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RESEARCH ARTICLE

Profile and roughness of electrorheological finishing optical surfaces

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Abstract This paper focuses on the process of electrorheological (ER) finishing optical surfaces. Experiments on *K9* mirrors were conducted. In one experiment, the operating distance was varied over 0.5–0.8 mm with the voltage at 2000 V. The maximum peak-to-valley (*PV*) reduction was obtained at the distance of 0.5 mm, where the *PV* value was reduced from 58.71 to 25.03 nm. In another experiment, the voltage was varied over 1500–3000 V with operating distance at 0.5 mm. The final surface roughness (*Ra*) achieved was as low as 2.5 nm. A higher voltage produced a higher relative reduction of the *Ra*. These experimental results validated the process.

Keywords electrorheological (ER), finishing, surface roughness

1 Introduction

In recent years, the size of many optical components has reduced and demands of surface figure accuracy of micro-sized glass lenses have increased considerably. These trends have prompted research in the finishing of small-size and high precision parts. Various field–assisted polishing processes have been developed. Among them, magneto-rheological polishing [1–3], magnetic fluid polishing [4] and magnetic abrasive polishing [5–7] are noticeable for the ultra-precision finishing of parts at macro and meso scales. However, these processes are not suitable for the production of micro-aspheric shapes due to difficulties in concentrating abrasive particles to tiny regions of small optics.

Electrorheological (ER) polishing was first proposed by Kuriyagawa and Syoji [8] in 1999, when ER fluid together with abrasives (diamond, green carborundum, or white fused alumina) in slurry was used in the polishing of micro-aspheric lenses and metallic dies. The ER fluid assisted finishing equipment was developed [9,10] and involved a spindle with a tungsten carbide tip. While the tip served as anode for ER polishing, the conductor workpiece was used as cathode.

Kim et al. also investigated ER fluid-assisted polishing and developed padless ultra-precision polishing using ER fluid [11–13]. A workpiece was put under a mass on a rotating platen, and a high voltage power supply provided the potential difference between the tool and the platen. Zhang et al. [14] developed a theoretical model for the size of the polishing spot. To prevent short circuiting, Tanaka [15] proposed putting a pad between the tool and the workpiece, and Kaku et al. [16] developed a resin-coated micro polishing tool using plasma chemical vapor deposition.

Not-withstanding many years of investigation, there are still drawbacks in existing ER polishing tools which restrict their practical applications. Traditional point-type tools contain only one of the electrodes in ER polishing. For non-conductor workpiece, an auxiliary electrode needs to be placed close to the surface of the workpiece. This implies custom made electrodes may be needed in some polishing work. Also, its location changes relative to the auxiliary electrode, when the tool is moved about on the workpiece to polish. As the electric field changes with the tool location, this can result in rather unstable removal and polishing performance.

2 Parametric designs for ER finishing

ER fluids are usually non-conducting and have low viscosity. The viscosity increases significantly when an

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electric field is applied. ER fluids contain ER particles. These particles are perceived to form aggregates which align with the electric field, causing the ER fluid to change instantly from liquid to visco-plastic solid.

When an electric field is setup near the tip of a polishing tool and the tool is immersed in an ER fluid, the fluid within the influence of the field becomes viscous and effectively forms a small flexible polishing pad at the tool tip. With addition of abrasive particles to the ER fluid, the abrasive particles are attracted to the ER particles in this virtual pad, due to electrostatics. Under movement of the tool relative to the work surface, the abrasive particles are dragged through the gap between the tool and the surface, resulting in removal of asperities of the surface.

Within certain range, the field strength plays a dominant role in the viscosity of the ER fluid and in the attraction of abrasive particles to the ER particles. Thus, producing of a strong electric field at the tool tip is critical to the realization of ER polishing.

An ER polishing tool with probe-like integrated-electrodes was proposed in our former paper [17], aiming at the polishing of small non-conducting surfaces. Based on the self-made setup, changes of the field strength along the z-axis with respect to the distance from the tip of the central shaft are shown in Fig. 1. The supply voltage is varied from 3000 to 1500 V. The tip of the shaft is at $z = 1$ mm. The field strength is proportional to the supply voltage. It is strongest at the tip and decreases away from the tip. At the distance 1 mm from the tip, the field strength is approximately half of its maximum value at the tip.

