# Experimental Investigation on Removal Mechanism at Tool Rotational Center in Glass Polishing

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KEYWORDS: Polishing, Abrasives, Processing

*Preston's law is a widely used equation that expresses time-dependency of material removal in polishing process. In this research, it is experimentally found that Preston's law does not hold at tool rotational center in glass polishing. Through polishing experiment, this type of removal is concluded to be basically a mechanical phenomenon and accelerated by chemical reaction. By observing the motion of abrasive particles during polishing, it is found that the abrasive particles travel on concentric trajectories around tool rotational center even in loose-abrasive polishing. By measuring the pressure distribution in static situation and the contact force during polishing, it is concluded that hydrodynamical effect does not occur in removal at tool rotational center. Finally, single particle polishing experiment is performed to investigate the relationship between distance from tool rotational center and removal depth by a single abrasive particle. As a result, removal depth by a single abrasive particle got maximum value at tool rotational center in all the conditions. From these results, it is concluded that the reason why Preston's law does not hold is because removal by a single particle increases at the rotational center.*

**NOMENCLATURE**

$z$ = material removal depth [nm]
$t$ = time [s]
$k$ = Preston coefficient [mm$^2$/N]
$p$ = contact pressure [MPa]
$v$ = relative velocity of polishing pad to the workpiece [mm/s]
$r$ = distance from the tool rotational center [mm]
$\omega$ = tool rotational speed [rpm]

## 1. Introduction

Preston's law is a widely used equation which expresses the time-dependency of polishing process[1]. Numerous researches have been performed on predicting material removal in polishing process based on Preston's law.

There is an increasing demand for finishing of small and complex components in various industries such as optics, medical and aero industrial fields[2]. In ultra-precision CNC polishing, sometimes it is necessary to keep the polishing tool rotation axis nearly perpendicular to the surface of workpiece to prevent the tool or machine from colliding with the workpiece when it has convex area. In such a case, the tool rotational axis crosses the surface of workpiece and the tool rotational center appears on the surface, where the relative velocity is theoretically zero. Although a correction of Preston's law for low polishing speed has been proposed[3], a literature survey did not return any previous research on material removal at the tool rotational center, especially on whether Preston's law holds true at that point.

In this research, it is experimentally found that Preston's law does not hold at tool rotational center in glass polishing. The reason will be investigated experimentally from a mechanical viewpoint.

## 2. Polishing simulation and experiment with spherical tool at zero-degree attack angle

### 2.1 Overview

According to Preston's law, $z$ can be obtained by calculating the following time-domain differential equation[1];

$$\frac{dz}{dt} = k\ p\ v \qquad (1)$$

where $k$ is called Preston coefficient and determined by the polishing conditions; type of abrasive, liquid, workpiece material and so on.

In this research, polishing with a spherical tool at zero-degree attack angle is considered as the basic condition to investigate on the removal at the tool rotational center. The setup is shown on fig. 1. First, removal rate is predicted based on Preston's law, and no removal is predicted at tool rotational center since $v$ is theoretically zero at that point. Next, polishing experiments are conducted to examine if Preston's law holds true at the rotation center of spinning polishing tools. Finally some possibilities are discussed as the reason for disagreement between the prediction and experimental data.

### 2.2 Simulation based on Preston's law

$p$ was calculated based on Hertz's contact theory[4], assuming polishing tool as a sphere of rubber, neglecting the effect of the thin polishing pad. Distribution of $p$ when the tool offset is 0.3 mm was simulated and the result is shown in fig. 2.

Distribution of $v$ can be simulated geometrically as follows;

$$v = r\omega \qquad (2)$$

Fig. 3 shows the relationship of $v$ and $r$ when $\omega$ = 1000 rpm.

According to Cook[5], $k$ = 2.0×10$^{-7}$ mm$^2$/N when the abrasive is 1.2 μm-$CeO_2$, liquid is water and workpiece is silica glass. Therefore, removal rate profile can be simulated and the result is shown on fig. 4. It is predicted that the removal is zero at the tool rotational center.

### 2.3 Polishing experiment

Polishing experiment was performed with the same setup as fig. 1. Polishing conditions are shown on table 2. It is known that $CeO_2$ in water has a strong chemical effect on silica glass[6]. In order to investigate if the abrasive's chemical effect is the critical reason for removal at tool rotational center or not, SiC and glycerol, which are non-chemically reactive on silica glass, were used as slurry.

