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lapping, linear motor lathe, mirror-like surface, high quality and productivity

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LAPPING FOR MIRROR-LIKE FINISH ON CYLINDRICAL INNER AND END SURFACES USING THE LATHE WITH LINEAR MOTOR

Lapping is an old traditional machining process that has been useful all along in the human history. Uniform surface finishing by manual hand lapping on cylindrical inner and end surfaces are very difficult. Additionally, the geometrical form accuracy and productivity are lower. In a previous study, the new lapping method for outer cylindrical surface using the lathe with linear motor has been reported. However, this method could not be applied directly for the cylindrical inner and end surfaces. Therefore, lapping for mirror-like finish on cylindrical inner and end surfaces using the lathe with linear motor is investigated. In this study, lapping tool was modified from previous study to be suited for the cylindrical inner and end surfaces. Then, lapping methods for inner and end surfaces were developed for uniform mirror-like finish. Surface roughness and geometrical form accuracy improvement were measured for both surfaces. The optimum conditions for high productivity and high quality mirror-like surfaces were investigated. It was concluded from the results that, the developed lapping system was able to process mirror-like surface on cylindrical inner and end surfaces. Moreover, the optimum conditions for the mirror-like surfaces were revealed experimentally.

1. INTRODUCTION

Inner surface quality of high precision machine components such as injection pump cylinders and hydraulic cylinders are critical for many industries. Additionally, mirror-like surface is required for high quality precision parts. Recently, linear motor applications [2,3] in machine tool industries have been developed for high productivity. In a previous study [4], we developed a high-speed lapping technology for mirror-like finish on outer cylindrical surface by using the lathe with linear motor. However, this method could not be

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applied directly for the cylindrical inner and end surfaces. A new method and arrangement of lapping system are required for inner and end surfaces.

Therefore, the research concerning about the lapping technology for mirror-like finish on cylindrical inner and end surfaces using the lathe with linear motor was carried out. At first, a suitable lapping system for cylindrical inner and end surface was developed. This developed lapping system included a new lapping tool and developed lapping slurry from another research [1] for cylindrical inner and end surfaces. Then, lapping methods for mirror-like finish on cylindrical inner and end surfaces were proposed. Surface roughness and form accuracy were measured for evaluation of the process. Finally, optimum lapping conditions for mirror-like surfaces were clarified experimentally with the newly developed lapping system.

2. DEVELOPMENT OF LAPPING SYSTEM FOR MIRROR-LIKE SURFACE ON CYLINDRICAL INNER AND END SURFACES

2.1. DEVELOPMENT OF INNER SURFACE LAPPING TOOL AND LAPPING METHOD

The newly developed lapping tool for the inner surface lapping is shown in Fig. 1. This lapping tool consists of cylindrical lapping head (lateral area of head was used for lapping) made by polypropylene, the spring for generating lapping pressure, and linear guide for stabilization of dynamic behaviour between the lapping tool and the main spindle while processing. The 78 mm long weak coil spring with stiffness value of 2.726 N/mm was used. Even though positioning accuracy of lathe and tool setting accuracy were poor; the spring was used to prevent the effect on processing accuracy as much as possible. In addition, the spring would also maintain the processing accuracy while the lapping head wear out occurs. For producing of high quality mirror-like surface, lapping head needed to be rapid contacting and detaching intermittently from the work surface for dressing (catching new grains) and cleaning (removing some chips) purpose. In addition, the smooth rapid Z and X axial tool feed were also required for stable lapping process. High speed linear motor drive of Z and X axial directions had to be effectively utilized in this study for mirror-like surface processing.

