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Development of a new lapping method for high precision ball screw (1st report)-feasibility study of a prototyped lapping tool for automatic lapping process

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Abstract

Ball screws are being lapped as a finishing process to improve the travel variation, drunkenness and surface finish in order to provide high precision requirements in various mechanical applications. However, the existing manufacturing method is very labor intensive that needs a highly skilled machinist to perform the hand lapping operations using the conventional laps which have two or three slits. These types of lap cannot eliminate and improve the special components of drunkenness such as ellipsoidal, triangular and other polygonal cross sections. This paper presents a new lapping method to determine the technical and operational feasibility of a prototyped lapping tool with the combination of a flexible lap and polyurethane elastomer which can be mounted in the vertical-type automatic lapping machine. This new type lapping tool with six slits, is especially designed which each section can move in radial direction wherein the uniform lapping pressure is applied on the test piece from six directions. Based on experimental results, it showed that the travel variation was greatly reduced along with drunkenness and lapping time.

Keywords: Ball screw; Lapping; Travel variation; Drunkenness; Error on travel; Lead error

1. Introduction

Ball screw is a precision machine element that uses steel balls between a screw shaft and a nut to transfer the force and motion which convert rotary into linear movement when screw is turned. They are being extensively used for accurate and high speed positioning to drive linear axes of machine tools, robotics, metrology instruments and numerous high precision applications.

Generally, the ball screws are lapped as a finishing operation to improve the lead accuracy, drunkenness and surface finish in order to provide high precision requirements in various mechanical applications. However, the existing manufacturing method is very labor intensive that needs a highly skilled machinist to perform the hand lapping operations using the conventional two or three slits lap. These types of lap cannot eliminate and improve the special components of drunkenness such as ellipsoidal, triangular, and other polygonal components. Recently, there are very few operators who are engaged in this specialized skill which becoming a serious problem in manufacturing industry. Y.P. Chang et al. [3] pointed out that because of lack of detailed understanding of the process mechanisms, fine tuning and process development for a new product has always been an empirical process with success dependent upon the skill of machine operator and engineer.

However, there have been few studies about the process of the lead accuracy enhancement and as to what kind of lapping method are advantageous to improve and eliminate the various sorts of error components in a screw shaft. Kyusojin et al. [1,2] reported that the theoretical analysis of the cylindrical lapping with new kind of lap, which had lapping teeth that are moving in radial direction, can rapidly decrease all components of any polygonal cross-sections. Therefore, this study aims to develop a new lapping method with high accuracy have been significantly considered to meet the much needed requirements of the industry. It is hoped that the findings from this study can be useful in

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Table 1
Operational conditions of conventional lapping process

Machine Used	Lathe-type
Speed of Rotation	200 rpm
Lapping Compound	FO #600
Lapping Oil	Rape Oil
Lapping Time	40 min for JIS—C3

identifying areas of weakness or lack of knowledge to those who are responsible for the technological advancement in manufacturing industry.

2. Present Trend of Conventional Lapping Process

2.1. Hand lapping operations

The existing condition of manual or hand lapping process operations which is being operated by a highly skilled machinist using lathe-type lapping machine. Table 1 shows the operational conditions of the conventional lapping process.

For manual or hand lapping operations, a 2-slits lap or commonly called as adjustable ring lap is used with a fixture which is a tool holding device to secure the operator in any distortion and heat being generated when metal surfaces of both tool and work adhered to one another. Hand lapping demands specialized skill of the operator, upon whom the quality and accuracy of the end-product should largely depend. Specifically, lapping a workpiece like "ball screw," skill is definitely required, since the proper lapping condition particularly the lapping pressure and speed depend on his feel and judgment. Furthermore, in all manual lapping, an ever changing contact must be made between the lap and the work. This will result in uniform lap wear and stock removal, good size control and better surface finish.