The electric field near the tool tip is also simulated using finite element analysis. Parameters used in the simulations are tabulated in Table 1. Simulation results are shown in Fig. 2. At the maximum supply voltage of 3000 V, the maximum field strength is 2.46×10^6 V/m. The field strength decreases monotonically with the supply voltage. Field strength is particularly high near the edge of the central shaft and the inner edge of the end face of the sleeve, which can be explained by charge concentration at the edges. Yet, one can see that such effects diminish rather rapidly from the edges and they are not noticeable beyond a small fraction of a millimeter from the edges. Overall, the field strength decreases quickly away from the tip of the central shaft which is consistent with the analytical model of the electric field developed above and the results in Fig. 2. These also suggest the assumptions of uniform distribution of charge on the surface of the anode and the cathode are acceptable and the analytical model provides reasonable prediction of the field strength as long as the point of interest is not within a small fraction of the edges.

3 Experiments

Experiments were conducted to examine the usefulness of the proposed tool with integrated electrodes for the polishing of non-conducting optics. The rate of material removal is expected to increase with the field strength. Two parameters to be studied in the current experiments are the supply voltage and the operating distance. In the last section, results show that they have strong influence on the field strength. Their effects on ER polishing were also investigated.

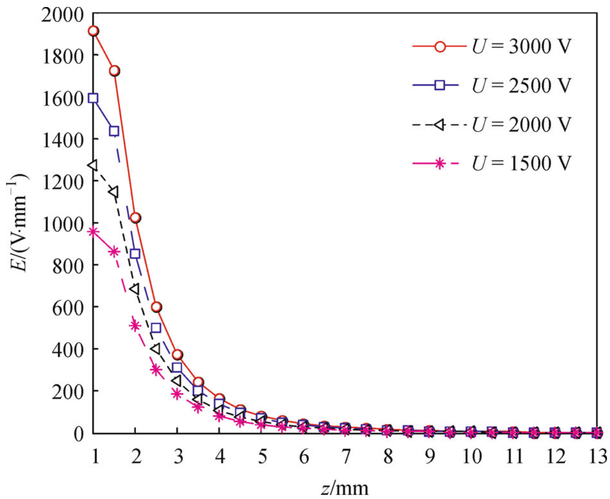


Fig. 1 Simulation of electric field strength along z-axis

The ER fluid used in the experiments was composed of 47.62% starch, 47.62% silicone oil, and 4.76% ceria. For all the experiments, the rotating speed of the central shaft was set at 1500 r/min and the polishing time at 30 min. The tool was perpendicular to the specimen. The specimens were made of *K9* glass and they were prepared using traditional grinding and polishing to a level of finishing suitable for the experiments.

3.1 Effects of the operating distance

The supply voltage was 2000 V. The operating distance was varied between 0.5 and 0.8 mm. The surface morphology of the specimens was measured before and after ER polishing with a FISBA-μ820 interferometer. The measured area was set at 10.7 mm × 9.6 mm, which was slightly smaller than the impression on the specimen by the tool. The CCD resolution of 1024 × 1020 pixels was suitable for form or waviness measurement or surface irregularities investigation over a larger range.

The captured surface profiles are shown in Fig. 3. Polishing leads to material removal. There is clear evidence that such removal in ER polishing can smooth the surface profiles and reduce the peak-to-valley (*PV*) values.

More obvious polishing effect can be observed when the operating distance is shorter. The final *PV* is smaller and the reduction in *PV* is larger when the operating distance is

Table 1 Finite element analysis parameters

material	air resistivity	material resistivity	supplied voltage	element type
0Cr18Ni9	$10^6\ \Omega\cdot\text{m}$	$9.7\times10^{-8}\ \Omega\cdot\text{m}$	1.5, 2.0, 2.5, 3.0 kV	PLANE67 & INF110