Fig. 5 shows the obtained removal footprints. In both cases, removal was observed at the center of footprint. Therefore, it can be said that Preston's law does not hold at the tool rotational center. Moreover, while removal depths in the two conditions are roughly on the same scale, the polishing time was 300 times longer in SiC + glycerol than $CeO_2$ + water. This is considered to be caused by the chemical effect of $CeO_2$ and water on silica glass.

From these results, it can be concluded that material removal at tool rotational center is basically a mechanical phenomenon, and that it can be accelerated by chemical reaction between abrasive particles and workpiece, or between liquid and workpiece.

## 3. Experiments on abrasive velocity distribution, contact pressure distribution and single particle polishing

### 3.1 Purpose

As the mechanical reasons for removal at tool rotational center, the following possibilities can be considered;

(a) Contact pressure distribution may differ from the simulation. Some hydrodynamic effect of slurry could be increasing contact pressure at the rotational center.

(b) Abrasive's velocity distribution may differ from simulation.

(c) $k$ may not be constant and may depend on $r$.

In this chapter, these 3 hypothesized reasons for material removal at the tool rotational center are investigated by experiments.

### 3.2 Contact pressure distribution

In this section, hypothesis (a) is examined by obtaining distribution of $p$ experimentally and measuring the contact force when the tool is rotating or not.

Fig. 6 shows the experimental setup. In this setup, the contact force was measured by force sensor (measurement range: 0 to 20 N, sensitivity: -80.71 pC/N). A pressure sensing sheet (Measurement range: 0.2 to 0.6 MPa) was fixed by a magnetic stand between the tool and the microscope glass and was pressed between them. Tool offset was 0.3 mm and tool rotational speed was 1000 rpm.

Fig. 7 shows the simulated and measured distribution of $p$. The measurement agreed well with the simulation although the measurement is quite noisy on the whole. This is considered to be

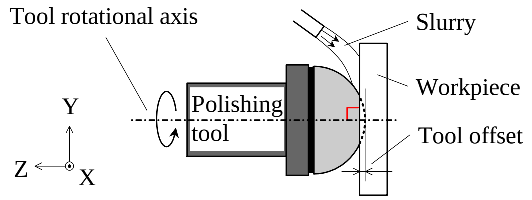



Fig. 1 Setup of zero-precess degree polishing

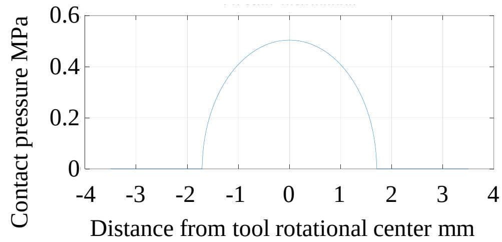



Fig. 2 Simulated contact pressure distribution

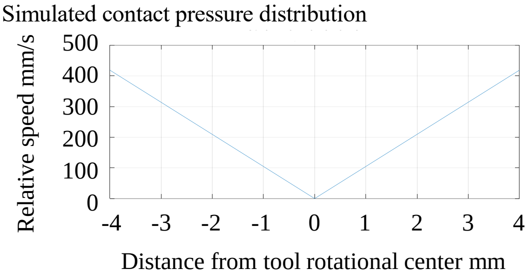



Fig. 3 Simulated velocity distribution

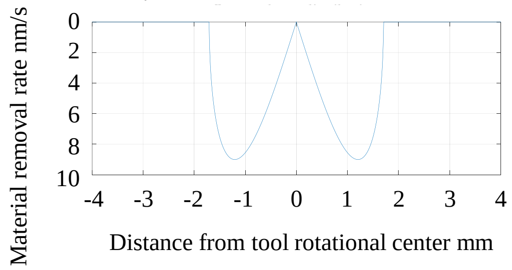
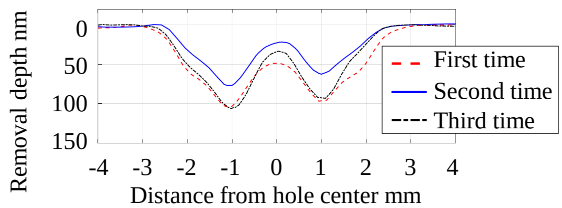