2.2. Conventional lapping tool

The conventional type lapping tool shown in Figure 1-a) is simple in design and usually made of gray cast iron (JIS FC20) and cut partially at the middle, to make it 2-slits lap. The threaded portion is made of smooth surface and close to size and shape of the ball screw. The length of the lap is just enough to operate easily with the workpiece because longer length of lap will be difficult and uncomfortable to handle, as it is imperative that it is adjusted tightly to the work that might affect the process. This lap is used with a fixture and adjustable screw, as shown in Figure 1-b), to enable precision adjustment to be maintained and controlled easily. However, when the screw is tightened, as the arrow shown in the figure, the lap can create only two (2) contact area on the work as the lapping progresses. Consequently, it can only make the lap into an elliptical shape which it became difficult to attain the true shape of a ball screw.

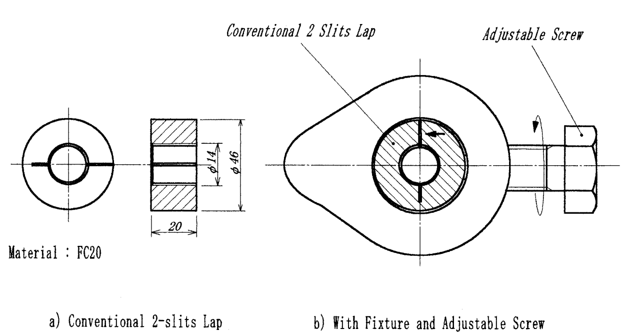

Fig. 1. Typical design of conventional lapping tool.

Table 2
Removal of polygonal components *n* using the given *k* angles of the lapping tool

		Regular Polygon of *k* Angles							
n	*k*	2	3	4	5	6	7	8	9
Ellipse	2		●						
Triangle	3	●		●					
Square	4		●		●				
Pentagon	5	●	●	●		●			
Hexagon	6				●		●		
Heptagon	7	●	●	●		●		●	
Octagon	8		●				●		●
Nonagon	9	●		●	●			●	

3. Details of the new type lapping tool

3.1. Theoretical analysis of cylindrical lapping

The theory of cylindrical lapping established by Kyusojin et al. [1] is applied in this study to correct the sorts of error component and eventually improve the lead accuracy of the ball screw.

In this theory, it is assumed that the shape of cross-sectional profile of the lapping tool is in the form of a regular polygon (with k angles) that is used to lap a workpiece. During lapping process, the lap is in contact with the external surface of the workpiece tangentially and it was calculated how the center of the lap shifts according to the shape of the workpiece. The results are presented in Table 2. The blanks in the table indicated that both centers of the lapping tool and the workpiece always coincide with each other. After lapping the workpiece, all protruded portions are eliminated to make the shaft contour accurately round. While the dotted marks (●) signify the lapping tool is turned eccentrically according to the uneven profile of the workpiece. In this case, the hill and valley portions are lapped uniformly. Hence, no amount of lapping is effective in bringing the workpiece contour into a high roundness. Therefore, a lapping tool that turns eccentrically cannot eliminate some lobed components of the workpiece.

Figure 2 illustrate the locus of the lap center (G) in the

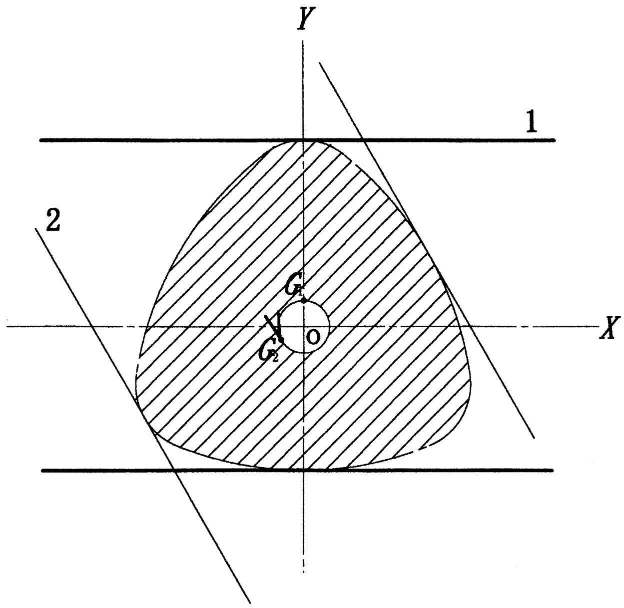

Fig. 2. Locus of conventional lap center.

triangular component of the cylindrical shaft. The two set of parallel lines represent the contact point of the conventional 2-slits lap. The first parallel line turns counter-clockwise from position 1 to position 2 along the triangular shape of the workpiece, thus the center of the lap shifts from G_1 to G_2. Consequently, no protruded portions of the workpiece are eliminated using the conventional lap.

