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Paper:

Improvement of Removal Rate of Tape Lapping by Applying Fluid with Ultrasonic Excited Cavitation

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Lapping with a lapping tape refers to a finishing process in which a new tape is continuously supplied to its processing area and pressed down with a pressure roller during its relative motions. In response to the growing demand for lapping high-hardness materials with high efficiency, lapping tapes with superabrasive grains formed in a textured structure with a bond have been recently utilized. In this study, we supply a working fluid that has passed through the slit between ultrasonically oscillating blades to processing points. Variations of sound pressure generate cavitation in the working fluid. Impulse waves due to the collapse of cavitation bubbles inhibit chips from getting adhered to the chip pockets of the lapping tape. We have lapped hardened SUJ2 with plural lapping tapes of different characteristics. In lapping with a lapping tape using diamond abrasive grains, we have improved the time constant for the changes in surface roughness in relation to the lapping time from 18.9 s to 7.6 s by superimposing ultrasonic oscillations; consequently, the lapping speed improved. We have compared the effects of ultrasonic oscillations for three types of lapping tapes and discovered that fewer abrasive grains and lower chip adhesion firmness due to the abrasive grains formed in a textured structure increased the effects of ultrasonic oscillations.

Keywords: ultrasonic cleaning, lapping tape, ultrasonically assisted machining, cavitation bubble

1. Introduction

Lapping with lapping tapes is used in the final finishing process of high-accuracy components for information appliances, precision instruments, transportation/transfer equipment, etc. to finish them with high efficiency. In lapping such high-accuracy components with a lapping tape, the lapping tape, which is pressed down onto the work surface at a constant pressure, grates on the work surface in its appropriate relative motions. A lapping tape contains abrasive grains adhered to its film surface. Similar to a grindstone used for grinding, abrasive grains adhered onto a lapping tape generate a higher lapping force than free abrasive grains, thereby enabling a high lapping efficiency. In addition, as abrasive grains are adhered onto a flexible substrate, curved surfaces, groove bottoms, and cylindrical inner surfaces with less variations in accuracy can be lapped. A flexible backup roller presses lapping tape down to a workpiece and oscillates it to provide constant pressure for lapping. In other words, lapping with a lapping tape should be performed between grinding and lapping based on its mechanism and characteristics. As a new tape is always provided for lapping, its constant and maximum lapping characteristics can be sustained.

High lapping efficiency is required for lapping high-hardness materials. Some researchers have attempted to improve lapping efficiency by improving lapping tapes. In a previous study [1], the roughness of a lapping tape was improved regardless of its pressed-down pressure by forming various rugged patterns on the lapping tape's substrate; in particular, "file-type" cross patterns angled opposite to the feed direction are effective for discharging chips. In another report [2], the effects of the working fluid on lapping characteristics when lapping a titanium alloy was investigated. Meanwhile, some studies regarding grinding have been conducted: in one study [3], a method for removing a grinding stone's loading using an adhesive tape was reported; in another study [4], a technique to reduce the feed rate of grinding fluid based on a characteristic discharge nozzle was developed. Furthermore, in one study [5], the loading of a small-diameter grinding stone was suppressed via its ultrasonic oscillations, and the effects of abrasive grain motion trajectory on surface roughness improvement were reported. In several previous studies [6–9], chips were prevented from being adhered to a grinding stone via ultrasonic cavitation. In a particular study [10], a technology for recovering grinding characteristics by removing chips that adhered to a used tape via ultrasonic oscillations was developed.

This aim of this study is to inhibit chips from adhering to a tape by generating cavitation excited by ultrasonic oscillations as well as to increase the surface roughness improvement rate per unit time. A higher improvement rate means a reduction in the lapping time as well as in the

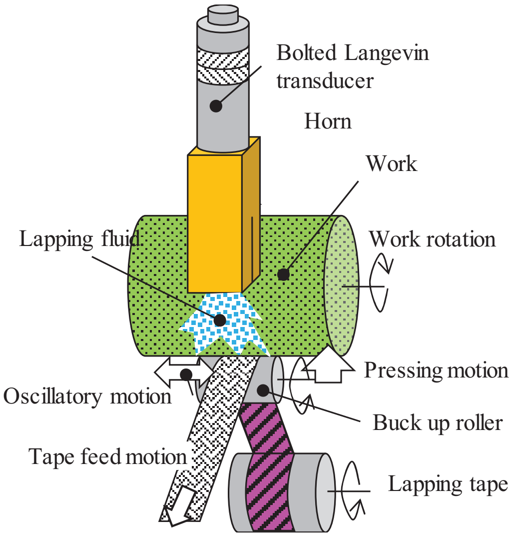


Fig. 1. Principle of tape lapping.

