

Glass polishing with bound-abrasive vibrating polishing tools

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Fixed-abrasive polishing of fused silica glass in conjunction with vibration under dry conditions was developed. Preliminary results show that material removal rate can be raised by up to >50% by applying vibration in fixed-abrasive polishing of fused silica. The likely reasons are reckoned to be outstanding capability of dispelling debris populated at the interface between polishing tool and glass, which is considered to hinder polishing process. On the other hand, surface roughness of polished fused silica is slightly degraded in vibration polishing compared to that without vibration. Certain periodical structure resulting from vibration appears on the machined surface, of which the spatial period is consistent with vibration. The mechanism of material removal in dry polishing is due probably to the synergy of chemical and mechanical effects between ceria and silica in polishing tool and workpiece, respectively. Ceria in the tool first bonds with silica to form Ce-O-Si systems under extreme pressure and then the Si-O de-bonds owing to the greater strength of the Ce-O; this way, debris forms and glass is polished.

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1. Introduction

Glass polishing, an ancient craft dating back to Newton's time, is usually finished by loose polishing process. Loose abrasive polishing is still a prevailing finishing technique, which is also applied to the polishing of optical and electronic substrate, inclusive of semiconductors, glass, ceramics and metals [1-2]. Typical loose abrasive polishing is comprised of 3 factors, polishing tools, polishing slurry and workpiece (Fig. 1). The polishing is fulfilled by the interaction among tools, slurry and workpiece, which is a three-body process. The motion of abrasives is stochastic and renders the process unpredictable, resulting in non-deterministic characteristics of the process. Aside from the physical nature of the loose polishing process, chemical reaction is considered to be of paramount importance to the polishing processes that employ abrasive softer or equivalent to the workpiece to be polished. The loose abrasive polishing possesses obvious superiorities: generating ultra-smooth surface (surface roughness $RMS < 1.0\text{nm}$), inducing little surface and subsurface damage [3-8]. However, some inherent shortcomings accompany the process, such as frequent dressing of polishing lap, minor "active" abrasives (<0.5%), lack of determinism, etc. Hence some institutes and organizations have turned to fixed abrasive polishing [9-11]. Fixed abrasive polishers will be instrumental in automatizing polishing process and

facilitating predictable manufacture. The abrasives are imbedded in a matrix made of polymers and no additional slurry is supplied during manufacturing. The process can be viewed as a two-body process. The distribution and the trajectories of the abrasives, to a certain extent, can be modeled. Moreover, the number of "active" abrasives participating in material removal is considerably increased. As a consequence, the process is more deterministic than loose abrasive polishing. 3M Company has succeeded in polishing STI (shallow trench isolation) with fixed abrasive polishing pad [10]. Noritake Corp. has manufactured the prototype of a new fixed-abrasive pad. The pads have some common features: the abrasive (usually ceria) is bound in foamed polyurethane which is impregnated with pores. Another type of fixed abrasive tool has recently developed for glass [11], in which the ceria abrasives and additives are mixed in the epoxy resin matrices. The surface roughness of glass polished with the tools approaches $Rq < 1.0\text{nm}$. Li et al. [12-14] also fabricated a fixed abrasive tool for glass polishing in collaboration with industrial organizations. Ceria is chosen as the polishing abrasives in the tool. Owing to the hardness of ceria that is comparable to glass, the glass is unlikely to be polished purely mechanically. It is chemical effects that are regarded as the crux in removing material.

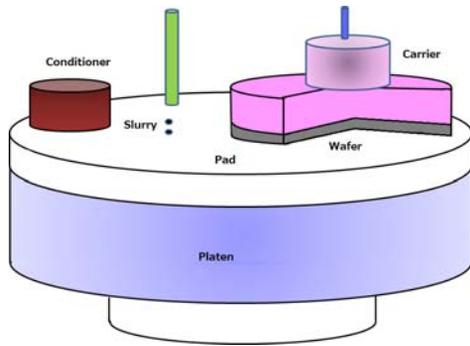


Fig. 1 Schematic of loose abrasive polishing system. The workpiece is pressed against a polishing pad. The pad and the workpiece can rotate independently. During the polishing, the slurry containing widespread use abrasives- ceria is circulated onto the polishing pad. The abrasives may roll and slide on the surface of workpiece. The reaction among rolling abrasives, workpiece and polishing pad is considered to be three-body process.