3.2. Design consideration and mechanism of the new type lapping tool

Based on established theory of cylindrical lapping, the basic concept have been considered to design the new type lapping tool. According to the theory, the center of the workpiece must coincide to the center of the lapping tool to reduce the travel variation, as indicated in the Table 2 (i.e., $k \geq n+2$). However, if the number of k angles or slits increases both centers may be unmatched because of too much flexibility, excessive motion of the lapping may occur. Nevertheless, the prototyped or new lapping tool was designed and fabricated which can apply the pressure uniformly into the center of the workpiece along the outside surface. The detailed design and specifications of new type lapping tool assembly are presented in Figure 3 and Table 3 respectively.

Table 3
Specifications of the new type lap

Total Length	57 mm
Outside Diameter	49 mm
Adjusting Stroke	2–4 mm
Number of Slits	6
Screw Shaft Diameter	14 mm
Length of Lap	30 mm
Weight	1.0 kg

The significant feature of the new type lapping tool is the combination of the two major parts, namely the flexible lap and rubber-like part (polyurethane). The flexible lap has 6 slits consisting of 3 slits on each side which were cut alternately at 120°apart, as shown in Figure 3. This lap has a balance mechanism because it has more contact areas on the workpiece to produce uniform lapping pressure from six directions, as compared to the conventional lap which has only two pressure points. In addition, the adjustable screw will move in downward axial direction when it is tightened. This is to compress the tool squeezer (polyurethane) to generate even movement in radial direction simultaneously with lapping teeth toward the center axis of the workpiece which will provide stable frictional force during lapping

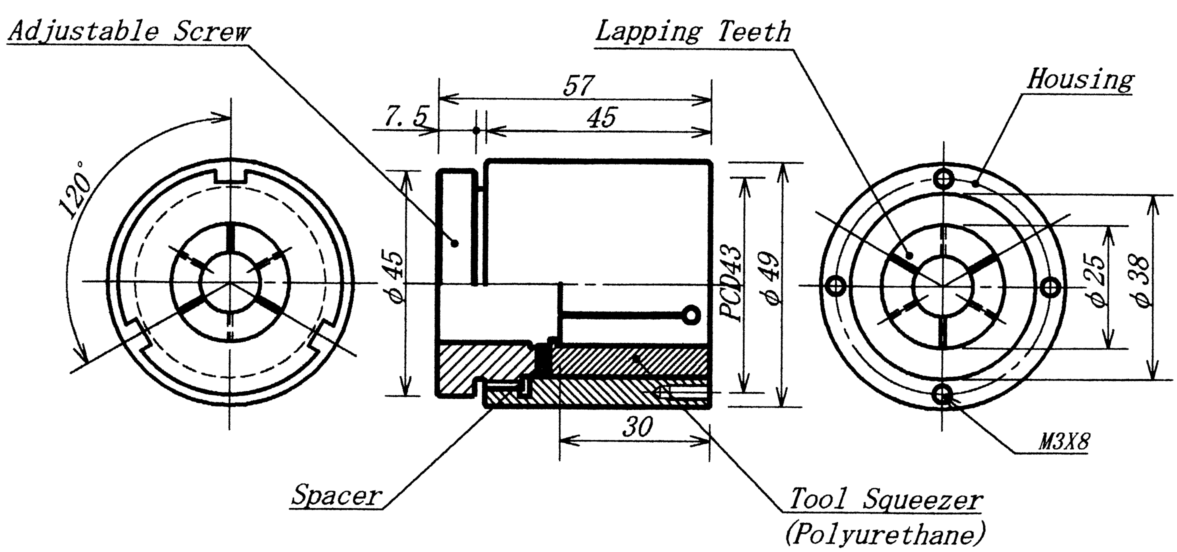

Fig. 3. New type lapping tool design.