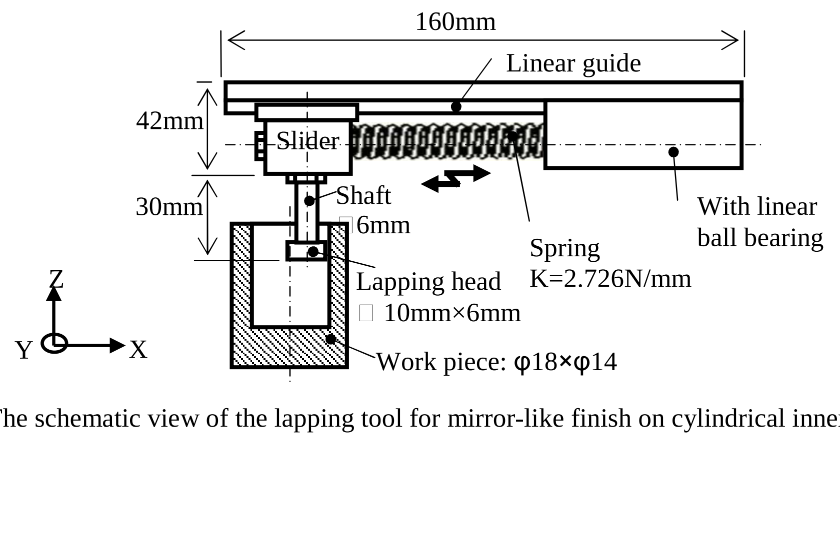


Fig. 1. The schematic view of the lapping tool for mirror-like finish on cylindrical inner surface

Outline of inner surface lapping procedure is illustrated in Fig. 2. During the inner surface lapping, lapping pressure was supplied towards the outer radial side by X axial direction tool feed.

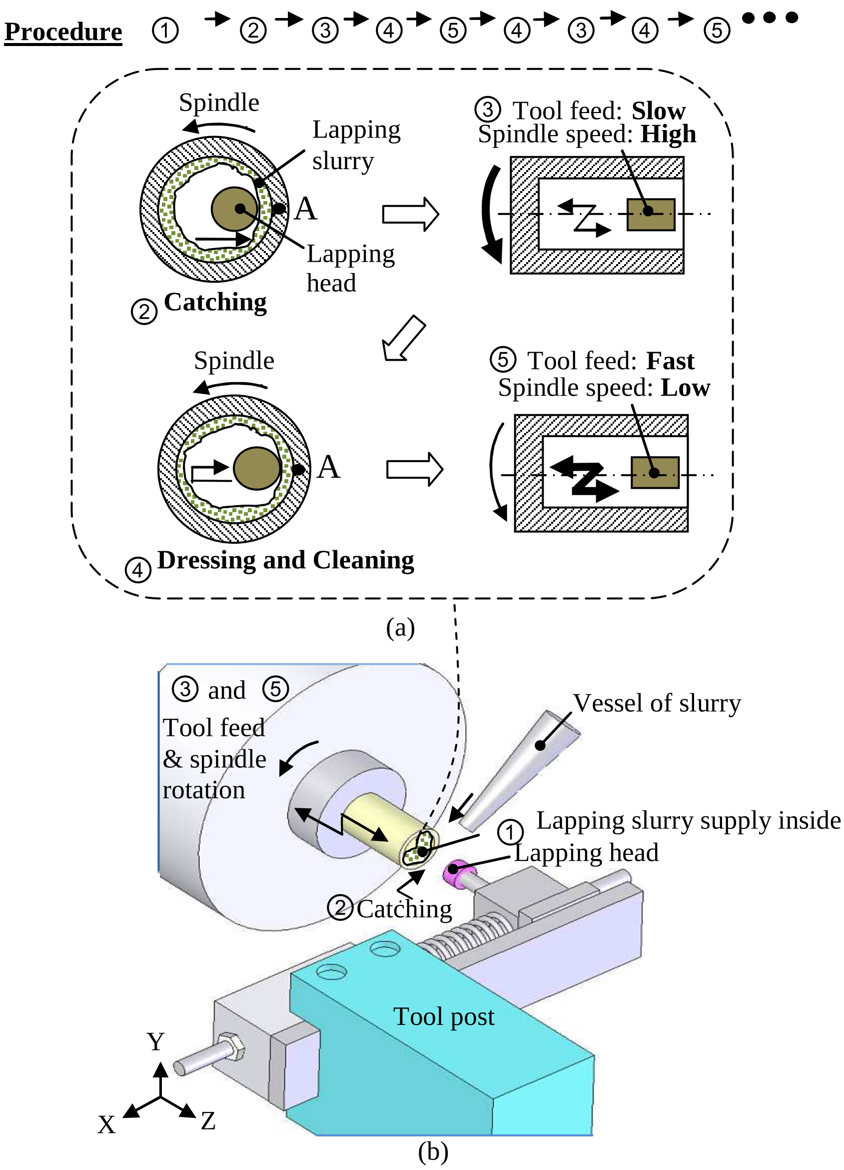


Fig. 2. Lapping method for mirror-like finish on cylinderical inner surface by the lathe with linear motor

