of flexible lapping tool holder and new type lapping tool, as shown in Fig. 3. These two major components are attached to lapping tool carriage which was designed not only as a basic component to support and hold the latter major parts but also to secure the precise linear movement during lapping process. The flexible lapping tool holder is supported by two pairs of leaf springs and polyurethane rubbers. It can sway and move simultaneously with any polygonal cross-sections of the workpiece so that the peak and valley portions can be lapped uniformly. Thus, it is also designed to eliminate the effect of eccentricity from the rotation of the workpiece due to deflection and deformation of screw shaft caused by dimensional errors on effective diameter. According to the theory [8], the center of the workpiece must coincide to the center of lapping tool to effectively remove any polygonal components. On the other hand, the new type lapping tool with six slits has a balance mechanism that produces uniform lapping pressure from six directions radially to eliminate and improve lead

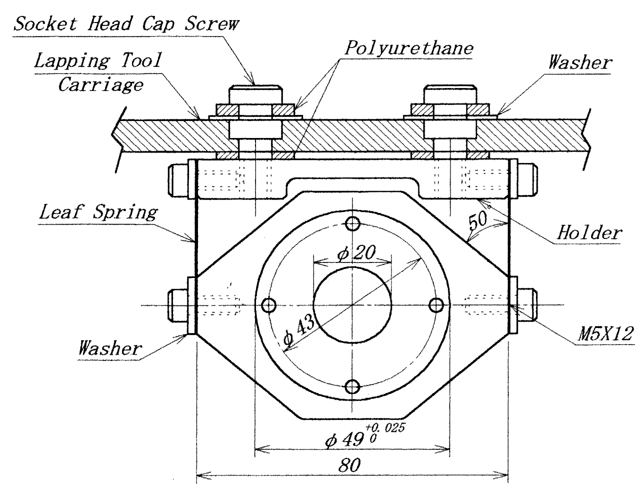

Fig. 3. Lapping tool assembly.

errors and special components of drunkenness. The complete descriptions can be found in the previous report [10].

4. Experimental apparatus and procedure

The performance test was carried out to determine the capability and operational feasibility of the new type automatic lapping machine with in-process torque monitoring system to establish a control system in both measuring and finishing processes. The experimental apparatus used in this study is presented in Fig. 4. It consists of personal computer, A/D board, pulse motor controller (PMC) board and AC servomotor with driver.

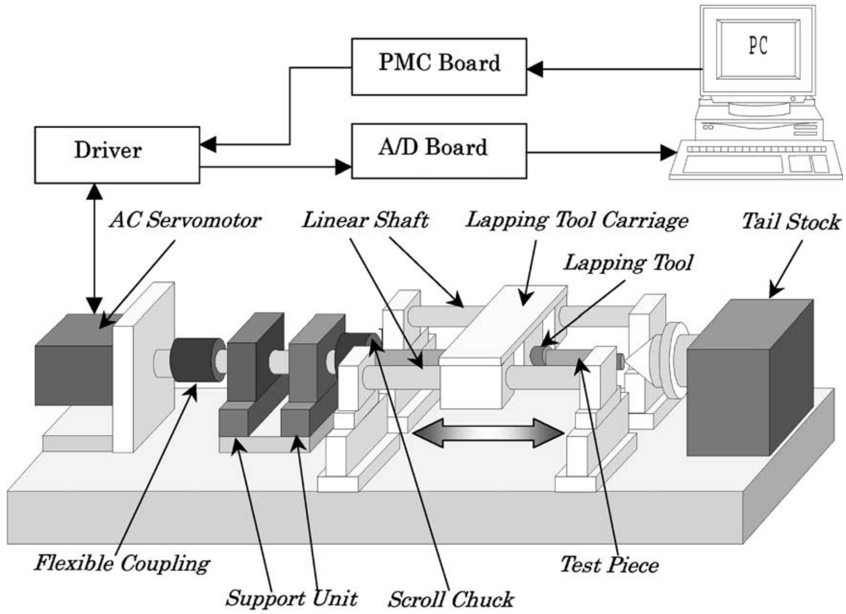

Fig. 4. Schematic diagram of the prototyped automatic lapping machine.

In lapping experiment, the test piece, which is engaged with the lapping tool, is held in the scroll chuck and tailstock with live center. The starting position can be set and adjusted using the jog and running functions of the motor driver, which has a built-in display and touch panel to control and monitor any process applications such as torque, motor speed, and positioning commands. PMC board to the driver controls the experimental system and the motor rotates clockwise and counter-clockwise directions through the master controller, which is the personal computer. The lapping tool assembly will move in linear motion from left to right and vise versa when the workpiece is turned by the servomotor. The measurement of lapping torque came from the voltage output from the servomotor that was detected by means of the driver. The torque data, which is from the measurement of 12 points on each one lead, was measured from the output signal and inputted into the computer through A/D board.