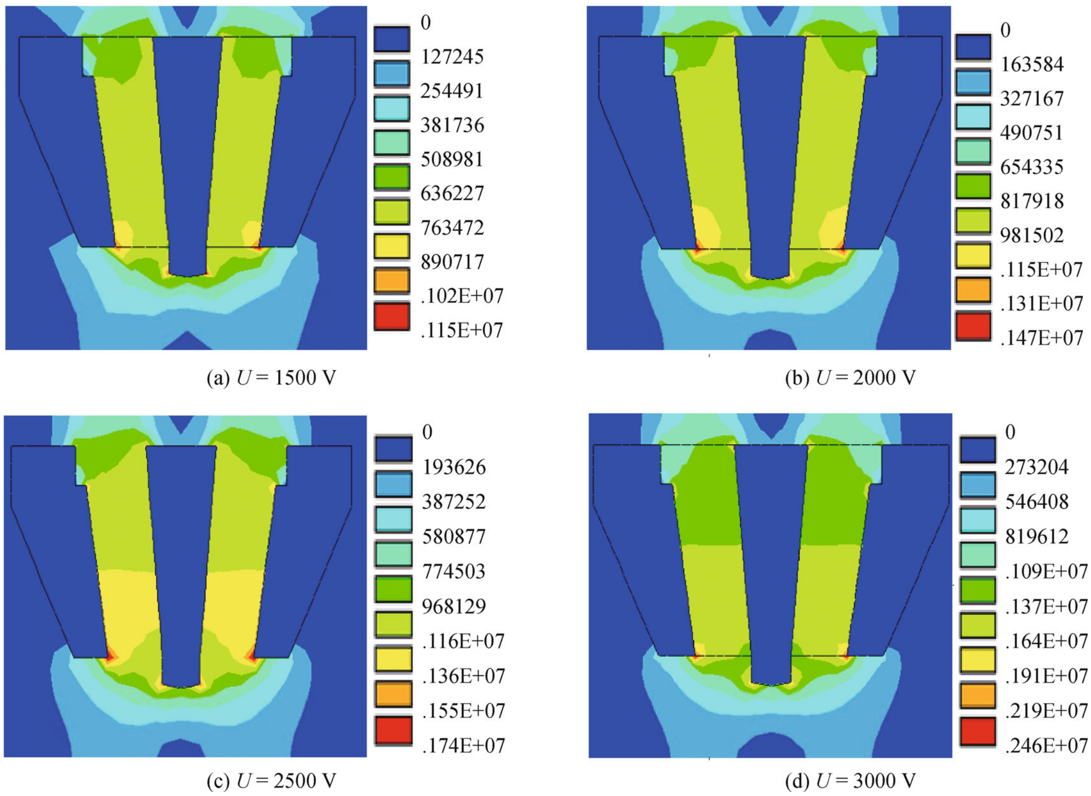


Fig. 2 Finite element analysis of electric field around tool head

shorter (Table 2). It is perceived that the ER fluid forms a virtual polishing pad around the tool tip, under the influence of the electric field. The stronger effects on *PV* reduction when the operating distance is shorter suggest that the stiffness of the virtual pad increases closer to the tip of the tool. The increase in stiffness is attributed to the higher viscosity of the ER fluid closer to the tool tip due to the increase in field strength near the tip. The greatest reduction in *PV* from 58.71 to 25.03 nm is obtained at the operating distance of 0.5 mm.