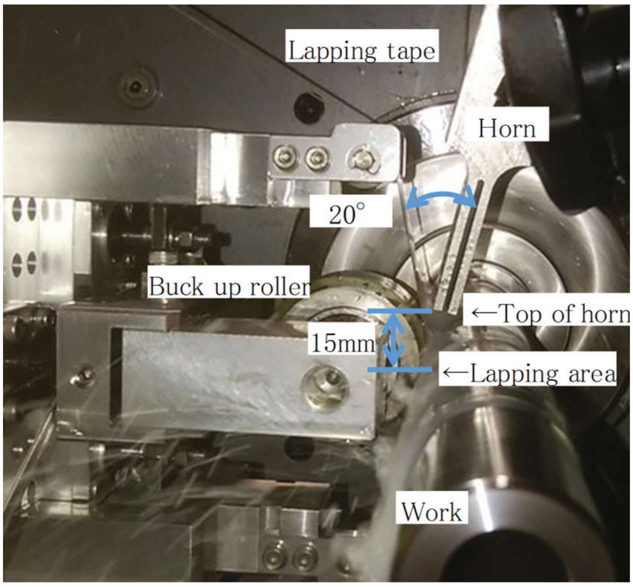


Fig. 2. Setup of experimental device.

amount of consumed tapes. In this study, we experimentally investigated the effects of the lapping tape's substrate thickness and the power supply to an ultrasonic transducer on the surface roughness improvement rate.

2. Tape Lapping

2.1. Principle and Features of Lapping

In finishing with a lapping tape, as shown in **Fig. 1**, the lapping tape is pressed down to the work surface via a backup roller to achieve constant pressing force between the lapping tape and workpiece with their appropriate oscillatory motions. When the tape is wound at an extremely low speed, a new tape with no loading is supplied at a constant rate. Consequently, tape lapping can be performed under stable lapping conditions continuously, thus making it a finishing technology suited to the mass production. In addition, special lapping tapes with chip pockets created by diamond abrasive grains formed via bonding are commercially available for lapping high-hardness materials with high efficiency; in fact, their usage has extended to the lapping of hardened steel, single-crystal silicon, and glass materials.

2.2. Tape Lapping Device

A tape lapping device was mounted on the lateral feeding table of an NC lathe to lap the outer peripheral surface of the workpiece fitted on the main spindle. **Fig. 2** shows the arrangements of the workpiece, tape lapping device, and ultrasonic oscillation superimposing device. The tape lapping device consists of a tape winding roller, a tension roller to apply tension to the tape to keep it from getting slack and a urethane backup roller (50 mm in diameter) to press the tape down onto the workpiece with an air cylinder at a constant pressure. The lapping conditions, as recommended by the tape lapping device manufacturer, are given in **Table 1**. We used SUJ2 of $\phi30$ (induction hardened, HRC58) as the workpiece. We used water-soluble lapping oil (Yushiroken FGS690, Yushiro Chemical Industry Co., Ltd.) as the working fluid. We set the tape feed rate at 6 mm/min, workpiece peripheral speed at 70 m/min and oscillation frequency at 1000 min^{-1}. In tape lapping, while a higher tape feed rate gets a new tape to act more on the processing points and increases the removal rate, it also increases the tape consumption as well as the tape lapping cost.

Table 1. Lapping condition.

Work material	SUJ2
Dimensions	$\phi30 \times 200$
Lapping fluid	Soluble type
Flow rate	3 L/min
Peripheral speed of work	70 m/min
Pressing force	100 N
Feed rate of tape	6 mm/min
Oscillation frequency	1000 min^{-1}

2.3. Ultrasonic Oscillation Device

It is well known that ultrasonic oscillations applied to a fluid generate cavitation in it and a large pressure acts locally to generate cleaning effects, so that such ultrasonic oscillations are widely used for ultrasonic cleaning. The ultrasonic oscillation device consists of a bolted Langevin-type ultrasonic transducer (HEC-2528P4B, Honda Electronics Co., Ltd.) and horn with fluid nozzle as shown in **Fig. 3**. The horn is 25 mm wide, the same as the lapping tape width; as such, the working fluid can be applied to the full width of the tape. In ultrasonic cleaning devices, drive frequencies in the audible range are effective for cleaning and removing oil

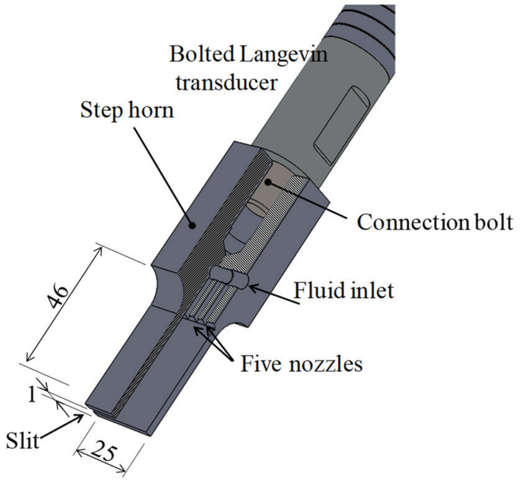


Fig. 3. Ultrasonic cavitation device.