4.1. Experimental conditions

The ball screw shaft is made of alloyed steel (JIS SCM 415) with hardness range of 58–62 HRC. The threaded surface is rough ground with the accuracy grade of C5 as specified in JIS B 1192:1997 for ball screw. The outside screw diameter is 14 mm, 2 mm lead, and 240 mm effective threaded length. It is lapped with the commercially prepared lapping compound, which had a mixture of abrasive grain (FO#600) and rape oil at a volume ratio of 1:1 and was charged with adequate amount on different portion of the screw shaft only at the start of every lapping process. The initial friction torque was set at a range of 1.8–2.2 N·m by tightening the adjustable screw of the lapping tool. This was adequately re-adjusted so that the lapping torque between the workpiece and the lap would be maintained at the average torque of 2 N·m. The lapping speed used was set at 200 rpm which is the same speed being used in conventional lapping operation while the lapping range used was about 100 leads with an allowance of 10 leads at each side of the test piece. The experimental lapping conditions are summarized in Table 2.

4.2. Test measurements

The test measurements were conducted 1 day after every lapping experiment to avoid the effect of lapping heat that will cause thermal errors on the test piece. The experiments were performed inside a controlled room temperature of 20°C and 50% relative humidity. The automatic lead measuring instrument has a laser interferometric tracking system that was used to measure the lead errors of the test piece which was represented by error on travel. The measurement of effective or pitch diameter was measured using the newly developed automatic effective diameter measuring device to obtain continuous data (12 points per revolution) necessary to compare the results from other measurements.

The overpin diameter of the test piece was measured through a three-wire method using digital micrometer, which

Table 2
Experimental conditions

Speed of rotation	200 rpm
Abrasive grain	FO#600
Lapping oil	Rape oil
Cycle rate	5 cycles/5 min
Lapping range	200 mm (100 leads)
Lapping torque range	1.8–2.2 N·m

has a resolution of 1 μm, with the standard three pin gauge of 1.5875 mm in outside diameter. This diameter is of the same size as the steel balls used in ball screw mechanism. This is to determine the lapping amount after each lapping process and measure the absolute values in every 10 leads along the effective threaded length of the screw shaft.

5. Results and discussion

This section explains the relationship among lapping torque, effective diameter, and error on travel to ascertain the technical feasibility and performance efficiency of the new type automatic lapping machine to meet the objectives of this study.

5.1. Influence of lapping torque on effective diameter and error on travel

The correlation analysis range observed in this study is from 30th lead to 90th lead where the optimum lapping process takes place. This is because the whole teeth of the lapping tool traveled over this range.

The relationship between effective diameter and lapping torque is shown in Fig. 5(a) and (b). The result in the graph indicates that the linear relationship is very strong between the two variables. A high correlation coefficient of 0.77 was obtained before lapping. After 10 cycles of lapping the result increased to 0.91. This value indicates that the relation between the lapping torque and the effective diameter is linear to each other. These results prove that when high lapping torque is detected, it indicates that there is a large effective diameter at that certain location of the workpiece. This can be easily interpreted because the tools and forces acting on them during individual process are both in radial direction. Hence, it can be determined that the effectiveness of in-process torque monitoring system have significant factor to establish the intelligent process control for measurement and finishing operations of ball screw.

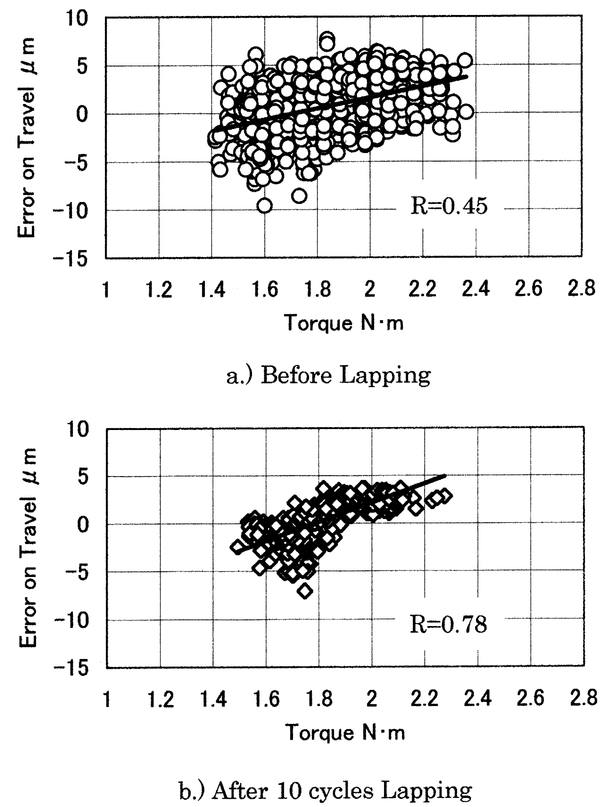

Fig. 6. Relationship between error on travel and lapping torque. (a) Before lapping. (b) After 10 cycles lapping.