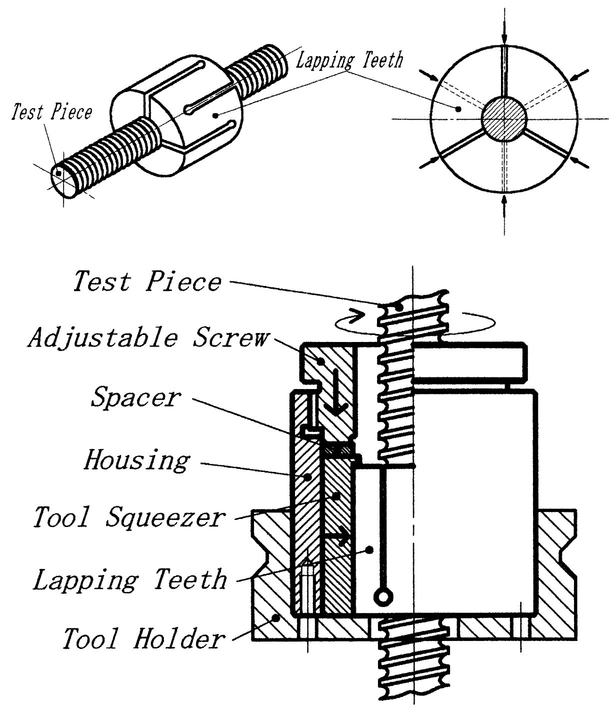

Fig. 4. Mechanism of the new type lap.

process, as shown in Figure 4. Therefore, this new type lapping tool is expected to improve travel variation, drunkenness and even enhance the surface finish of the ball screw.

4. Experimental apparatus and method

4.1. Specifications of the test piece

The test piece used in this experiment, is made of structural alloyed steel (JIS SCM415) which is the commonly used material for ball screw because of its excellent properties such as, low deformation to heat treatment, good hardenability and grindability. Likewise, it is case hardened through carburizing within the range of 58–62 HRC to ensure its toughness and has a good resistance to impact force and wear. Before lapping, the test piece is ground to enhance the surface finish and to achieve the required dimensions and tolerances. The detailed specifications of the test piece are given in Table 4.

4.2. Vertical-type automatic lapping machine

The lapping machine used in this experiment is shown in Figure 5. The vertical-type automatic lapping machine was especially designed and constructed to perform lapping process like a highly skilled machinist handles the lapping operations. This machine can sense the interactions of the lapping tool, abrasive grains and the ball screw through the load cell that is installed in the tool carriage. The load cell senses the lapping torque generated during lapping process which, in this case, is the same as how the skilled machinist feels the lapping and friction torque applied on the workpiece.

Table 4
Specifications of the test piece

Effective Length of Threaded Part	260 mm
Screw Shaft Outside Diameter	14 mm
Lead	2 mm
Lead Angle	2° 46′
Steel Ball Diameter	1.5875 mm
Accuracy Grade Code	JIS–C5
Heat Treatment	Carburizing
Hardness	HRC58 ~ 62
Material	JIS SCM415
Screw Groove	Gothic Arch
Twist Direction	Right

The automatic lapping machine consists of control board, personal computer, A/D board, PMC/PIO board, AC servo motor, load cell and stepper motor.

The test piece, which is engaged with the lapping tool, is held in the chuck and live center of the tailstock. The lapping tool assembly that is attached on the tool holder of the carriage, and which is supported with pneumatic air, moves upward and downward with the rotation of the test piece.