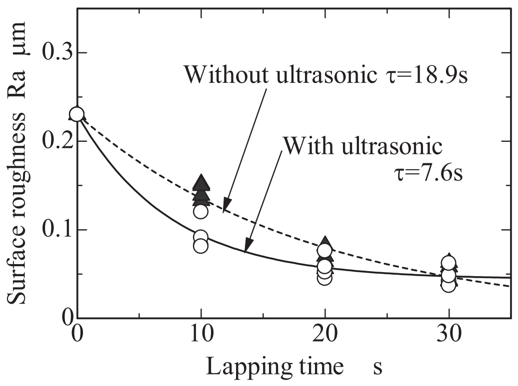


Fig. 4. Improvement of surface roughness.

and fat dirt, chips, burrs, etc. Meanwhile, high frequencies exceeding 100 kHz are used to clean fine objects such as particles on circuit boards in manufacturing semiconductor [11]. Therefore, in this study, by considering the chips adhered to the lapping tape and the working fluid's viscosity, we excited ultrasonic oscillations in a frequency band that was relatively close to the audible range. Because we selected a commercially available ultrasonic transducer with a diameter of 25 mm to match the horn's width, we set the ultrasonic transducer's drive frequency at 28 kHz. We set the appropriate oscillatory horn dimensions to excite oscillations in a longitudinal mode by analyzing the electric field-machine coupled oscillations on an analytical model using the oscillatory horn coupled to the Langevin transducer. In order to generate greater sound pressure caused by cavitation in the vicinity of the processing points, we adopted a stepped horn shape, 46 mm in length on the small end side to generate larger amplitudes of oscillations at its tip point. We provided a 1 mm slit in the longitudinally forward part from the horn's middle part and provided five nozzles at the bottom of the horn. The working fluid passing through the slit from the inlet at the middle of the horn, is discharged from the nozzles and passes through the slit before being applied to the processing points from the horn's tip point. As the oscillatory horn's tip constitutes an antinodal line in a longitudinal vibration mode, the closer to the processing point, the greater is the expected effects of the ultrasonic oscillations. In this study, considering the operability of the oscillatory horn and the operating ranges of the tape-lapping device and lathe, we set the distance between the oscillatory horn and processing point to 15 mm. We tilted the ultrasonic oscillation superimposing device by approximately 25° to the lapping tape to maximize a grinding fluid that approach processing point.

We evaluated the cavitation generated by the ultrasonic oscillations of the ultrasonic oscillation device used in this study using a hydrophone type ultrasonic sound pressure meter (Sonosaver DX, Otari), which is typically used to evaluate the performances of ultrasonic cleaning machines. Because the instrument can measure the relative sound pressure levels as voltage values, we compared them with the measurements of a commercially available desktop ultrasonic cleaning machine (Sonocleaner 200D, Kaijo: rated power 200 W, frequency 38 kHz). We filled the cleaning tank with tap water to a level of 90 mm, as specified by the manufacturer, and measured the sound pressure levels from near the cleaning tank bottom to the water surface to obtain a maximum value of 180 V at a height of 10 mm from the bottom. Meanwhile, the ultrasonic oscillation device used in this study comprised a sensor probe installed 15 mm away from the horn tip and discharged 3 L of working fluid per minute, as in actual lapping. The measured results were as follows: 2.2 mV when the power supply to the ultrasonic transducer was 30 W, and 7.0 mV when it was 60 W. In other words, although the proposed ultrasonic oscillation device's relative sound pressure level per supplied power was as low as approximately one-tenth of that of the ultrasonic cleaning machine, the former device seems to be able to act an impulsive force owing to the collapse of cavitation at the processing point.

3. Experimental Results

3.1. Effects of Ultrasonic Oscillations in Tape Lapping

Tape lapping selectively removes the projecting parts of a workpiece in a manner similar to constant-pressure lapping. **Fig. 4** shows the changes in arithmetic average surface roughness with respect to the lapping time. We used a lapping tape 662XA (diamond grain diameter: 9 μm) manufactured by 3M Japan Limited. The substrate of the lapping tape was textured with triangular prisms of 50 μm on the side, as formed by the bonded diamond abrasive grains. It has cutting edges and chip pockets like a file. Its feed speed was 6 mm/min. The surface roughness of the workpiece was measured by scanning it in the axial direction. We plotted the surface roughness measured at a total of four points, 90° apart from each other, on the workpiece's entire circumference and then exponentially

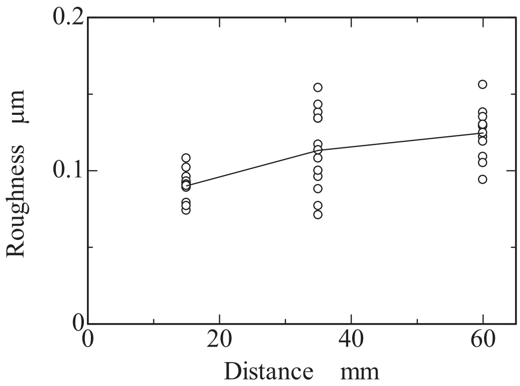


Fig. 5. Effect of ultrasonic by clearance between horn and working point.