At first, the developed lapping tool was installed at tool post of linear motor lathe. The lapping slurry was supplied into the rotating cylindrical work which was fixed at the collect chuck of main spindle (see procedure ① in Fig. 2(b)). Lapping head took diamond grains in the lapping slurry at position (A) by X axial tool feed (see procedure ② (a)). The lapping process was carried out on the work surface with the diamond grains that were taken on the lapping head. Then, the relative speed (called lapping speed) was provided by suitable combination of the Z axial tool feed and the spindle speed (see procedure ③and ⑤in Fig. 2(a)). In procedure ③, combination of high spindle speed with slow Z axial tool feed were provided. However, in procedure ⑤ the fast Z axial tool feed and slow spindle speed were applied. With these two arrangements of spindle speed and feed speed combination, the different lapping directions were provided in procedure ③ and ⑤. Between the lapping procedure of ③ and ⑤, dressing and cleaning was performed in order to obtain the stable lapping process (see procedure ④ in Fig. 2(a)). Then, the lapping was continued in the following procedure of ③→④→⑤→④→③→・・・.

2.2. DEVELOPMENT OF END SURFCAE LAPPING TOOL AND LAPPING METHOD

The outer cylinder flat end face and inner cylindrical bottom end surface are similar. Moreover, the surface roughness measurement and the observation of the mirror-like surface conditions can be processed easily with outer cylindrical flat end surface in this experiment. Hence, the outer cylinder flat end face was used as the inner cylindrical end surface in this lapping process. Fig. 3 shows the schematic view of the developed lapping tool for the end surface lapping. In order to apply lapping pressure on the end face, the assemble position of the lapping head on the slider was changed and lapping tool was installed axially on the Z direction. Cylindrical polypropylene lapping head was used for this lapping process. During the process, lapping pressure was supplied vertically on the work surface by Z axial tool feed.

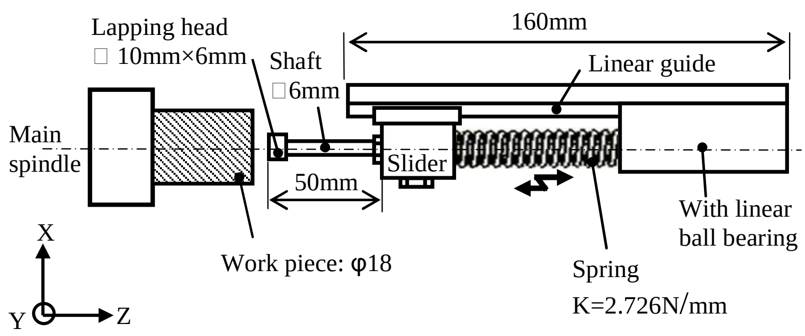


Fig. 3. The Schematic view of lapping tool for mirror-like finish on cylindrical end surface

Fig. 4 shows the outline of end surface lapping procedures. At first, the developed end surface lapping tool was installed on the tool post of linear motor lathe. The lapping slurry was supplied on rotating cylindrical work end surface (see procedure ① in Fig. 4).

The lapping head took diamond grains from the lapping slurry at (C) by Z axial tool feed (see procedure ② in Fig. 4). Then, the relative speed (called lapping speed) was provided by combination of spindle speed and X axial tool feed (see procedure ③ and ⑤ in Fig. 4). The lapping was carried out on work surface with the diamond grains which were taken on the lapping head. High speed spindle rotation and low X axial tool feed were set at procedure ③ . Procedure ③ and ⑤ are similar processes, but low spindle rotation and high X axial tool feed rate were set at procedure ⑤. By that way, the lapping direction in procedure ⑤ was processed with different lapping direction from the previous lapping direction of procedure ③. Between the process of procedure ③ and ⑤, dressing and cleaning operation were performed (see procedure ④). For dressing and cleaning, the lapping head was frequently detached rapidly in sequence and re-pressurized on the work surface by Z axial tool feed. From that point, the lapping process was conducted with the following procedure of ③→④→⑤→④→③→・・・.