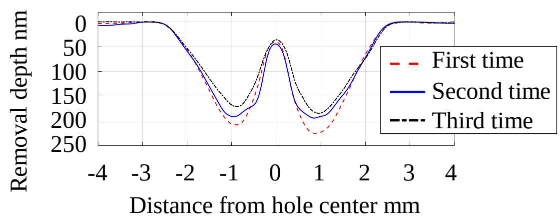

Fig. 4 Simulated removal rate distribution

Table 1 Polishing conditions

| | | | |
|---|---|---|---|
| Name of condition | | $CeO_2$ + water | SiC + glycerol |
| Slurry | Abrasive | 1.5 μm-$CeO_2$ | 1.2 μm-SiC |
| | Liquid | Water | Glycerol |
| | Concentration | 40 g/L | 20 g/L |
| Workpiece | | Silica glass | |
| Tool rotational speed | | 1000 rpm | |
| Tool offset | | 0.3 mm | |
| Polishing time | | 10 s | 3000 s |
| Number of repetitions | | 3 | |




(a) $CeO_2$ + water (polishing time: 10 s)




(b) SiC + glycerol (polishing time: 3000 s)

Fig. 5 Measured removal depth profiles

caused by asperity of the polishing pad.

Fig. 8 shows measured force profiles when the tool was rotating and when it was not. The contact force decreased exponentially after initial contact. This is considered to be caused by viscoelasticity of the rubber in the tool. Although mechanical vibration can be observed during tool rotation, the total force agrees with the integrated measurement from the pressure sheet. Therefore, it can be said that the contact force is not affected by tool rotation. Hence it can be concluded that there is no measurable hydrodynamic effect in zero-degree attack angle polishing, and that distribution of $p$ is not affected by tool rotation.

### 3.3 Abrasive velocity distribution

This experiment aims to examine the hypothesis (b). The motion of abrasive particles is directly observed with an optical microscope and a high-speed camera and their velocity distribution is derived and compared to that of the polishing pad.

Fig. 9 shows the experimental setup. The polishing tool was connected to a servo motor and rotated at 1000 rpm. The polishing tool was pressed onto a microscope glass as workpiece. The workpiece was fixed on a punched angle bar. A shear force sensor was fixed under the angle bar and was used to detect contact of the polishing tool and the workpiece. Tool offset was 0.3 mm. An optical microscope was fixed on the opposite side of workpiece to the polishing tool. High-speed camera was connected to the optical microscope to record the image obtained with the optical microscope. Abrasive and liquid of the slurry was 1.5 μm-$CeO_2$ and water, respectively, and the concentration was 20 g/L. Table 2 shows the observation conditions.

Fig. 10 shows the observed abrasive particles and their trajectories. It can be seen that the abrasive particles travel on concentric trajectories around the rotational center. Speed distribution of abrasive particles were obtained from the trajectories and is shown on Fig. 11. The straight lines show the speed distribution of polishing pad simulated by equation (2). As shown on this figure, abrasive's velocity distribution agreed well with that of polishing pad.

### 3.4 Single particle polishing

Single particle polishing is conducted in order to simplify the problem and to examine the hypothesis (c).

First, removal depth by a single particle is predicted by Preston's law. Suppose glass workpiece is polished with a flat polishing tool, the contact pressure is uniform at $p_0$ and load onto each particle is the same inside the nominal contact area. Set $T$ as the polishing time. Between $z$ and $r$, the following relationship should hold;

$$z = \frac{dz}{dt}T = kpvT = kp_0vT = kpr\omega T \propto r \quad (3)$$

Suppose the abrasive particles should distribute uniformly inside the contact area. Set $N(r)$ as the number of abrasive particles located at a distance $r$ away from the tool rotational center. Since the distribution is uniform, $N(r)$ is considered to be in proportion to $r$;

$$N(r) \propto r \quad (4)$$

Set $z_0$ as removal depth by a single particle located at $r$ away from the tool rotational center. $z_0$ can be obtained as follows;

$$z_0 = z/\{N(r)\} \quad (5)$$

From equations (3) and (4), both of the numerator and denominator of the right side of equation (5) are in proportion to $r$. Thus $z_0$ is supposed never to depend on $r$ according to Preston's law.