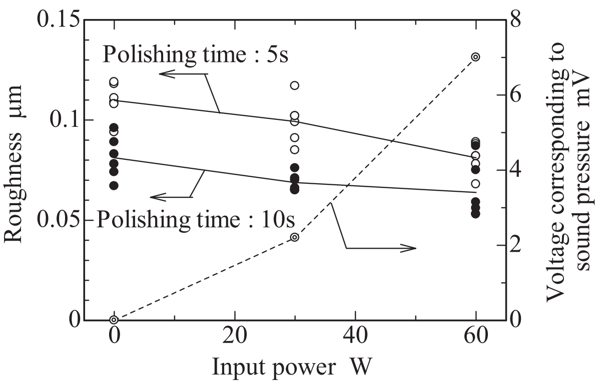


Fig. 6. Change in surface roughness and sound pressure by input power to transducer.

approximated them using the least-squares method to obtain the time constants, as shown in **Fig. 4**. The surface roughness of the cylindrical ground surface during preprocessing was 0.22 μmRa. With or without ultrasonic oscillations, the surface roughness was improved significantly at the initial stage of lapping and approached a constant value as the lapping time elapsed. Without ultrasonic oscillations, the surface roughness at the point when 10 s had elapsed was 0.15 μmRa, at a time constant of 18.9 s. Meanwhile, with ultrasonic oscillations, the surface roughness improved rapidly at the initial stage of lapping and reached 0.10 μmRa at the point when 10 s had elapsed, at a time constant of 7.6 s. With or without ultrasonic oscillations, when the lapping time exceeded 30 s, the abrasive grains used for the lapping tape reached their limits in lapping capability when the final surface roughness value was 0.05 μmRa. The abovementioned experimental results show that ultrasonic oscillations are effective for improving the rate of change (volume removal rate) per unit time.

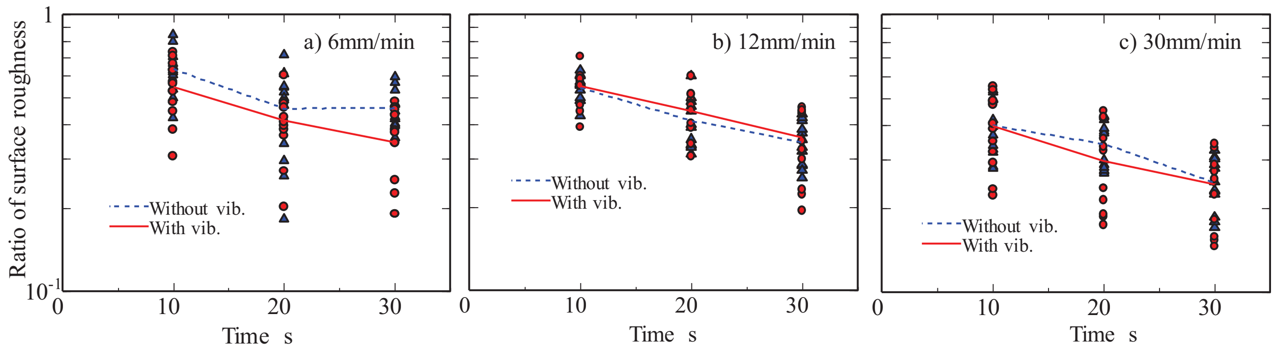
Because the impulsive force of cavitation generated by the ultrasonic oscillations attenuated in accordance with the distance from the ultrasonic oscillatory horn, the effects of cavitation on inhibiting chips from getting adhered are also considered to decrease in accordance with the distance. In the experiments, we set the lapping tape's feed speed to 6 mm/min and the lapping time to 10 s. **Fig. 5** shows the surface roughness measured at eight points on the work surface by varying the distance from the ultrasonic oscillatory horn tip to the processing point by 15, 35, and 60 mm. In the experiments, we lapped three workpieces and fitted their average values linearly. As the distance from the oscillatory horn to the processing point increased, the surface roughness increased. Whereas the average surface roughness is 0.10 μmRa or less when the distance from the horn tip to the processing point was 15 mm, the average surface roughness was approximately 0.13 μmRa when the distance was 35 mm. In other words, the abovementioned measurement results indicate that the horn tip must be positioned as close as 20 mm or less from the processing area to allow the ultrasonic oscillations to sufficiently generate their effects.

As mentioned in Section 2.3, the oscillation amplitude of the horn varied with the power supplied to the bolted Langevin transducer, imposing some effects on the cleaning capability. In the experiment, we varied the supplied power: 0 (without ultrasonic oscillations), 30, and 60 W. **Fig. 6** shows the voltage corresponding to the hydrophone's sound pressure at the processing point for each supplied power and the arithmetic average surface roughness at 5 and 10 s. As shown in **Fig. 6**, as the supplied power increased, the voltage corresponding to the sound pressure increased, whereas the arithmetic average roughness decreased accordingly. The surface roughness generated by lapping the workpiece for 5 s with ultrasonic oscillations at the supplied power of 60 W corresponded to that generated by lapping it for 10 s, proving the effects of ultrasonic oscillations on reducing the lapping time.