The relative change of an indicator is expressed as

$$K=\frac{a_1-a_2}{a_1}, \tag{1}$$

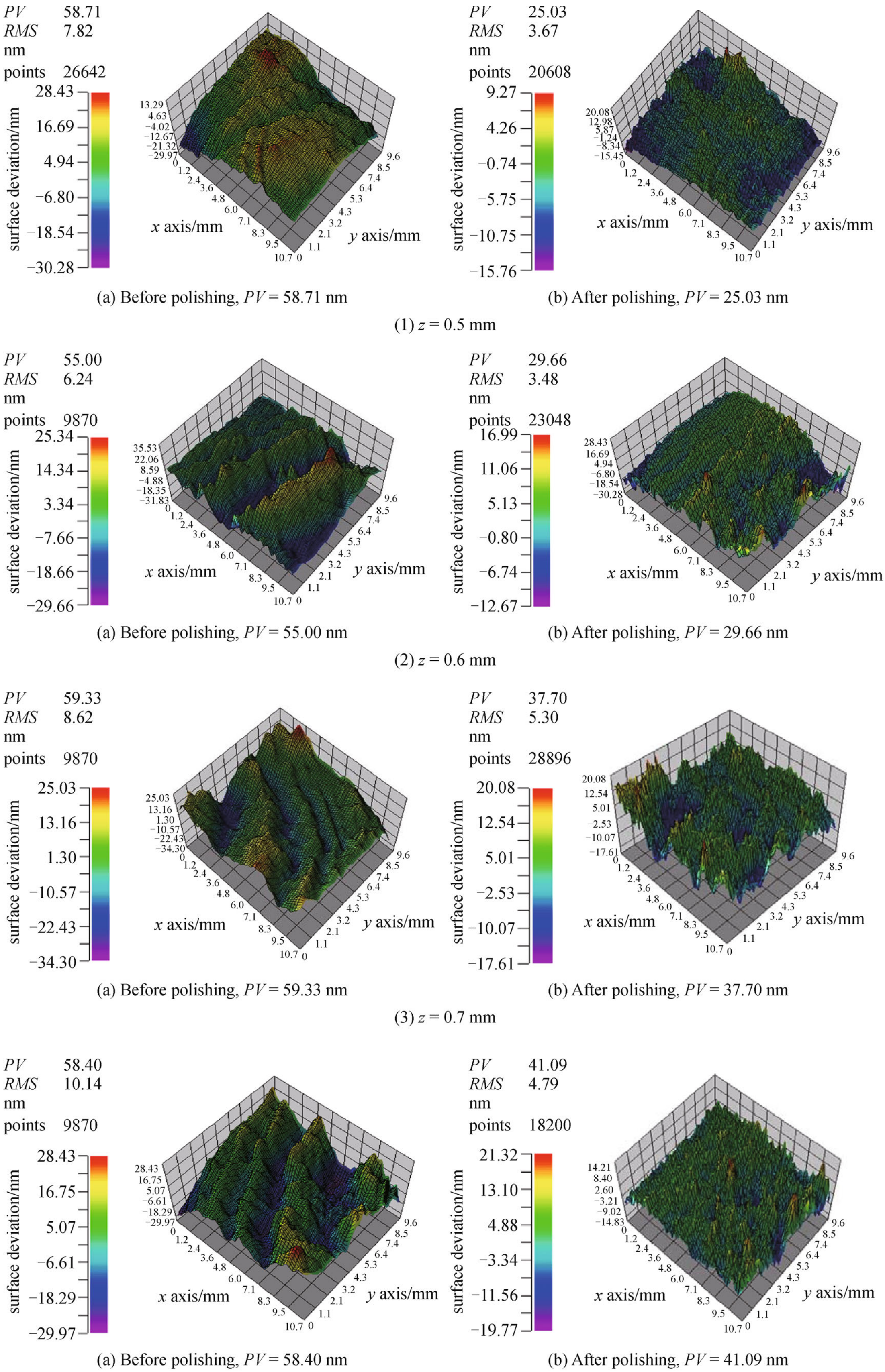
where a_1 and a_2 are respectively the value of the indicator before and after processing.

The relative change of *PV* is plotted against the operating distance in Fig. 4. The monotonic trend of the plot suggests the removal of surface irregularities is more effective and faster when the tool is closer to the specimen.

Root-mean-square (*RMS*) of a surface profile gives more averaged measurement (Table 3). The relative change of *RMS* is also plotted against the operating distance in Fig. 4. The result also suggests a monotonic trend, except for the case at the operating distance is 0.8 mm. Inspection of the surface profiles in Fig. 3 reveals that more material was indeed removed for the cases of the operating distance from 0.5 to 0.7 mm. The specimen for the 0.8 mm

Table 2 *PV* vs *z*

z/mm	before (a_1)/nm	after (a_2)/nm	(a_1-a_2)/nm	K/%
0.5	58.71	25.03	33.68	57.37
0.6	55.00	29.66	25.34	46.07
0.7	59.33	37.70	21.63	36.46
0.8	58.40	41.09	17.31	29.64