Fig. 12 shows the experimental setup. A diamond stylus was

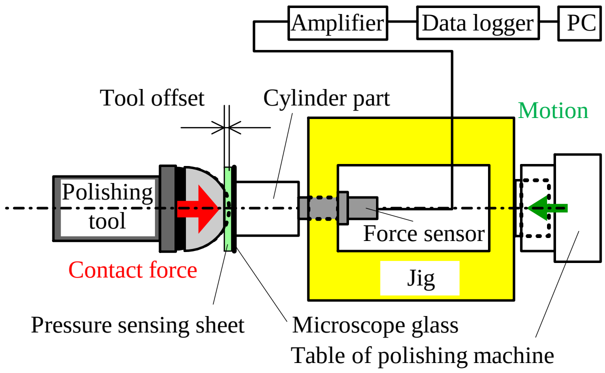



Fig. 6 Setup of contact pressure measurement

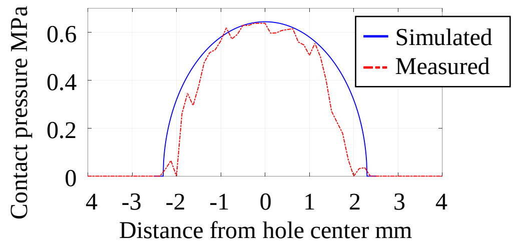



Fig. 7 Simulated and measured contact pressure distribution

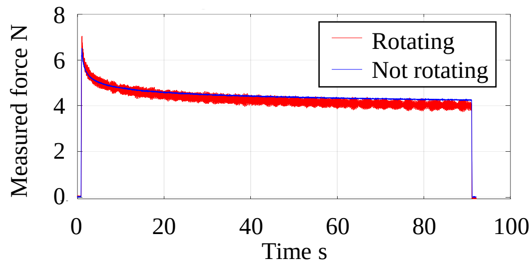



Fig. 8 Measured contact force profiles when the tool is rotating or not

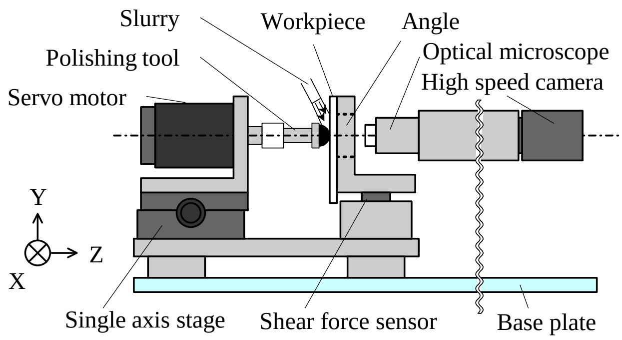



Fig. 9 Setup for observing motion of abrasive particles

Table 2 Observation conditions

| | |
|---|---|
| Frame rate | 1000 fps |
| Pixels | 320 × 240 |
| Observation time | 3 s |

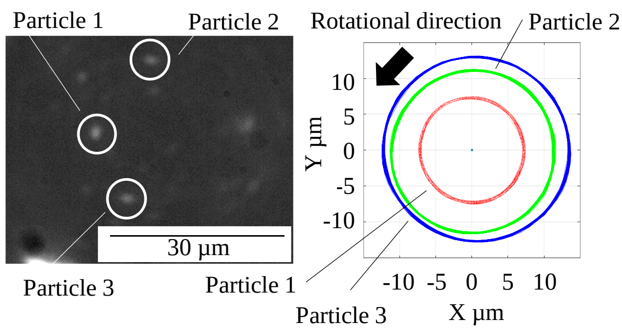



Fig. 10 Observed abrasive particles (left) and their trajectories (right)

regarded as an abrasive particle. The stylus was fixed on a fine force sensor (measurement range: ±0.5 N, resolution: 0.1 mN) and the silica glass workpiece was rotated at 200 rpm for 2000 s. During the rotation, the measured force was fed back to the piezoelectric stage (travel range: 30 μm, resolution: 1 nm) to keep the force constant. The stylus's relative position to the rotational center (trajectory radius) was changed and grooves with different radii were made. Depths of the grooves were measured by Atomic Force Microscope (AFM) (Position control resolution: 1 nm, minimum force sensitivity: 2 pN). Table 3 shows the polishing conditions.

From the measured surface profiles, depths of the grooves were extracted for all the conditions and were plotted against the trajectory radius on fig. 13. In all the combinations of tip radius, constant force and liquid, the depth was largest at the rotational center. From this fact, it can be said that the removal by a single particle gets maximum at the 0 mm trajectory radius, or the tool rotational center. Preston coefficient is considered to depend on the distance from the tool rotational center.