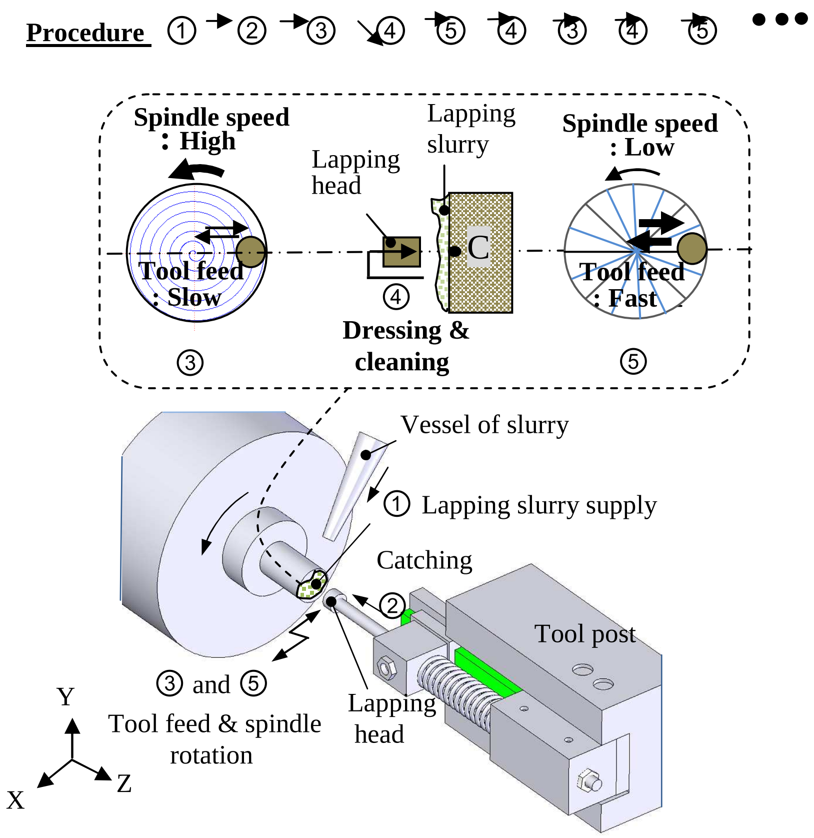


Fig. 4. Lapping method for mirror-like finish on cylindrical end surface by the lathe with linear motor

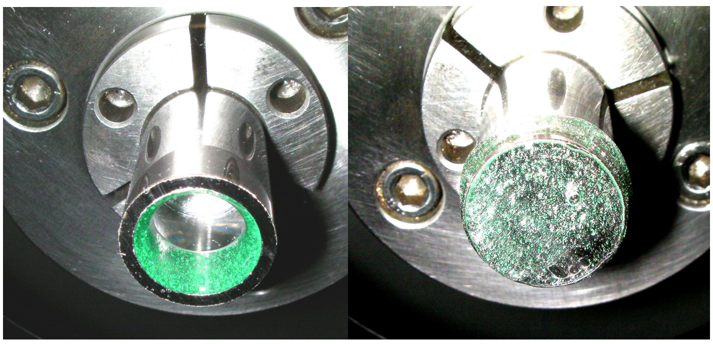
2.3. DEVELOPMENT OF LAPPING SLURRY FOR APPLICATION WITH LINEAR MOTOR LATHE

During inner surface lapping, slurry was relatively easy to be kept in the hole. However, it was quite difficult to keep lapping slurry on the end surface because of gravity and centrifugal forces. The special lapping slurry was required for end surface lapping. Lapping slurry needs to maintain the dropping and scattering of slurry at variable spindle speed during the process. Additionally, grains density variation in the lapping slurry due to spindle rotation was also required to be stable. Hence, special lapping slurry was prepared as the previous report [4].

The specification of developed lapping slurry is shown in Table 1. It is a water based solution of polymer Polyethylene oxide (PEO) with concentration of 2.0 wt%. The concentration of diamond in lapping slurry slurry is 4.0 wt%. From the preliminary experiment results, slurry dropping and scattering did not occurred on end surface when the spindle rotation was in the range of 3~700 min^{-1}. Moreover, uniform state of the diamond abrasive grains in side the lapping slurry was maintained between these spindle rotation ranges. Because, developed lapping slurry [1] could keep the diamond abrasive grain firmly between the molecules of the polymer to resist the gravitational and centrifugal forces. The conditions of lapping slurry on the □18mm work piece rotated at 700 min^{-1} is shown in Fig. 5. Lapping slurry contained grains normally on both inner and end surfaces of the work piece at that spindle speed.