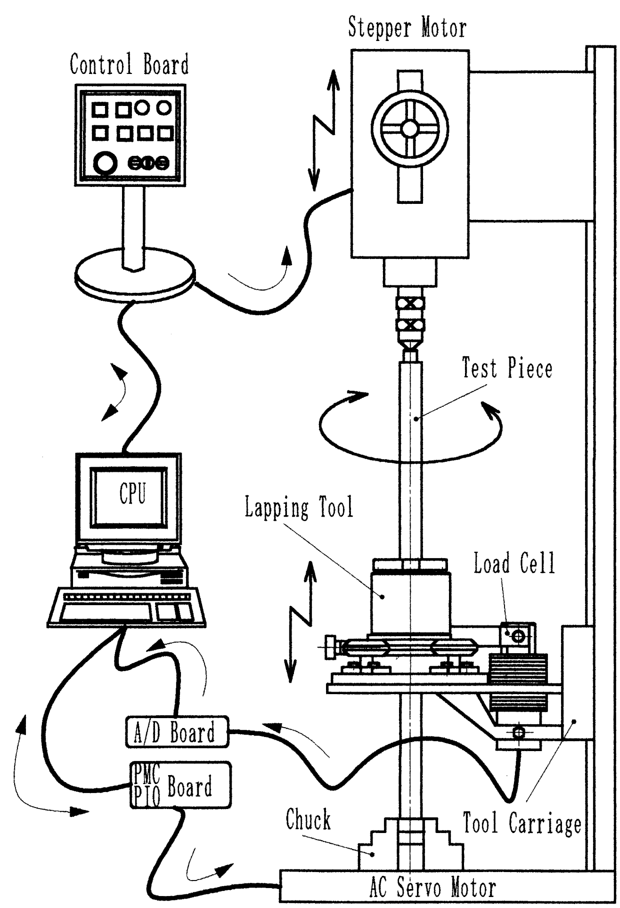

Fig. 5. Schematic view of the automatic lapping machine.

Table 5
Lapping conditions

Speed of Rotation	200 rpm
Lapping Compound	FO #600
Lapping Oil	Rape Oil
Number of Cycle	8 Cycles/5 min.
Lapping Torque Range	1.2–1.4 N · m
Friction Torque Range	1.8–2.2 N · m

The personal computer reads where the lapping range was set from the rotation of AC servo motor, which rotates clockwise and counter-clockwise motion and is being controlled by PMC/PIO board. The control board is used to setup the test piece in the machine and to start the lapping operation. In particular, it controls the major operation of the machine such as upward and downward movement of tailstock, the rotation of the chuck by AC servo motor and the coolant system. The lapping torque is detected by the load cell and the torque measured is inputted into the computer through A/D board.

4.3. Experimental conditions

The experiment is conducted using vertical-type automatic lapping machine. The lapping conditions are summarized in Table 5 and the experimental conditions used in this study are discussed, as follows :

1. The test piece is made of alloyed steel (JIS SCM415) which was heat treated at the hardness range of 58 to 62 HRC. The threaded surface was rough ground with the accuracy grade of JIS - C5. It had a outside screw diameter of 14 mm, lead of 2 mm and effective threaded length of 260 mm.
2. The lapping speed used was set at 200 rpm which is the same speed being used in hand lapping operations
3. Lapping range was about 200 mm which is equivalent to 100 leads
4. The lapping compound used was a mixture of FO#600 and rape oil at about a volume ratio of 1:1. It was applied on different portions of the screw shaft at the beginning of every lapping process
5. The friction torque range used was set from 1.8 to 2.2 N · m using torque wrench after adequately re-tightened the adjustable screw at three different points of the screw shaft. While the lapping torque range used was about 1.2 to 1.4 N · m

5. Results and discussion

This section explains the difference between the two lapping tools to ascertain the technical feasibility and performance efficiency to meet the objectives of this study.