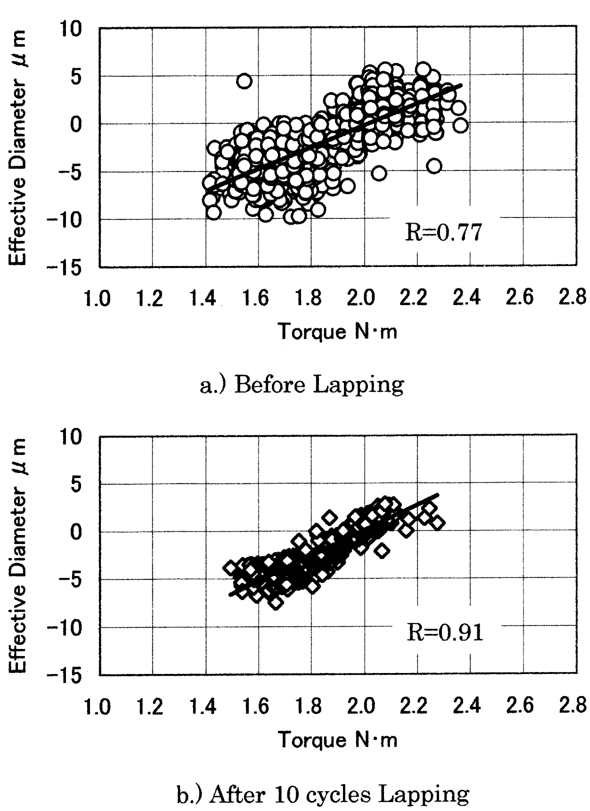

Fig. 5. Relationship between effective diameter and lapping torque. (a) Before lapping. (b) After 10 cycles lapping.

In the case of lead error, it is observed in Fig. 6(a) and (b), that the correlation coefficient of 0.45 before lapping is not strong enough due to the fact that the initial results of error on travel that measured after grinding process was considerably large. However, after 10 cycles of lapping process the lead errors and surface finish of the workpiece were improved. Thus, the correlation coefficient remarkably increased from 0.45 to 0.78, which showed the closeness of linear relationship between error on travel and lapping torque. This revealed that the new type automatic lapping machine has a high predictable performance to improve the travel variation and special components of drunkenness.

The changing process of overpin diameter after every lapping cycle is presented in Fig. 7. The overpin diameter test

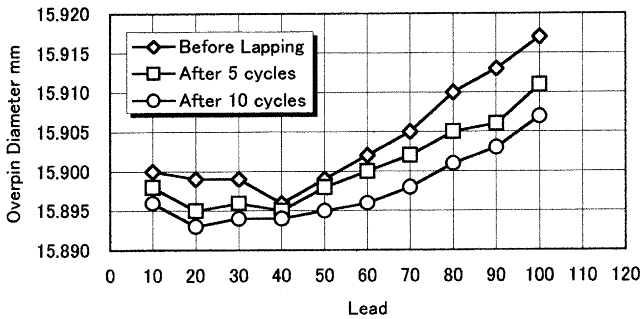

Fig. 7. Changing process of overpin diameter.

measurement was conducted three times in every 10 leads after each lapping process to increase the reliability of results and the mean values were used to accomplish and evaluate the curves. The figure indicates the deformation and tapered profile of the screw shaft before lapping wherein the large dimensional errors were measured from 60th lead up to 100th lead. The results showed that the portion which had a large overpin diameter, had a high removal of lapping amount due to higher lapping torque that took place at this point. While in the smaller portion at 40th lead, only an ample lapping amount was removed. The average lapping amount removal of 2–3 μm was achieved in every lapping cycles except in the range of larger overpin diameter which has the maximum stock removal of 3–6 μm after 10 cycles of lapping process.

5.2. Analysis on lead errors

Fig. 8(a) and (b) illustrates the changing process of travel variation before and after lapping process using the new type lapping machine and the previously developed lapping tool with six slits. The results of the graph were obtained from the calculated values based on data of error on travel through least square method to get the maximum width of the actual travel curve, as the travel variation. Fig. 8(b) showed the remarkable improvement of lead accuracy particularly the rapid decrease of travel variation after short lapping cycles. The results indicate that the experimental conditions used have considerable effect on the overall performance of new type lapping machine which is significantly contributed by proper monitoring and control of lapping torque and its newly designed mechanisms.

Moreover, the curve shows that the travel variation was greatly reduced from 17.42 μm to 9.20 μm after only 10 cycles of lapping process. The rate of reduction that was achieved in the experiment was better than the previously reported lapping method [10]. Evidently, the results revealed that the new lapping system could improve any sort of lead errors for short lapping period.