As it is well known, machining performance, at least material removal rate, can be improved by introducing ultrasonic vibration into manufacturing processes. The easy-to-implement adds to the universality of ultrasonics to machining processes. Numerous hybrid polishing processes entailing ultrasonics have been postulated, represented by ultrasonic drilling, grinding, and so forth. The ultrasonics has been applied to the loose abrasive polishing [15]. The abrasives in the slurry are energized by ultrasonics, which impact the surface of workpiece. The sliding, rolling and impaction of the abrasives results in removal of materials from the workpiece surface. The smoother surface and greater material removal rate have been confirmed. The reason is assumed to be that more abrasives will contact and remove the material from workpiece surface and sliding distance can be prolonged by the use of ultrasonics during the polishing process. Inspired by the fact that machining performance can be ameliorated on the introduction of ultrasonic vibration into machining processes, we here “appropriate” this creed to amalgamate ultrasonic vibration with newly developed fixed abrasive polisher with anticipation of the improvement either in material removal rate or in surface quality. The polisher is composed of ceria abrasives, bonding materials and chemical additives. No aqueous additives or slurries were utilized. Our preliminary results of ultrasonic fixed-abrasive polishing suggest that material removal rate (MRR) is considerably enhanced after integrating ultrasonic vibration whilst surface roughness does not deteriorate appreciably. The related experimental setup is detailed, which is followed by our latest results.

2. Experimental

An experimental setup is assembled as depicted in Fig. 2. A customized ultrasonic vibrator produced by bonding a PZT ceramic device onto a metallic body is installed together with a force sensor. The detailed structure and dimensions of the vibrator were determined by FEM using a commercial software (PIEZO plus 4.0) given the prerequisite f_{L1} (the frequency of 1st longitudinal vibration mode of the vibrator) = f_{B4} (the frequency of 4th bending vibration mode of the vibrator). Thus, an elliptical (i.e., 2D) ultrasonic vibration can be generated on the end face of the metallic body when two phases of AC voltages with a phase difference are applied to the PZT device at the same frequency of $f = f_{L1} (= f_{B4})$, resulting in the elliptical ultrasonic vibration of a fixed-abrasive polishing pellet glued to the end face of the metallic body. The pellet is composed of ceria, prevailing abrasives in glass polishing community. The ceria is bound with special epoxy mixed with chemical additives. In addition, the pellet is full of abundant pores with diameter of tens of microns. The possible effect of pores may be to accommodate the polishing swarf and to expedite the dissipation of the heat generated in polishing process, which is conducive to the generation of the surface with low surface roughness and high material removal rate. The external downward load was supplied by a pair of compression springs and was calibrated with the force sensor (a dynamometer Kistler 9257A, Switzerland). The downward load is determined by the relative displacement of the polishing head. A circular fused silica sample was placed on the lower platform. The platform is able to rotate with its central axis. The detailed experimental parameters are tabulated in Table 1. In addition, the vibrator can oscillate in horizontal direction with amplitude of A and velocity of V_x by a linear motion actuator.

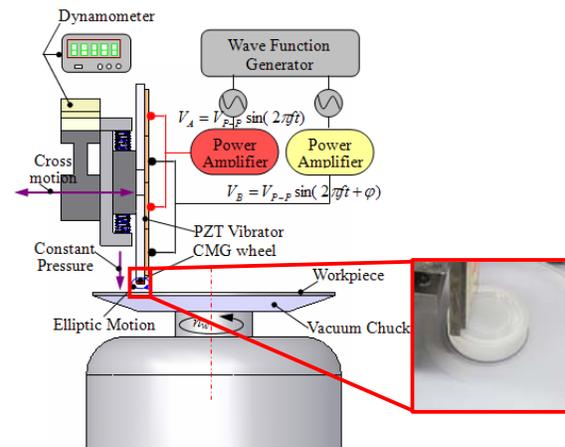


Fig. 2 Schematic illustration of experimental apparatus.

Table 1. Detailed processing parameters.