(a) Before polishing, $PV = 58.71$ nm (b) After polishing, $PV = 25.03$ nm

(1) $z = 0.5$ mm

(a) Before polishing, $PV = 55.00$ nm (b) After polishing, $PV = 29.66$ nm

(2) $z = 0.6$ mm

(a) Before polishing, $PV = 59.33$ nm (b) After polishing, $PV = 37.70$ nm

(3) $z = 0.7$ mm

(a) Before polishing, $PV = 58.40$ nm (b) After polishing, $PV = 41.09$ nm

(4) $z = 0.8$ mm

Fig. 3 Changes of surface profile ($U = 2000$ V)

Table 3 *RMS* vs *z*

z/mm	before (a_1)/nm	after (a_2)/nm	(a_1-a_2)/nm	K/%
0.5	7.82	3.67	4.15	53.07
0.6	6.24	3.48	2.76	44.23
0.7	8.62	5.30	3.32	38.52
0.8	10.14	4.79	5.35	52.76

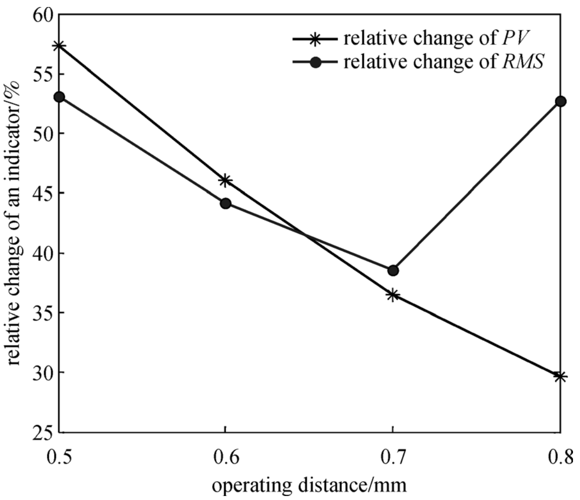


Fig. 4 Relationships between relative change of *PV* and of *RMS* and operating distance (U = 2000 V)

operating distance contained relatively more narrow ridges and grooves on the surface. It was likely that, for that specimen, a larger reduction in *RMS* could be achieved with less removal of material.

3.2 Effects of the supply voltage

The operating distance was set at 0.5 mm. The supply voltage was varied between 1500 and 3000 V. The surface roughness (*Ra*) of the specimens was measured before and after ER polishing with a wyko NT1100 interferometer. The measured area covered 227 µm × 298.5 µm. The CCD resolution of 736 × 480 pixels was adequate for roughness measurement or surface irregularities investigation over a smaller range.

Comparison of the surface profile before and after polishing was shown in Fig. 5. Results indicate successful reduction of the surface roughness *Ra* in the nanometer range. In this range, resulting surface profiles did not resemble the original profiles. The *Ra* of the original surfaces was between 4.1 and 8.5 nm (Table 4). The *Ra* of the resulting surfaces was between 2.5 and 2.8 nm, with the exception of the case of U = 2000 V where *Ra* was 3.92 nm. These suggest that, within the voltage range, the supply voltage did not play a significant role in the achieved *Ra*. For the case of U = 2000 V, one can see a long and broad ridge across the surface which may be the reason of the higher *Ra* of 3.92 nm. A likely explanation is inhomogeneity of the specimen as all the other specimens seem to have rather unremarkable surface profiles after polishing.

The relative change of *Ra* is plotted against the supply voltage in Fig. 6. The effect on the rate of *Ra* reduction seems to be larger with a larger supply voltage. Relatively speaking, the effect is more distinct when the voltage is increased from 1500 to 2000 V, compared to the increase from 2000 to 2500 V. It is about to level off when the voltage is beyond 3000 V.

Presence of abrasive particles in the ER fluid is important to material removal and *Ra* reduction. The rate of removal depends on the amount of abrasive particles in contact with the surface. A larger supply voltage seems to induce better attraction of the abrasive particles to the ER particle aggregates.