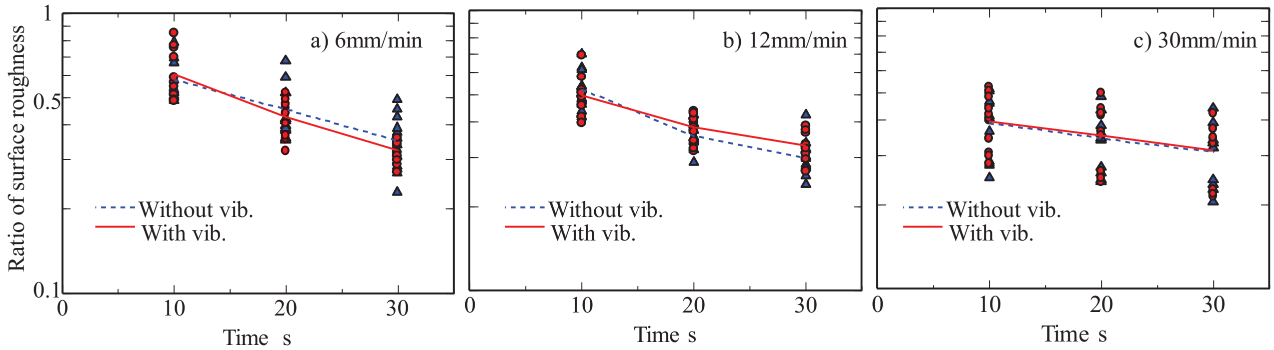
3.2. Difference in Effects of Ultrasonic Oscillations with Different Lapping Tapes

Similar to a grinding process, the lapping tape's lapping characteristics can be controlled by its abrasive grain, grain diameter, density, and substrate. In this study, we selected three types of lapping tapes used for lapping high-hardness steel-based materials and compared their lapping characteristics. Lapping tape A comprising white alumina of grain size #2000 (Micro-Finishing Film 362L, 3M Japan Limited, substrate thickness 75 μm) and lapping tape B (VARIOFILM, Mipox; substrate thickness 125 μm), whose abrasive grains were randomly adhered and may be inferior in terms of high-hardness material lapping, are widely used because of their affordability. Meanwhile, the lapping tape with adhered diamond abrasive grains mentioned in the preceding subsection is denoted in this section as lapping tape C.

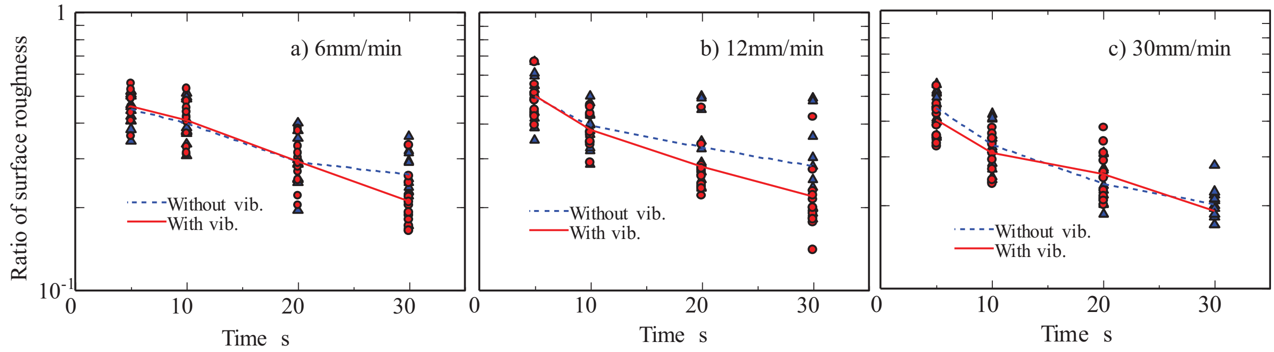
We experimentally compared their effects on improving the lapping characteristics of the abovementioned three types of lapping tapes. The ultrasonic oscillation application conditions and tape lapping conditions were the same as those described in the preceding subsection. **Fig. 7** shows the changes in the improvement rate of the workpiece's arithmetic average roughness with regard to the lapping time at tape feed speeds of 6, 12,



(a) Tape A (WA, #2000, 75 μm)



(b) Tape B (WA, #2000, 125 μm)

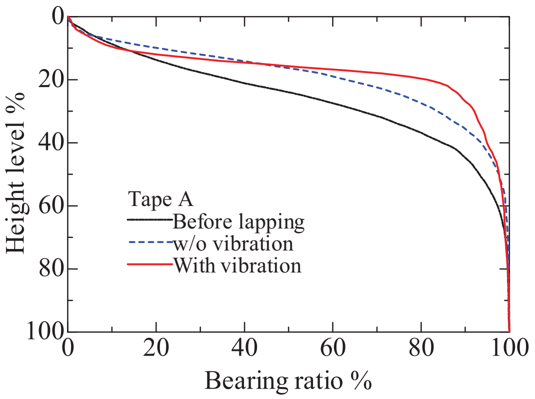


(c) Tape C (SD, 9 μm, 75 μm)