Sample	Fused silica	$\Phi 50\text{mm} \times 10\text{mm}$
	Initial surface roughness Ra	$\sim 200\text{nm}$
Pellets	Dimension	$\Phi 4\text{mm} \times 1\text{mm}$
	Abrasive	CeO_2
Ultrasonics	Frequency	15.3kHz
	Applied voltage Vp-p	150V
	Phase difference	135°
Stroke in X direction	A	3mm
Velocity of oscillation	Vx	3mm/s, 6mm/s, 9mm/s
Downward load	L	$\sim 4\text{N}$, $\sim 8\text{N}$, $\sim 12\text{N}$
Rotation rate	ω	$\sim 400\text{rpm}$, $\sim 600\text{rpm}$, $\sim 800\text{rpm}$

Ultrasonic vibration of polishing head was tested with a laser Doppler vibrometer (Ono Sokki LV-1610, Japan) around natural frequency. The trajectory of the ultrasonic vibration of polishing head was captured with an oscilloscope (LeCroy WaveJet 314, USA). The vibration amplitude is roughly proportional to the applied voltage.

The machined region was an annular zone $\sim 15\text{mm}$ away from the center of the sample. Four measurements of surface roughness were made near the middle of the annulus at 3, 6, 9, 12 o'clock positions with an optical profilometer at $10 \times$ magnification (Zygo Newview 600, USA). The reported surface roughness is the average of the four measurements. The material removal was evaluated with a contact stylus profiler (Tokyo Seimitsu Surfcom480A, Japan). The surface roughness and material removal were inspected every 10min after cleaning the surface with ethanol. Each sample was machined for 60min.

3. Results and discussion

3.1 Material removal rate (MRR) of polishing with and without vibration

The material removal rate was compared between two polishing techniques under various processing parameters. It is found that the MRR is indeed increased after the ultrasonics was switched on (Fig. 3). The MRR can be

increased by at least 50% in some cases, from $\sim 4\mu\text{m/h}$ to over $6\mu\text{m/h}$. The increase in the MRR is attributed to the strong dispelling of polishing debris in UV polishing (Fig. 4). The debris is considered to be deleterious to the machining process, which can hamper the chemical and mechanical effects at the interface between ceria abrasives and silica glass. The results also show that there exists an optimum reciprocation velocity in X-axis (Fig. 5). Both over-fast and over-slow velocity will not benefit the MRR. The reasons is unclear, because the X-axis velocity is far lower than the linear speed of the workpiece and therefore should have minor effects on the linear speed and material removal rate on the premise that the Preston's formula is applicable [16]. However, if the Preston's formula is reasonable in our cases, then the MRR should increase with the rotational rate. But the MRR actually rises first as the rotation rate is increased and will drop as further increased rate (Fig. 6). The causes are conceived to be chemical actions that are strongly affected by temperature determined by the friction heating and dissipation of the heating. Less and greater linear speed will lower the generated heat and temperature and the highest is achieved at a rotation rate where a balance is struck between dissipation and generation of heating. The temperature during machining is still ongoing.

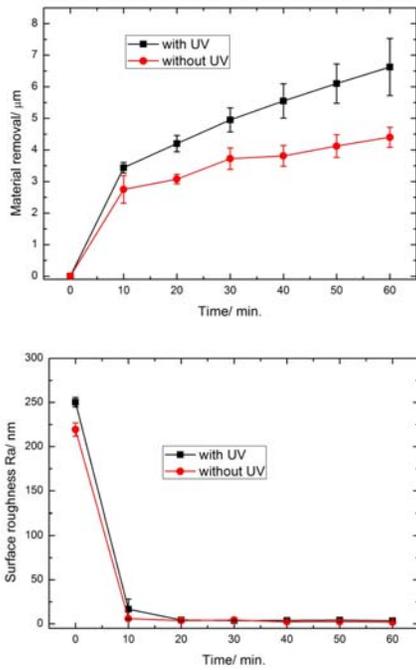


Fig. 3. The material removal rate and surface roughness in the processes with and without vibration.

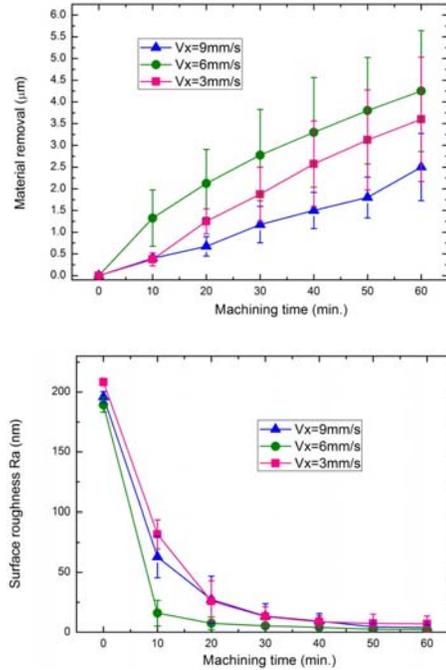


Fig. 5 The material removal rate and surface roughness in the processes with vibration under varied reciprocation rates.