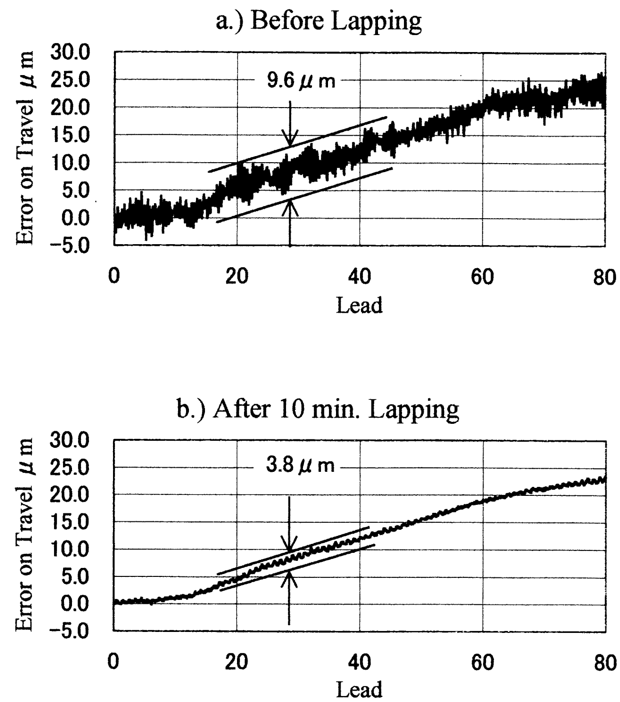

Fig. 6. Changing process of error on travel using new type lap.

5.1. Data analysis of the new type lapping tool

5.1.1. Error on travel

Figure 6(a-b) presents the changing process of error on travel before and after lapping process. The lead test measurement was performed for four (4) times after each lapping process to make the data more reliable and the calculated average from the measured leads was used to accomplish the graphs. The figure shows that the curve of the actual travel in relation with travel variation and drunkenness were reduced significantly and the curve almost became smooth after the final lapping.

Moreover, the actual mean travel, which is represented by straight line, indicates gradual improvement on the final result. The effect of this outcome was caused by the grinding condition before lapping, thus the error from grinding process can not be improved by lapping alone. Since lapping is a process of removing small amount of material to refine and correct minor imperfections on the surface of the workpiece.

The figure indicates that the maximum width of the actual travel curve, as the travel variation, was obtained from the calculated values based on data of error on travel through least square method. The graph showed the remarkable decrease of travel variation on final lapping time. The findings indicates that the experimental and lapping conditions used have a positive effect on performance of new type lapping tool.

In addition, the maximum width value of the travel variation before lapping was about 9.60 μm and this value according to JIS standard for ball screws, is pertaining to

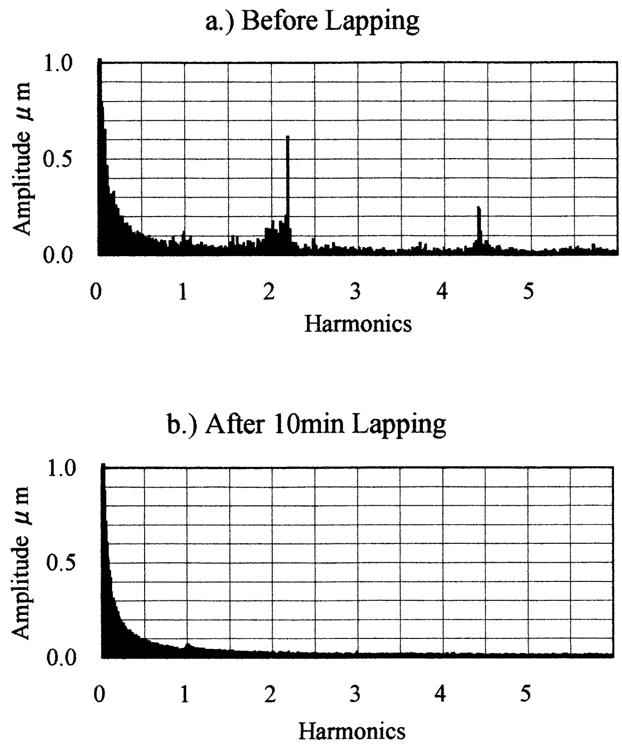

Fig. 7. Changing process of Fourier coefficients using new type lap.

accuracy grade code which is equivalent to C5. This type of grade is not within the required accuracy grade used in the ball screw production. The commonly used grade of accuracy is at least C3 code or a drunkenness value of approximately 2 to 3 μm before lapping. However, for experimental purposes such value was used in this study. As a final result, after 10 min lapping, the travel variation was greatly reduced to only 3.8 μm which is equivalent to C3 of accuracy grade. Furthermore, the lapping process was finished in a very short period, which the 75% reduction in lapping time was achieved as compared to manual or hand lapping process. Clearly, the results showed that the new type lapping tool can improve the travel variation, despite of the fact that the test piece is out of standard condition before lapping.