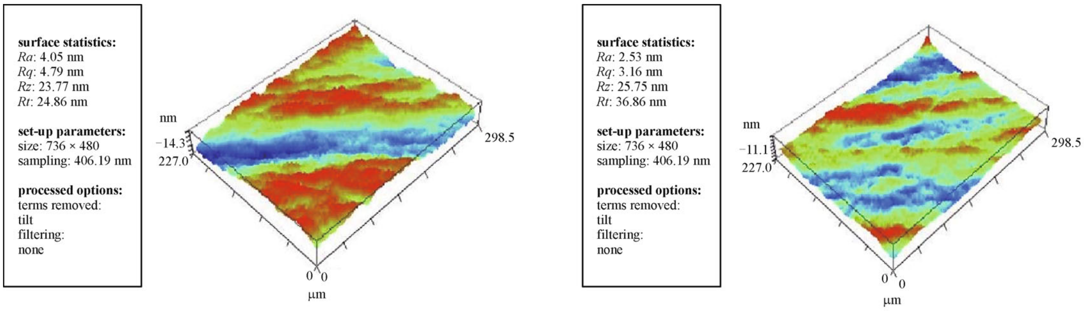
Leveling off of the curve in Fig. 6 indicates that further increase in the supply voltage cannot lead to further significant increase in removal rate. It is possible that further voltage increase did not help to attract additional abrasive particles. It is also possible that there was no further formation of ER particle aggregates.

In traditional polishing, the final *Ra* of a surface depends mainly on the size of the abrasive particles. To a lesser extent, it also depends on the force on the polishing tool. In the current experiments, the final *Ra* did not vary notably with the supply voltage. This is reasonable since the same type of abrasives was used in all the experiments. Although the supply voltage affected the viscosity of the virtual pad, to some extent, the indentation of abrasive particles, the effects on the *Ra* was negligible.

4 Conclusions

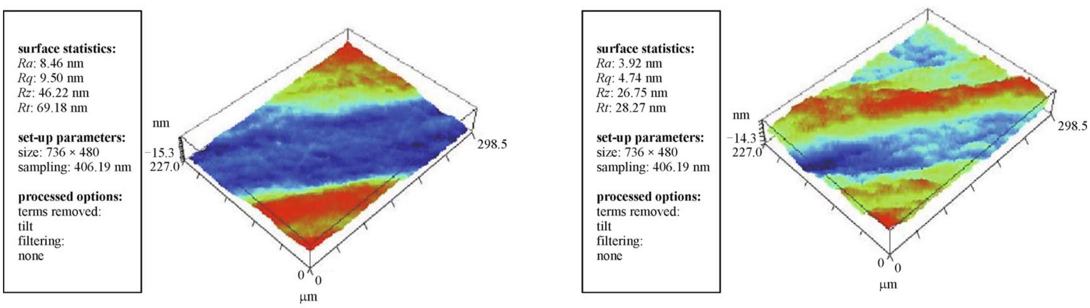
A parametric design for ER finishing was constructed. Finite element method was also employed to simulate the field strength. Both indicate that the field strength near the tip increases with the supply voltage and decreases away from the tip. According to the model, the field strength is reduced by about one-half at 1 mm from the tip.

Experiments on *K9* glass specimens were conducted. At the supply voltage of 2000 V, reduction of *PV* and *RMS* of the surface profile were demonstrated for the operating



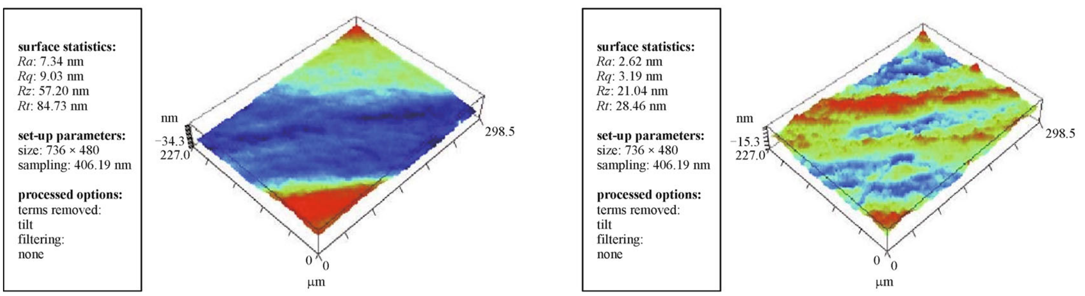
(a) Before polishing, $Ra = 4.05$ nm (b) After polishing, $Ra = 2.53$ nm