(a)



(b)

Fig. 4. The debris on and around the pellet (a) with vibration (b) without vibration.

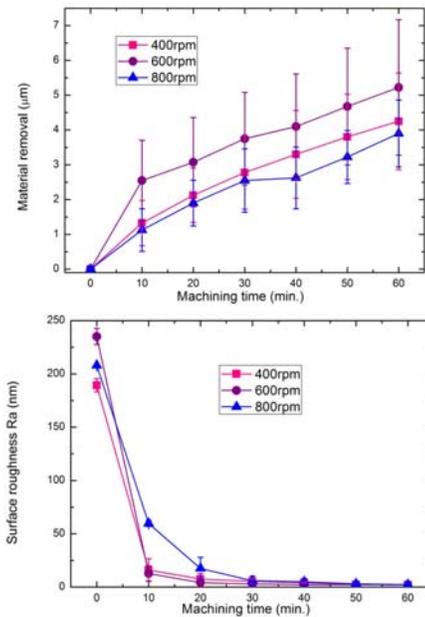


Fig. 6. The material removal rate and surface roughness in the processes with vibration under varied rotational rates of workpiece.

3.2. Surface roughness of polished glass with and without vibration

Another phenomenon can also be readily identified that the ultrasonic vibration mildly deteriorates the surface roughness. The surface roughness was also compared after

there were no discernible cracks by grinding. The results show that the surface roughness Ra by “with UV” polishing populates the range of 2~5nm while that by “without UV” mostly falls into 1~4nm, lightly smaller than that in “with UV” polishing (Fig. 7). The best surface roughness by both machining techniques is <2.0nm. Typical morphology of machined surface is displayed in Fig. 8. The fused silica by “with UV” process takes a patterned surface with a spatial period of $\sim 35\mu\text{m}$. The computed period is $\sim 41\mu\text{m}$ ($=v \cdot t = \omega \cdot r \cdot t = 2\pi \cdot n \cdot r \cdot t = \sim 41\mu\text{m}$) consistent with the measured one, implying that the patterned surface results from ultrasonic vibration.

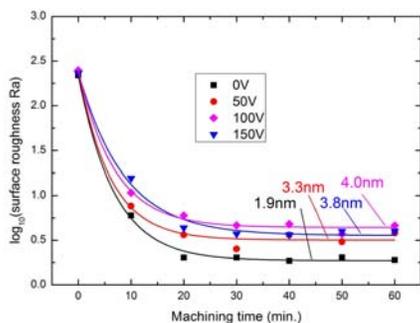


Fig. 7. Variation of surface roughness during polishing.

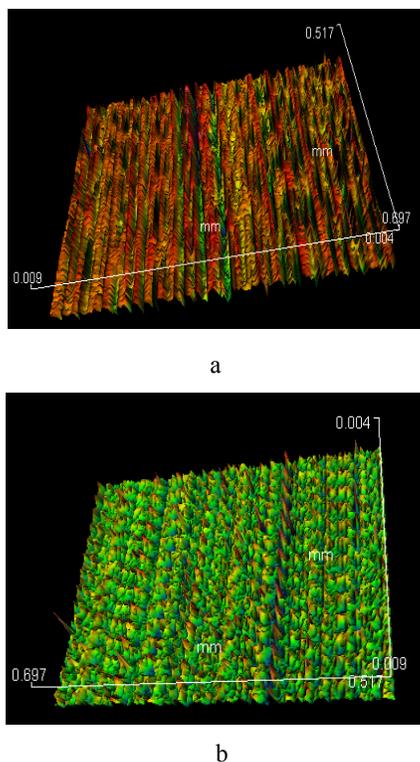


Fig. 8. Surface morphologies machined by (a) “without UV” and (b) “with UV”.