Table 1. Specifications of lapping slurry

Mixture ratio of solvent	Water : PEO = 98 : 2 wt%		
Viscosity	158 Pa・ s (at 0.1 rps)		
Shearing stress	15.8 Pa (at 0.1 rps)		
Size of diamond (μm)	#400~500 (30~45)	#1200 (12~22)	#2500 (4~8)
Concentration of diamond in slurry	4.0 wt%	4.0 wt%	4.0 wt%



(a) Inner surface (b) End surface

Fig. 5. Conditions of lapping slurry on the work surfaces at spindle speed 700 min^{-1}

3. EVALUATION OF PROCESS CHARACTERISTIC FOR INNER AND END SURFACES LAPPING BY DEVELOPED LAPPING SYSTEM

3.1. EVALUATION OF THE INNER SURFACE LAPPING

Inner cylindrical work surface lapping was performed with the developed lapping tool. Surface roughness and geometrical accuracy were measured to evaluate the effectiveness of the process. The lapping speed (resultant vector of inner perimeter speed and Z axial feed rate) could be processed normally 3000 mm/min reported in the previous study of outer cylindrical lapping [4]. Fig. 2 shows the inner surface lapping procedure. Three different work materials of Cemented carbide (JIS V10), medium carbon steel (JIS S45C) and Brass were used for experiments. Diamond grains sizes of #400~500, #1200 and #2500 were used in this experiment according to the surface roughness improvement. The lapping condition for mirror-like finish on inner surface is shown in Tab. 2.

Table 2. Lapping conditions for mirror-like finish of inner surface

<table>
<tr><th colspan="2">Lapping slurry</th><th colspan="4">See Table 1</th></tr>
<tr><td rowspan="2">Lapping Pressure (MPa)</td><td>Catch diamond</td><td colspan="4">10
(Spindle speed 20 min^{-1})</td></tr>
<tr><td>For lapping</td><td colspan="4">4</td></tr>
<tr><td colspan="2">Lapping speed (mm/min)</td><td colspan="4">3000</td></tr>
<tr><td colspan="2">Fig. 2(a)</td><td colspan="2">③</td><td colspan="2">⑤</td></tr>
<tr><td colspan="2">Spindle speed (min^{-1})</td><td colspan="2">68</td><td colspan="2">3</td></tr>
<tr><td colspan="2">Feed speed (mm/rev)</td><td colspan="2">0.1</td><td colspan="2">900</td></tr>
<tr><th colspan="2">Work pieces</th><th>S45C</th><th colspan="2">V10</th><th>Brass</th></tr>
<tr><td rowspan="3">Lapping time (min)</td><td>#400~500</td><td>15</td><td colspan="2">15</td><td>15</td></tr>
<tr><td>#1200</td><td>15</td><td colspan="2">20</td><td>15</td></tr>
<tr><td>#2500</td><td>10</td><td colspan="2">10</td><td>20</td></tr>
<tr><td colspan="2">Total time (min)</td><td>40</td><td colspan="2">45</td><td>50</td></tr>
</table>

During the process, surface roughness was measured periodically with the stylus type surface roughness profilometer at the single chuck position of work piece. After processing of final mirror- like stage, work piece was disconnected from the chuck. Then, it was cut axially by wire cutting machine for accurate measurement. The cut surface was measured with the laser profilometer to confirm the mirror -like surface finishing. The form accuracy of cylindricity, circularity and straightness were also measured only before and after lapping because the work piece was impossible to be removed during process. Fig. 6 shows the relationship of surface roughness improvement with lapping time. After processing of 40~50 min, all materials (V10, S45C and Brass) became mirror-like surface with surface roughness value Rz (maximum height) about 0.1μm. The photograph of final mirror-like surfaces after lapping is shown in Fig. 7.

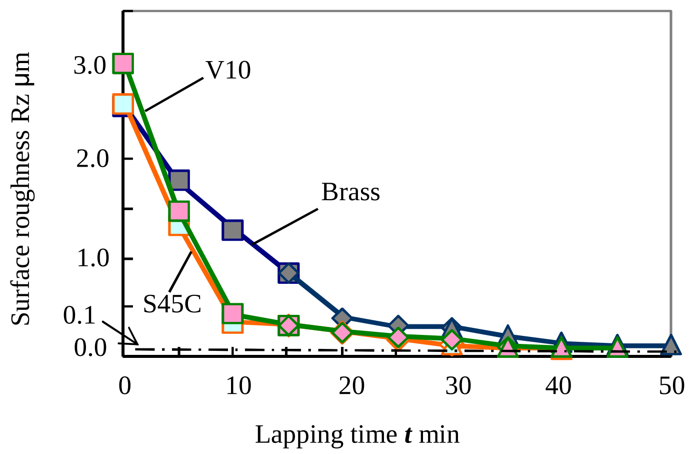


Fig. 6. Relationship between surface roughness and lapping time for inner surface