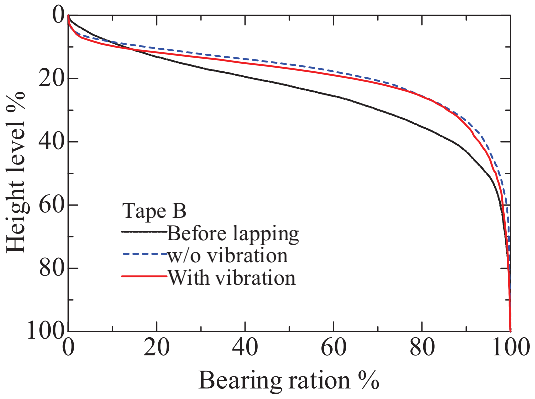
Fig. 7. Improvement in lapping efficiency.

and 30 mm/min. In order to verify the reproducibility of the experiment, we conducted the experiments under the same conditions on three workpieces. As some variations existed in the surface roughness of the workpieces before tape lapping, we plotted the surface roughness of the workpieces after tape lapping as the ratio of improvement of the surface roughness. We measured the surface roughness of the workpieces at four points, 90° apart from each other on the workpieces' entire circumferences, presented the values measured at 12 points as markers, and linearly fitted their average values. Because the surface roughness demonstrated an exponential improvement tendency, we used semilog graphs. As shown in **Fig. 7(a)**, the lapping efficiency of tape A, which uses conventional abrasive grains with ultrasonic oscillations, improved the surface roughness by approximately 10% at a feed speed of 6 mm/min. However, the difference in lapping efficiency at feed speeds of 12 and 30 mm/min was minimal; this is attributable to the tape's processing points being inhibited from loading when its feed speed was sufficiently high, thereby reducing the effects of ultrasonic oscillations. As for tape B with conventional abrasive grains adhered onto the substrate, no distinct differences were observed in the effects of the ultrasonic oscillations regardless of the tape's feed speed. Meanwhile, for tape C with bonded superabrasive grains, we confirmed the effects of the ultrasonic oscillations on improving the surface roughness at the lapping time of 20 s or longer at the tape's feed speed of 6 mm/min, and at the lapping time of 10 s or longer at the tape's feed speed of 12 mm/min; this indicates that as the terminal value of the surface roughness decreases, the target surface roughness can be achieved in a shorter lapping time.

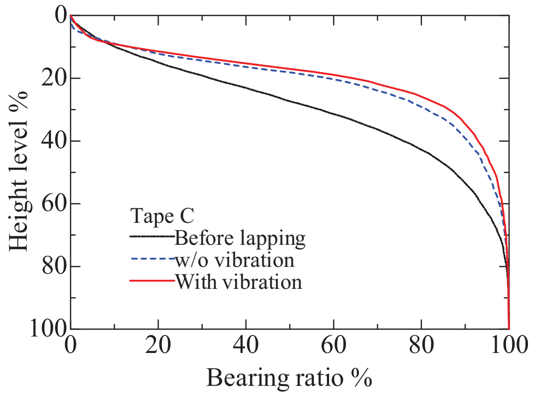
Tape lapping is used as a lapping technology to create a plateau surface by selectively removing top of rough surface profile. In order to clarify the tape lapping fea-



(a) Tape A (WA, #2000, 75 μm)



(b) Tape B (WA, #2000, 125 μm)



(c) Tape C (SD, 9 μm, 75 μm)

Fig. 8. Lapping progress evaluated based on bearing area curve.

tures, we compared tapes A, B and C by their bearing area curves. **Fig. 8** shows the bearing area curves for lapping with tapes A, B, and C for 10 s at a feed speed of 6 mm/min with and without oscillation vibrations. We observed that when the projecting parts on the rough surface were selectively removed, the disconnection levels in the bearing area curves tended to be flat and less varied in regions of small load length ratios, whereas they declined significantly in regions with large load length ratios. Lapping with tape A, which uses conventional abrasive grains, and with tape C, which uses superabrasive grains, yielded plateau surfaces, which were obtained by ultrasonic oscillations. Meanwhile, lapping with tape B yielded almost no effects via ultrasonic oscillations. These experimental results are similar to the abovementioned comparison results regarding the arithmetic average surface roughness.