5.1.2. Frequency analysis

Figure 7 displays the harmonics amplitude at each lapping time. The frequencies showed in the figure was based on calculated values using Fourier transform which is obtained from the data of the lead measurement of error on travel. The frequency before lapping indicates the amplitude highlighted by the two peaks which is represented by ellipsoidal and square components of drunkenness. The ellipsoidal component has an initial amplitude of about 0.62 μm and this was greatly reduced to only 0.03 μm while the square component decreased rapidly from 0.25 μm to just 0.01 μm at final lapping time. This indicates that the new type lapping tool can absolutely eliminate the specified components of drunkenness.

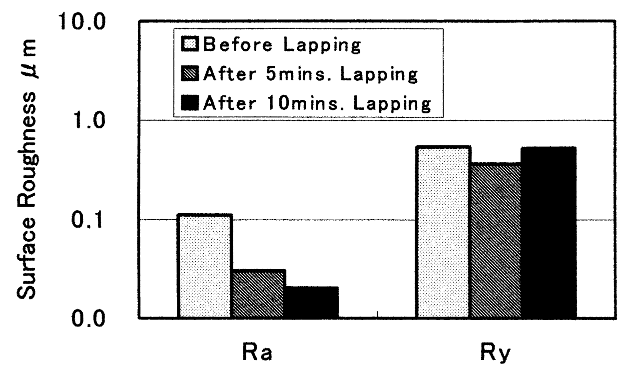

Fig. 8. Surface roughness on rotational direction.

Furthermore, the results of the surface roughness using the new type lapping tool are presented in Figure 8. The behavior of the graphs showed appropriate improvement of surface finish in the rotational direction for a short period of time. From these data, the effect of lapping pressure and the amount and size of lapping media supplied on the test piece have significant factors on the enhancement of the surface roughness.

5.2. Comparison of results between conventional and new type lapping tool

This experiment was conducted to compare the performance between the conventional and the new type lap to determine their suitability for automatic lapping process.

5.2.1. Error on travel

The changing process on error on travel using conventional lapping tool is illustrated in Figure 9 (a-b). The same measurement procedures as the new type lapping tool was done and the average values were used. The figure illustrates that the axis of ordinate represents the error on travel while the axis of abscissa represents the measured leads of the test piece. The results of the curve of actual travel show gradual reduction until the last lapping time. It indicates insignificant effects on the travel variation and drunkenness which are important parameters to be improved. While in new type lapping tool, these parameters reveal sound effects in a rapid rate of lapping process.

In the figure, the curve shows that the travel variation was reduced from 14.5 μm to 10.5 μm which is still within the accuracy grade of JIS - C5. In the case of new type lapping tool, about 6 μm reduction of travel variation was achieved for short period of lapping process compared to conventional lapping tool the reduction is 4 μm for 45 min of lapping time. These results pointed out that the 2-slits lap has the drawback due to its form and it is difficult to improve the travel variation and even the drunkenness for short period.

5.2.2. Frequency analysis

The changing process of Fourier coefficients using the conventional 2 slits lap is shown in Figure 10. The frequencies in