The polygonal components and amplitude of drunkenness at each lapping stage is shown in Fig. 9(a) and (b). The large error components were caused by grinding process

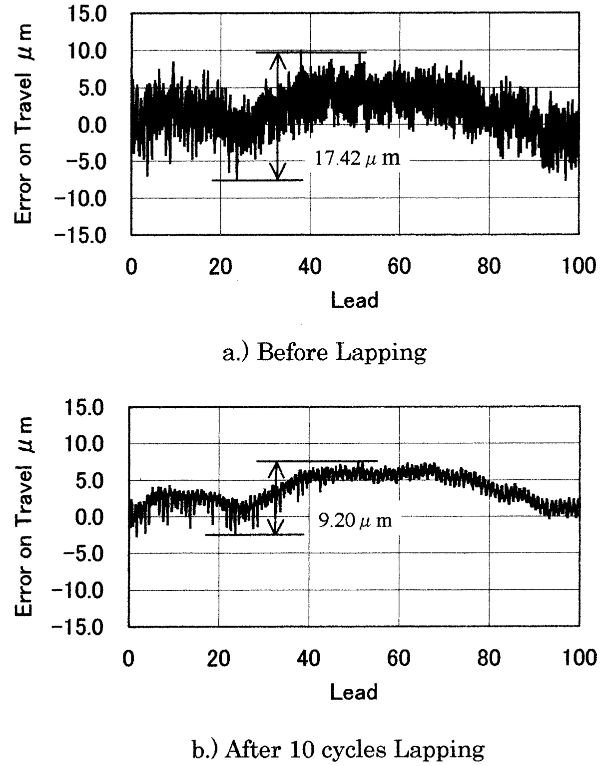

Fig. 8. Changing process of travel variation (a) Before lapping. (b) After 10 cycles lapping.

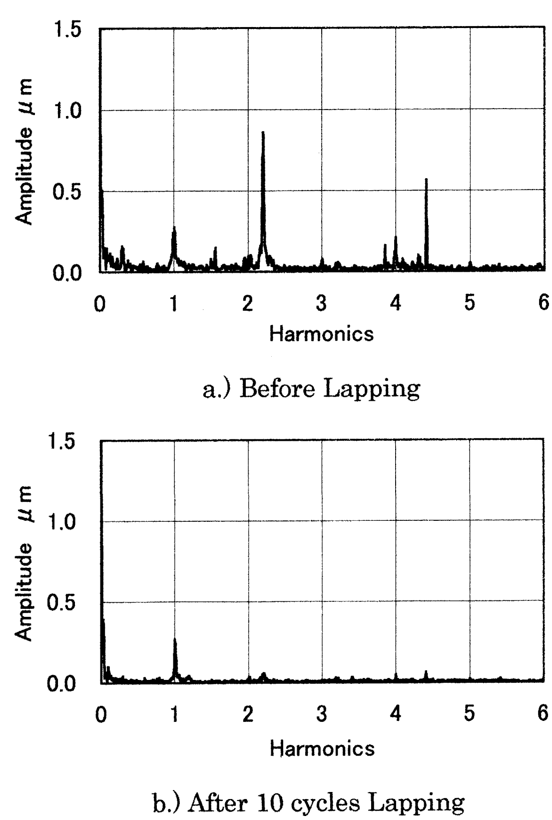

Fig. 9. Variation of amplitude on harmonic analysis in each lapping period. (a) Before lapping. (b) After 10 cycles lapping.

which affected the lead accuracy of the screw shaft. The frequencies in the experimental results illustrate the two protrusive peaks of spectra that appeared on two- and four-lobed cross-sectional shapes which is represented by ellipsoidal and square components of drunkenness, respectively. The results show that the two-lobed component decreased rapidly from 0.81 μm to 0.05 μm while in the case of four-lobed component, it was greatly reduced from 0.57 μm to only 0.03 μm. The average reduction rate of about 90% for the two components was obtained in a very short lapping process.

6. Conclusions

From the performance evaluations of the newly developed automatic lapping machine, the following conclusions were made:

1. The results in correlation analysis proved that the very strong linear relationship among lapping torque, effective diameter, and error on travel with high correlation of coefficient could establish a control system with monitoring function as a new approach of manufacturing technique for high precision ball screw.
2. The experimental results showed that the new lapping method could adequately predict the effective diameter and error on travel by observing the lapping torque.
3. The value of travel variation was significantly reduced from 17.42 μm to 9.20 μm in a short period of lapping time. The results signified that the new lapping method could enhance the lead accuracy and special components of drunkenness.
4. The reduction in cycle time will increase the production efficiency and reduce manufacturing cost without deteriorating the quality and accuracy of the workpiece.

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