3.3. Adhesion Conditions of Chips

The tape lapping characteristics seem to be improved by the effects of cavitation on inhibiting chips from getting adhered to work. Furthermore, it was assumed that the abrasive grain wear and falling affected the lapping characteristics. However, when removing the adhesions from the lapping tape after use, no falling or wear was detected in the abrasive grains; this suggests that the approximate lapping capability of a lapping tape can be reproduced, as reported in [10]. Therefore, in this study, we did not consider the abrasive grains' falling or wear. In the experiments, we compared the adhesions removed from the lapping tape loaded with chips during lapping by applying a sole working fluid and a working fluid on which ultrasonic oscillations were superimposed 3 mm away from the lapping tape. The power supplied to the ultrasonic oscillation excitation transducer was 30 and 60 W. To evaluate the lapping tape's adhesion areas, utilizing the adhesion's opacity and the tape's optical transparency, we photographed the light transmitted through the tape's back surface using a digital camera, transformed it to binary values based on the difference in luminosity between the adhesions and the tape, and calculated the tape's loading rate from the area ratio between the adhesions and the measuring object range. To apply the working fluid, we adhered a mask with an opening only in the 4-mm-wide region to a 25.4-mm-wide tape adhered with chips. We minimized any variations in the chip adhesion conditions by shifting the mask appropriately in each experiment. **Fig. 9** shows the transmitted photo images of the lapping tape after use, where adhesions are shown in black and loading rates are described. In the first-half of the lapping (on the left side of the broken line) when many projecting parts existed on the lapped surface or large removals, the loading rate reached 80%–90%; however, as the lapping progressed and the removal decreased, the loading rate decreased to 80% or less. The application of a working fluid with no superimposed ultrasonic oscillations failed to remove the adhesions from any one of the lapping tapes. Meanwhile, the application of a working fluid with ultrasonic oscillations superimposed on tapes A and B reduced their loading rates. In particular, in the second-half of lapping with tape A (on the right side of the broken line), its loading rate decreased by 27%–33%.

In the second-half of lapping with tape B, its loading rate decreased by 35%–43%. For tape C, which uses diamond abrasive grains, in the first-half of its lapping comprising many adhesions, its loading rate was between 82% and 87%. In the second-half of its lapping, when chips were accumulated solely in the chip pockets, its chip pocket function appeared to have retained its lapping capability. The application of a working fluid with ultrasonic oscillations superimposed on the tapes in the above-

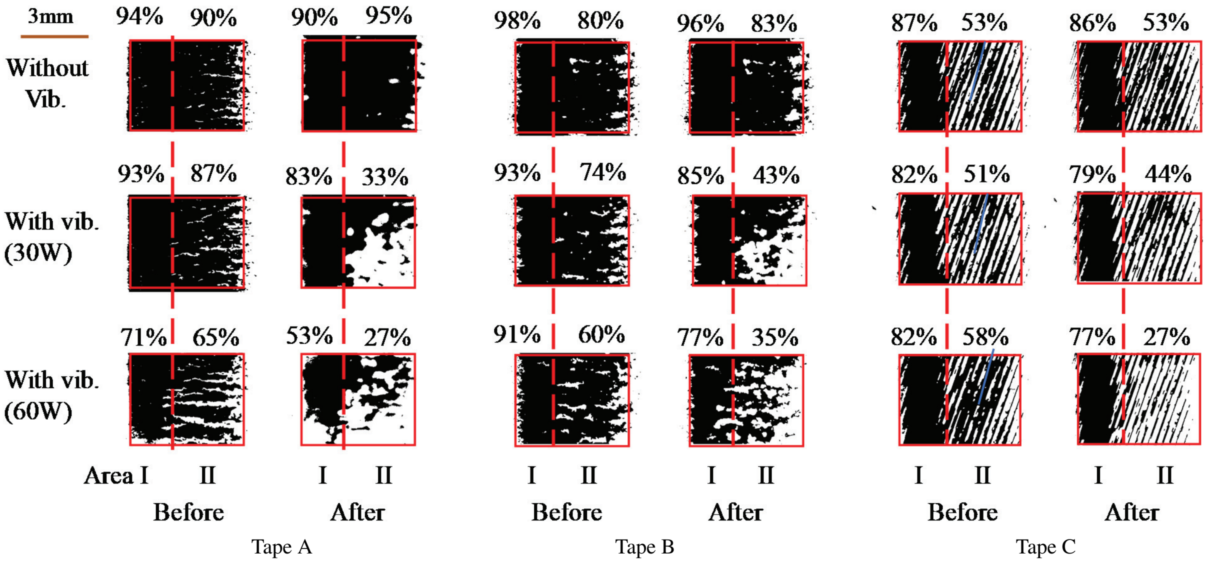


Fig. 9. Adhesion removal by applying working fluid.

mentioned adhesion conditions barely changed the adhesion conditions in the first-half of lapping, whereas it decreased the adhesions by 10%–30% in the second-half of lapping. The abovementioned experimental results indicate that the application of a working fluid with superimposed ultrasonic oscillations is effective in removing adhesions, and that the different lapping tapes exhibited different adhesion removal characteristics.