3.3. Probable material removal mechanism in dry polishing

The elements in polishing pellet and debris were examined to disclose the possible mechanism of material removal. In the EDX analysis, we find only the Ce element in pellet whilst the abundant Si element was detected in debris (Fig. 9), suggesting that glass is removed by either mechanical or chemical actions. But we infer that the material is removed by chemical actions in that the hardness of ceria is not more than glass [17-18]. Based on the results, we surmise that the material removal process is as follows: firstly, the ceria reacts with silica in solid-state phase under the circumstances of exceedingly high pressure to form new substances with lower hardness than glass bulk and ceria on the topmost of fused silica and then the resultant softer substances are removed by ceria abrasive mechanically and plastically; alternatively, the Ce in ceria abrasives bonds with Si in glass, next silica material is torn away from glass as a lump on account of greater strength of Ce-O bond than Si-O bond and lastly the lump is disengaged and this way the glass material is removed. The actual mechanism of material removal needs further investigations. Returning to the point, we ascribe the reduction in material removal rate to the adsorption of silica onto the surface of ceria abrasive as it could hinder and even stop chemical reactions between ceria and silica. As a consequence, the material removal rate is decreased. In our experiments, less intense pressure is preferable so that the polishing can proceed smoothly. The reason for the outstanding performance in material removal rate by “with UV” process may lie in the exceptional capacity to dispose the polishing debris between pellets and surface being machined. The debris is considered to be detrimental to machining in grinding process. In our experiments, the debris resulting from the chemical reaction products and/or silica can increasingly cover the surface of pellets and thereby undermine potential reactions between CeO_2 and SiO_2 . As a result, the material removal rate is decreased accordingly because of the accumulation of polishing debris. The material is removed due crucially to the synergy of chemical and mechanical actions. It is presupposed that ceria bonds with silica to form Ce-O-Si systems and then the Si-O de-bonds owing to the greater strength of the Ce-O. This way, the glass is polished and debris forms. If the debris caulks at the interface of the polisher and glass workpiece, the MRR will drop because silica on the surface of debris suppresses the chemical bonding, which also corroborates indirectly the interpretation for greater MRR in UV-assisted polishing. The surface roughness was also compared after there were no discernible cracks by grinding.

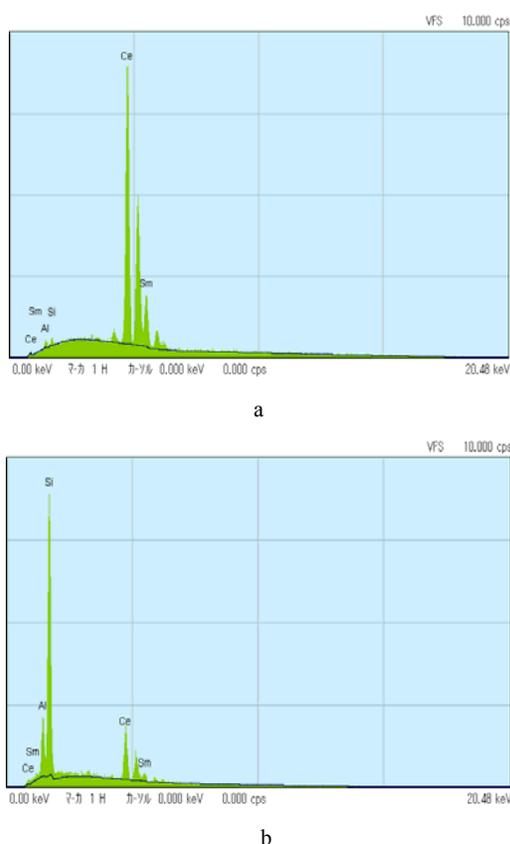


Fig. 9. EDX spectra of (a) pellets and (b) debris: ample Si appears in debris while little Si can be found the pellets.

4. Summary

We propose a polishing process in which vibration is integrated into new fixed abrasive polishers. The results evidence that material removal rate is improved upon the introduction of vibrations compared to that without vibrations. Increasing the vibration amplitude, the material removal rate is also raised. It is the outstanding debris-dispelling ability of vibration-assisted polishing that benefits the material removal rate. The material is removed due crucially to the synergy of chemical and mechanical actions. It is postulated that ceria bonds with silica to form Ce-O-Si systems and then the Si-O de-bonds owing to the greater strength of the Ce-O. This way, the glass is polished and debris occurs. If the debris caulks at the interface of the polisher and glass workpiece, the material removal rate will drop because on the surface of debris is silica which suppresses the chemical bonding, which also corroborates indirectly the interpretation for greater removal rate in vibration-assisted polishing.

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