Fig. 8 shows the measurement result of form accuracy before and after the lapping. It was found that Cylindricity, circularity and straightness were improved greatly after lapping. Because, the eccentricity effect of the internal surface influenced in this lapping process. For example, if the eccentric value adds on the work surface, the lapping pressure and rate of material removal will decrease. However, if the eccentric value becomes minus, the result will have reverse effect. There is, the lapping pressure will increase. Concretely, the rate of material removal and geometrical accuracy will improve inevitably. In regarding to the straightness, the positioning accuracy of Z axial feed of the linear motor lathe influence greatly on it. As mentioned above, the developed lapping system for the inner surface was capable of mirror-like surface. Furthermore, the form accuracy of cylindricity, circularity and straightness also improved simultaneously.

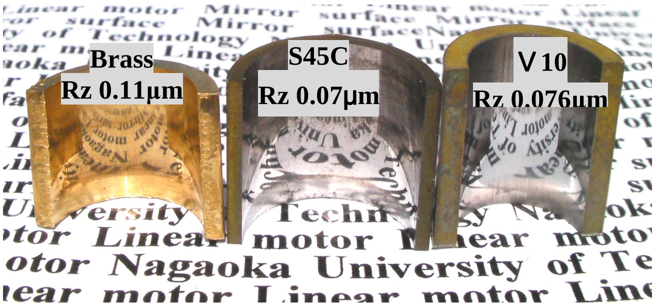


Fig. 7. Photograph of mirror-like surface regarding three materials

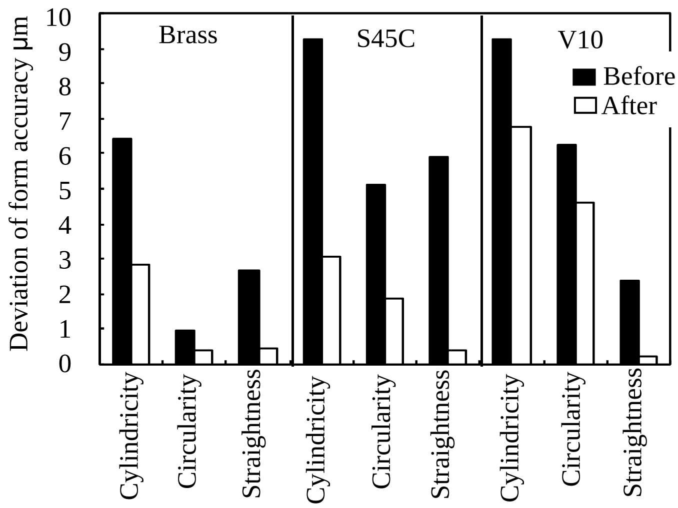
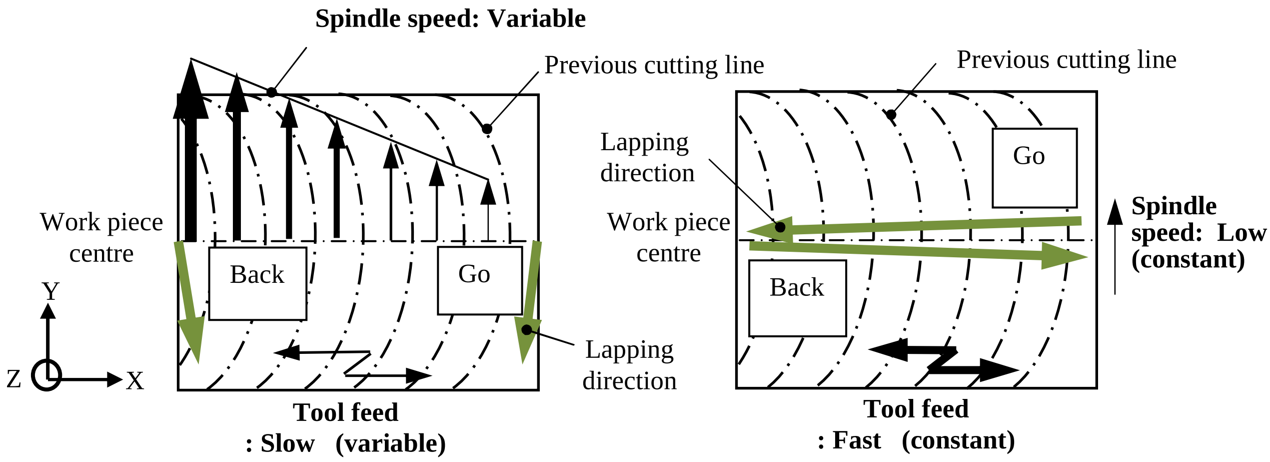