(1) $U = 1500$ V



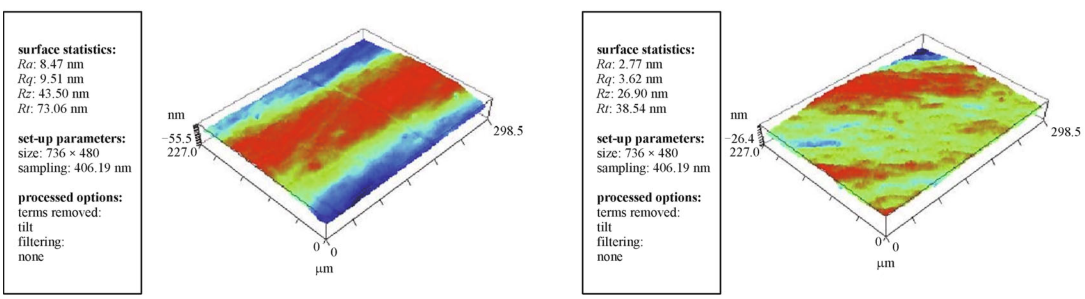
(a) Before polishing, $Ra = 8.46$ nm (b) After polishing, $Ra = 3.92$ nm

(2) $U = 2000$ V



(a) Before polishing, $Ra = 7.34$ nm (b) After polishing, $Ra = 2.62$ nm

(3) $U = 2500$ V



(a) Before polishing, $Ra = 8.47$ nm (b) After polishing, $Ra = 2.77$ nm

(4) $U = 3000$ V

Fig. 5 Changes of the surface roughness (operating distance = 1.5 mm)

distance between 0.5 and 0.8 mm. The *PV* was reduced from 58.71 to 25.03 nm and the *RMS* was reduced from 7.82 to 3.67 nm for the operating distance is 0.5 mm. The faster reduction of surface irregularities is attributed to the

Table 4 *Ra* vs *U*

U/V	before (a_1)/nm	after (a_2)/nm	(a_1-a_2)/nm	*K*/%
1500	4.05	2.53	1.52	37.53
2000	8.46	3.92	4.54	53.66
2500	7.34	2.62	4.72	64.31
3000	8.47	2.77	5.70	67.30

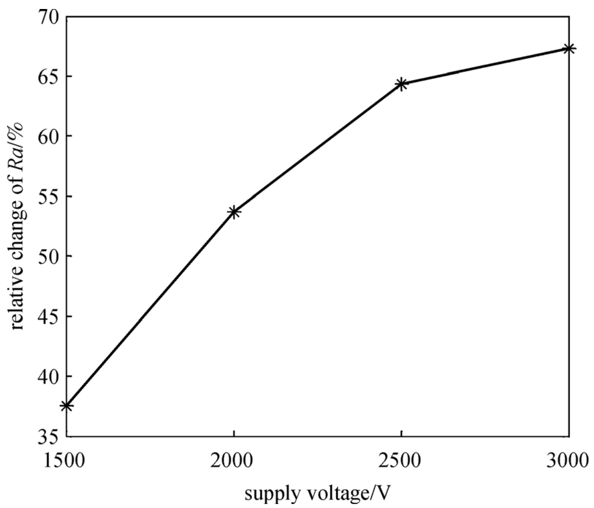


Fig. 6 Relationship between relative change of *Ra* and supply voltage (operating distance = 0.5 mm)

higher stiffness of the virtual pad near the tool tip where the field strength is higher.

Experiments were also carried out at the operating distance of 0.5 mm with the voltage from 1500 to 3000 V. The *Ra* of the resulting surfaces was between 2.5 and 2.8 nm. The supply voltage did not play a significant role in the achieved *Ra*. However, the relative change of *Ra* was larger when the supply voltage was higher. The larger change seems to be caused by the higher ability in attracting abrasive particles to the ER particle aggregates at higher supply voltage.

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