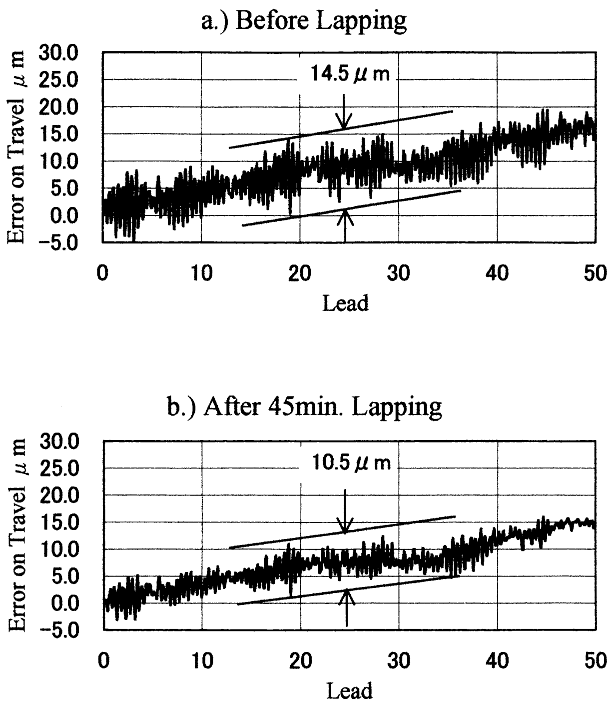

Fig. 9. Changing process of error on travel using conventional lap.

the figure illustrate the two peaks apparently exist on ellipsoidal and square components which the same behavior appeared on new type lapping tool. This condition proves that the sorts of error component are brought by grinding process which affected the lead accuracy of the test pieces. The results show that the ellipsoidal component decreases from 0.54 μm to 0.23 μm while the square component reduces from 0.34 μm to 0.13 μm. The reduction rate of the two components on the frequency is about 40% before lapping until the final lapping time. This reduction is not enough to express significant improvement on the components of drunkenness. Compared to new type lapping tool, these components can be removed due to stable gripping torque that produce homogeneous pressure on the test piece during lapping process.

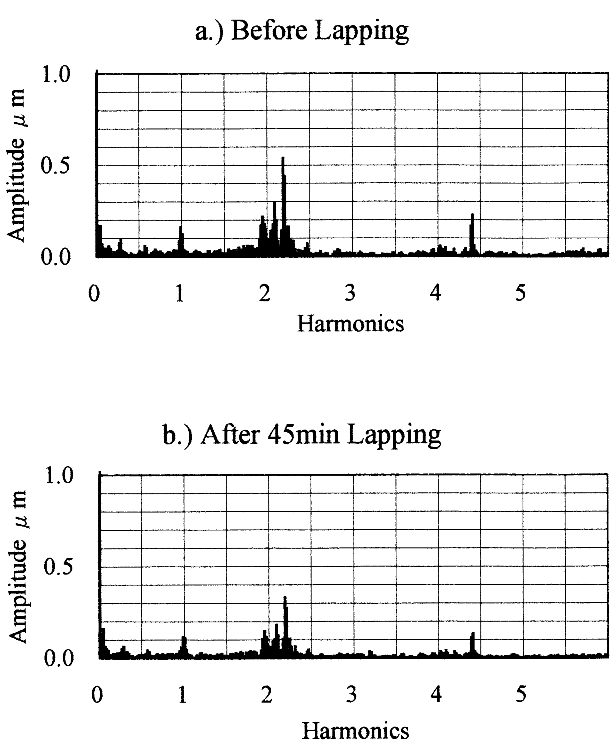

Fig. 10. Changing process of Fourier coefficients using conventional lap.

Therefore, the results of the experiment conducted on the conventional lap proved that the theoretical analysis with 2 slits or in the case of $k = 2$, were unable to eliminate such harmonic components. Hence, this type of lapping tool may not be recommended for use with the automatic lapping machine.

6. Conclusions

Based on experimental results, using the new lapping method and as compared and analyzed with conventional lap, this study indicates that:

1. The values of travel variation were greatly reduced from 9.6 μm to 3.8 μm in a short period of lapping process. The result proved that the new type lapping tool can improve the travel variation effectively
2. The results of error on travel using new type lapping tool were analyzed through frequency (Fourier coefficient). After 10 min of lapping, the harmonics component with the maximum amplitude of about 0.62 μm before lapping was decreased rapidly to only 0.03 μm. This revealed that the new lapping tool can eliminate any components of drunkenness particularly from two to six lobes.
3. The lapping time was reduced remarkably to only 10 min as compare to conventional lap of 45 min and even with hand lapping process of about 40 min

These findings provide evidence that new type lapping tool studied can effectively operate with the automatic lapping machine and eventually improve the lead accuracy, drunkenness and surface finish to meet the needed requirements in high precision manufacturing industry.

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