Fig. 8. Relationship between improvement of form accuracy before and after lapping for inner surface

3.2. EVALUATION OF THE END SURFACE LAPPING

Inner cylindrical end surface lapping was performed on the outer cylinder flat end surface because these surfaces were similar in nature. Moreover, evaluation of process was easy on outer cylinder flat end surface. In cylindrical end surface lapping, lapping tool movement was performed by X axial tool feed while lapping pressure was applied vertically onto it. In this lapping, application of simple tool feed with spindle revolution could not obtain a uniform mirror-like surface. Because of the reasons described as follows; (1) the lapping speed increases proportionally with increase of radius and it becomes zero at centre



(a) Lapping of circular direction (b) Lapping of radial direction

Fig. 9. Lapping algorithm for mirror-like finish on end surface

of cylindrical end surface, (2) previous cutting line cannot remove with only one circular lapping direction provided by simple tool feed. Hence, horizontal lapping direction provided by suitable feed on the end surface becomes necessary.

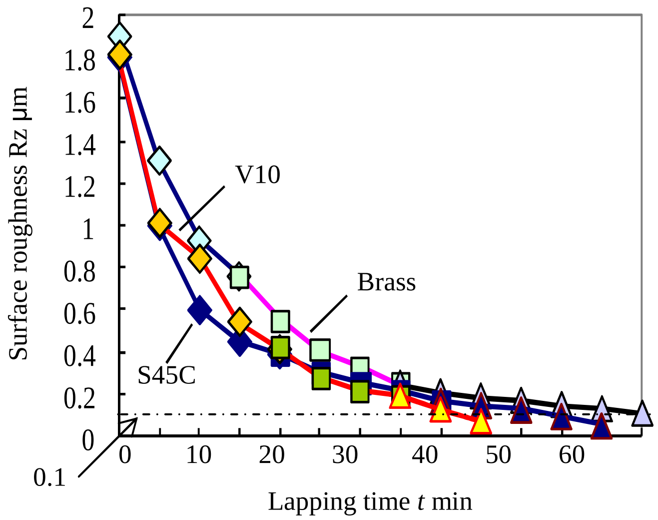


Fig. 10. Relationship between the surface roughness and the lapping time for end suraface

The developed new algorithm for uniform mirror-like surface on end surface lapping is described in Fig. 9(a) and (b). As mentioned above (in order to solve the problem of (1) and (2)) circular lapping direction was provided by variable main spindle speed corresponded to radius for constant lapping speed (see Fig. 9(a)). By this way, the material removal of circular lapping direction became constant. For radial lapping , main spindle rotation was reduce to 3 min^{-1} (the lowest limits of spindle speed where end surface can keep the lapping slurry) and high speed X axial tool feed performed the horizontal lapping direction which was nearly perpendicular to the previous circular lapping direction (see Fig. 9(b)).

The end surface lapping was carried out with the lapping procedure described as in Fig. 4. The condition for mirror-like finish on end surface lapping is shown in Tab. 3. Similar work materials and abrasive grain sizes were used in this experiment. During the process, surface roughness was measured periodically by the stylus type surface roughness profilometer. At final finishing stage, surface roughness was also measured by laser profilometer to confirm mirror-like surface finish. The relationship of surface roughness improvement with lapping time is shown in Fig. 10. All three materials of V10, S45C and Brass became the mirror-like finish of surface roughness Rz (maximum height) value about 0.1µm after processing of 45~65 min. Photographs of the final mirror- like surface of three materials after lapping is shown in Fig. 11. The measurement result of the improvement of flatness before and after the lapping is shown in Fig. 12. Higher improvement of flatness was found and it could be concluded that the reason was similar to the form accuracy (Cylindricity, circularity and straightness) improvement of inner cylindrical surface lapping.