3.4. Number of Abrasive Grains Contributing to Lapping

In order to understand why the effects of ultrasonic oscillations varied with the lapping tape type, we placed a pressure-sensitive paper (Prescale, Fujifilm) between the workpiece and the backup roller and compressed it by applying a pressure of 100 N, the same pressure used for lapping, such that the number of abrasive grains contributing to lapping can be visualized. We used a pressure-sensitive paper suitable for low-pressure use that can respond to a pressure ranging from 2.5 to 10 MPa to determine the contact area between the workpiece and the lapping tape. The experimental results indicated no difference between the contact area and workpiece for the lapping tapes investigated: each type of lapping tape was in contact with the workpiece in an area measuring 24.4 mm wide and 1.6 mm long, from which we have obtained a lapping pressure of 2.6 MPa. The contact area, despite being affected by the backup roller's elastic deformation, appeared irrelevant to the substrate thickness. We used a pressure-sensitive paper for medium-pressure use that can respond to a pressure ranging between 10 and 50 MPa to visualize the contact area between the workpiece and abrasive grains, on which high pressure or actual processing points were imposed. **Fig. 10** shows photographs of the pressure-sensitive paper used in this study, where the area on which pressure was imposed was colored in red, from which the abrasive grains contributing to lapping can be visualized through their dispersal on the pressure-sensitive paper. The number of abrasive grains contributing to lapping in the area 2 mm in the tape width direction and 1 mm in the tape feed direction was six for tape A with a 75-μm-thick substrate, and 40 for tape B with a 125-μm-thick substrate. As for tape C with abrasive grains formed in a file-shaped texture structure, its ridge lines are shown as contact traces. A comparison of the photographs of tapes A and B reveals that the thicker the tape's polyester substrate, the more significant is the substrate deformation by the lapping pressure [1]. Hence, the numerous lapping abrasive grains on tape B generated firm adhesions, causing the superimposition of ultrasonic oscillations to fail to sufficiently inhibit adhesions.

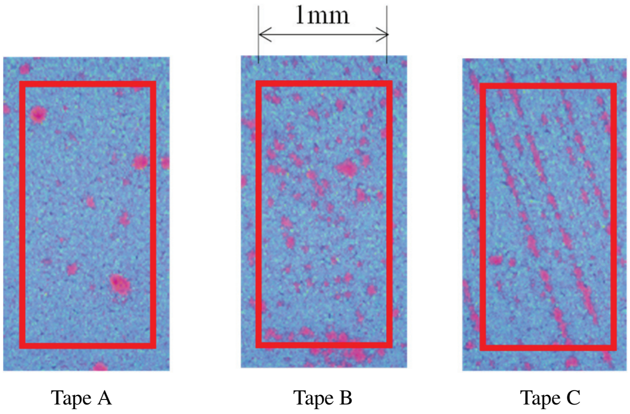


Fig. 10. Number of working grains.

4. Conclusions

In order to improve the lapping efficiency (improvement rate of surface roughness per unit time) in tape lapping, we proposed a method that superimposes ultrasonic oscillation on a working fluid. The working fluid discharged from the nozzles establishes contact with the ultrasonic oscillatory horn before being supplied to the processing points. We experimentally compared various types of lapping tapes of different substrate thicknesses. The following experimental findings were obtained.

(1) We fabricated a stepped-type ultrasonic oscillatory horn that is suitable for tape-lapping devices. It comprised a single slit and its structure enabled ultrasonic oscillations to be superimposed on a working fluid that had passed through its slit. We measured the impulsive force of cavitation using a hydrophone type sound pressure meter and discovered that the measured sound pressure was approximately one-tenth of that of the ultrasonic cleaning device in supplied power ratio.

(2) We compared the improvement rates of surface roughness to verify the effects of ultrasonic oscillations. We performed lapping with a lapping tape with diamond abrasive grains of 9 μm average diameter formed via bonding. We approximated changes in the surface roughness with respect to the lapping time using an exponential function to obtain the time constant. The time constant improved from 18.9 s in inertia lapping to 7.6 s by applying ultrasonic oscillations, thereby proving the effects of ultrasonic oscillations on improving the lapping speed.

(3) We discovered that the closer the horn tip was to the processing point, the more improved was the surface roughness. Furthermore, the sound pressure generated by cavitation increased in a shorter distance between the horn tip and processing point. Therefore, we speculated that the abovementioned effects were due to ultrasonic cavitation.

(4) We performed lapping using lapping tapes (75 and 125 μm in substrate thickness) comprising #2000 WA abrasive grains and measured the resultant surface roughness; we discovered that whereas the lapping tape with a 75-μm-thick substrate improved the rate of change of the surface roughness, the lapping tape with a 125-μm-thick substrate generated no improvements. In order to compare the adhered chip's firmness, we cleaned the lapping tapes after using them by applying a working fluid onto them. We discovered that whereas the working fluid with no superimposed ultrasonic oscillations did not remove the adhesions from the tapes, that with superimposed ultrasonic oscillations successfully removed the adhesions from the tapes; more adhesions were removed (approximately 50% of the adhesions) in the second-half of lapping than in the first-half. A larger power was supplied to the ultrasonic transducer, resulting in better adhesion removal.

(5) We used pressure-sensitive paper to verify differences in lapping when lapping tapes of different substrate thicknesses were used. We discovered no difference in the tape's contact area at different lapping pressures, whereas the number of abrasive grains that involved in lapping increased as the substrate became thicker; this is attributable to the fact that the chips that were firmly adhered onto the tapes rendered the ultrasonic oscillations deficient in terms of their adhesion inhibition effects, depriving them of their capability.

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