## 4. Conclusions

Preston's law was examined, focusing on material removal at the tool rotational center. As a result of the polishing experiment, removal was observed at that point, which is against Preston's law. In order to clarify the mechanical reason, experiments on contact pressure, motion of abrasive particles and single particle polishing were conducted. As a result, contact pressure distribution and motion of abrasive particles agreed well with the simulation. Removal by a single particle got maximum at the 0 mm trajectory radius, or tool rotational center against Preston's law. Thus Preston coefficient is considered to depend on the distance from the tool rotational center.

## ACKNOWLEDGEMENT

This work was supported by the Grant-in-Aid for Scientific Research No. 17K14571 from the Japan Society for Promotion of Science, and the grant program for research and development from the Mazak foundation. The authors acknowledge support from Zeeko Ltd. in loaning the polishing system and measurement equipment.

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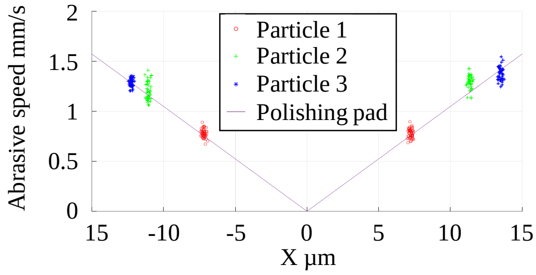


Fig. 11 Obtained abrasive speed distribution

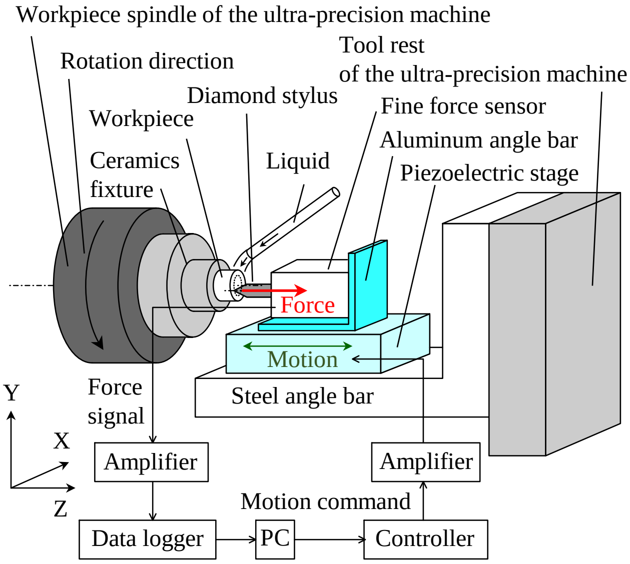


Fig. 12 Setup of single particle polishing

Table 3 Conditions for single particle polishing

| Tip radius of diamond stylus μm | | 10 | 25 | | | |
|---|---|---|---|---|---|---|
| Liquid | | Water | | | | Water -insoluble cutting oil |
| Constant force mN | | 16 | 10 | 35 | 100 | 100 |
| Trajectory radius mm | 0.00 | ○ | ○ | ○ | ○ | ○ |
| | 0.05 | ○ | | ○ | ○ | ○ |
| | 0.20 | ○ | ○ | ○ | ○ | ○ |
| | 0.50 | | | ○ | | |
| | 1.00 | ○ | ○ | ○ | ○ | ○ |
| | 2.00 | ○ | | ○ | | |

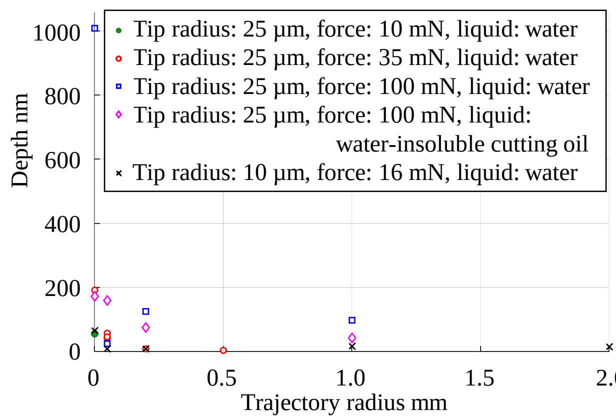


Fig. 13 Relationship between trajectory radius and removal depth in the single particle polishing