Table 3. Basic lapping conditions for mirror-like surface of cylindrical end surface

Lapping slurry		See Table 1		
Lapping pressure (MPa)	For catch diamond	50 (spindle speed 10 min^{-1})		
	For lapping	30		
Lapping speed (mm/min)		3000		
Lapping algorithm		Fig. 9(a)		Fig. 9(b)
Spindle speed (min^{-1})		53,60,68,80,95, 120,160,238,477		3
Feed speed (mm/rev)		1		900
Work pieces		**S45C**	**V10**	**Brass**
Lapping time (min)	#400~500	20	20	15
	#1200	20	15	20
	#2500	20	10	30
Total time (min)		60	45	65

Fig. 11. Photograph of the end surface regarding three materials after lapping

The newly developed lapping algorithm and positioning accuracy of X axial tool feed influence greatly on it. It was confirmed that newly developed lapping system was capable of producing mirror- like finish. Additionally, the developed system can improve the flatness simultaneously. Finally, optimum process condition for the end surface lapping was examined under five different process conditions. The experiment conditions are shown in Tab. 4. In this experiment, S45C was used as work material. Fig. 13 shows the experiment results of the five different lapping process conditions. All process conditions satisfy the mirror-like surface finishing. From the results, the process condition 5 was able to reduce the lapping time to one-fourth from the basic process condition of 1 by increasing the lapping pressure, lapping speed and spindle rotation. Thus, condition 5 was regarding as the optimum condition for higher productivity mirror-like finish surface. Furthermore, that condition was the process limitation of taking diamonds to lapping head during process and the application limit of the linear motor lathe for which the machine vibration needed to be taken into consideration.

Table 4. Lapping conditions for mirror- like finish with productivity

Lapping pressure (MPa)	For catch diamond	50 (spindle speed 10 min^{-1})				
	For lapping	30	30	40	45	45
Feed speed (mm/rev)	Fig. 9(a)	1	20			20
	Fig. 9(b)	900				800
Spindle speed (min^{-1})		See Table 3				See
Lapping speed (mm/min)		3000				4000
Lapping time (min)	#400~500	20	15	10	5	5
	#1200	20	15	10	10	5
	#2500	20	10	10	5	5
Total time (min)		60	40	30	25	15

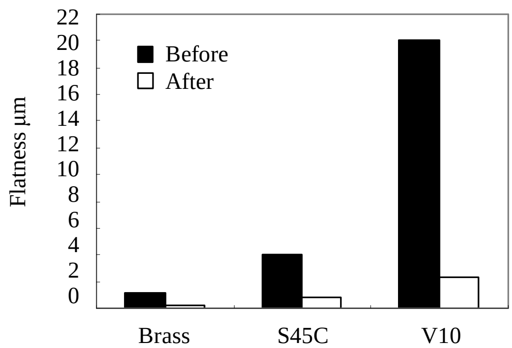


Fig. 12. Relationship between improvement of flatness before and after lapping for end suraface

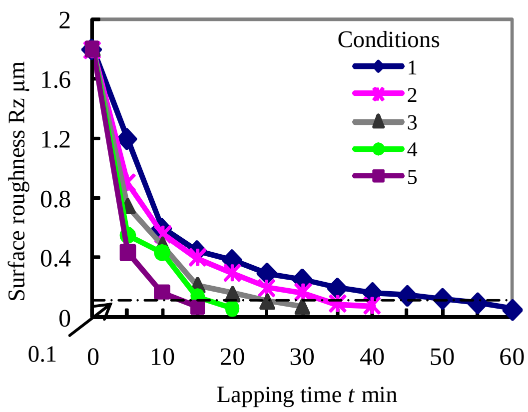


Fig. 13. Improvement of lapping conditions for high productivity

4. CONCLUSIONS

It is concluded from the result that; (1) The newly developed lapping system was able to process the mirror-like surface finish for the work materials of Cemented carbide (V10) , medium carbon steel (S45C) and Brass. (2) The optimum conditions for the mirror- like surface on cylindrical inner and end surfaces were revealed experimentally.

REFERENCES

[1] IYAMA, T., TANABE, I., TAKAHASHI T., 2009, Optimization of Lapping Slurry in Automatic Lapping System for Dies with Cemented Carbide and Its Evaluation (in Japanese), *Transactions of the Japan Society of Mechanical Engineer*, *Series C*, 75/749, 210-215.

[2] KARITA, M., 1995,High Performance Technology in Linear Motor (in Japanese), *Journal of the Japan Society for Precision Engineering*, 61/3, 347-350.

[3] MIZUNO, T., 2001,Machine Tool of Expanding Linear Motor Drive (in Japanese), *The Journal of The Institute of Electrical Engineers of Japan*, 121/9, 620-623.

[4] MOE, A.L., TANABE, I., IYAMA, T., NASU, F., High Speed Lapping for Mirror-like Finish using the Lathe with Linear Motor, *Submitted in XXI CIRP Sponsorship Conference on Supervising and Diagnostics of Machining Systems.*