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RESEARCH ARTICLE

Design of integrated-electrode tool for electrorheological finishing of optical glasses

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Abstract Electrorheological (ER) finishing utilizes the flow of electrically stiffened abrasive fluid through a preset converging gap formed by the work-piece surface and a moving tool. An ER finishing tool characterized by cathode integrated with anode together is proposed, whose electric field distribution is finite-element-analyzed (FEA) and is useful to finish both conductive work-piece and non-conductive ones. Experiments were performed to finish a K9 glass by this tool. After 30 minutes polishing, the surface roughness was reduced from 8.46 to 2.53 nm Ra which is better than previously reported 2.9 nm. The result verified the validity of the integrated-electrodes tool for non-conductive optical glasses.

Keywords electrorheological (ER) finishing, roughness, material removal

1 Introduction

At present, optical systems have been applied in consumer products, projection and display systems and life science. There is an ever-increasing demand for shrinking the size of the aspheric or complex optical surfaces. For the applications of high surface finishing (surface roughness achieves a nanometer range), the surfaces need to be further polished to improve the surface roughness. Non-contact polishing may offer a way to produce very good surface finishing, as there is not a solid polishing tool to press directly onto the part surface. There were investigations on magnetorheological finishing (MRF) [1–3]. Kordonski et al. [4] adopted MRF to polish optical components out of brittle materials to satisfy the requirements of subsurface damage-free and super-smooth accuracy. Cheng et al. [5] performed study on the design of MR tool and process parameters experimentally. Miao et al. [6] proposed a modified Preston's equation to estimate the removal rate of MRF material for optical glass by model and experimental analysis. Electrophoresis polishing is proposed by Suzuki et al. [7] that the abrasive particles are concentrated in a polishing area by the effect of electric field, by which also good surface finishing is produced for large and mesoscale parts. However, it is difficult to concentrate abrasive particles to a tiny area and generate a small pad for polishing such small parts as lens, mirrors and dies size in several millimeters.

Many high-precision optical components are made of glass in the last thirty years. High-precision optical elements for stepper lenses and camera are examples of critical components in optical manufacturing that demand surface accuracy on the order of surface micro-roughness less than 10 nm RMS [8]. Electrorheological (ER) finishing is one of the most promising smart polishing methods, which utilize the flow of electrically stiffened abrasive fluid through a preset converging gap formed by the work-piece surface and a moving tool. Material removal as the abrasive fluid is dragged through the gap between the tool and the surface. ER fluid is a functional fluid, and its viscosity can be varied with the intensity of the applied electric field. Kuriyagawa et al. [9] firstly reported this technique, and mixed the ER fluid with abrasives as finishing slurry for the finishing of micro parts, and the roughness of a BK7 glass was reduced from an initial 18.6 to 4.4 nm Ra successfully. This polishing method for silicon surface using the ER fluid has been also presented by Kim et al. [10]. At last, average surface roughness of 2.9 nm was obtained as a result of the polishing of silicon surface whose initial average roughness was about 50 nm. There were also efforts to establish better understanding of processes in modelling of the electromechanical features by Kim et al. [11], improving of the surface roughness on Tungsten carbide moulding dies by Kaku et al. [12], and finding the effective area in ER

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polishing and Zhang et al. [13]. However, in previous works, polishing the non-conductive material such as optical glass, an auxiliary electrode is needed to surround the glass surface to be polished. Temporality, when the rotational axis electrode is moved on the surface of glass, the circular type electric field is not equality and the removal function is instability. In addition, in the ER fluid-assisted polishing of conductive material such as tungsten carbide, the rotational axis tool is used as cathode and the conductive work-piece is directly used as anode. What's more, the gap between the tool tip and the work-piece has to be controlled in micron-size level, too far to generate strengthened electric field and too close to prevent electric breakdown. These previous researches were focused on understanding its effects of process parameters on ER polishing, analytically or experimentally, and little work was reported on the design of ER finishing tool. This work proposes an advanced ER tool characterized by cathode integrated with anode together, which demonstrates the ability to meet high standards of surface accuracy by overcoming many of the fundamental limitations inherent to those traditional finishing technique, such as the difficulty integration of cathode and anode electrodes and it's hard to polish non-conductive work-piece. The structure and the electric field distribution of the integrated electrodes tool are designed and analyzed. Then the confirmation experiments to verify the polishing effects of the tool are performed also.

2 Tool design and analysis

Major dimension of targeted surfaces for polishing is from a few millimeters to larger ones. The tool-tip diameter is expected to be less than 1 mm, so that the functional zone of ER finishing can be considerably smaller than 3 mm in size. The tool should also be round-ended to avoid concentration of electric charge at the edge. The requirement that the work-piece material may be non-conducting implies that the tool/spindle should contain both the anode and the cathode as the work-piece surface cannot be conveniently used as an electrode. It is reckoned that the working voltage is about 1500–3000 V across. To sum up the whole condition, an integrated electrode tool is specially designed, and a schematic diagram of the integrated electrode tool designed is given in Fig. 1. A rod is to be driven by an electric motor and rotated about Z-axis. This rotating rod is shaped as a pin-type tip and forms the cathode. A non-rotating cylindrical tube near the rod-end and concentric to the rod forms the anode. The anode is designed as a hollow cone with a columnar tube, and a plane section taken somewhere above the vertex. Both the anode and the cathode are made of steel materials. This eliminates the need for rotating tool to be in physical contact with the power supply. The spacing between the rod and the tube should not be too big so that the overall diameter can be small, it also should not be too small to avoid short-circuiting. The cathode is well grounded and the exposed part of the anode is well shielded. The mechanical components is well aligned and rigidly supported to reduce vibration during processing which could cause loss of functionality and short-circuiting.

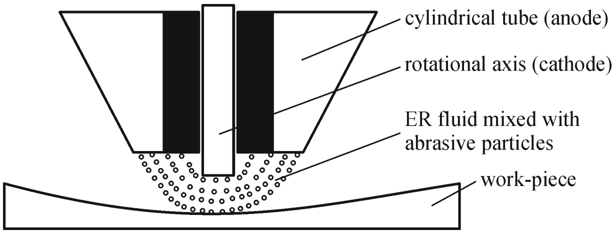


Fig. 1 Schematic diagram of pin-type ER finishing tool

The integrated electrodes tool combines the anode and cathode, and the schematic diagram of the tool designed is given in Fig. 2. The schematic diagram of the polishing head is given in Fig. 3.

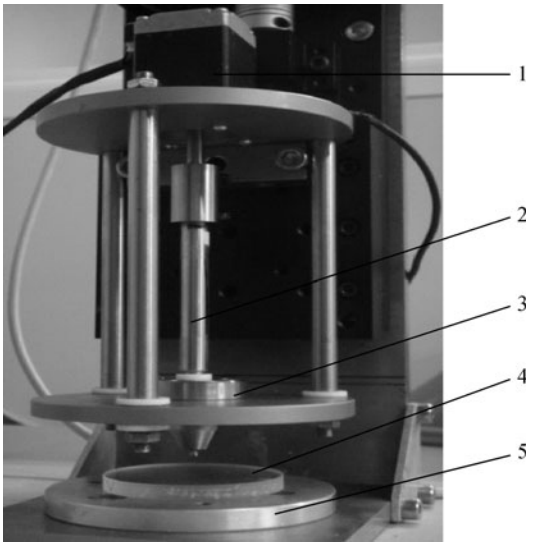


Fig. 2 Schematic diagram of integration tool. (1) Motor; (2) rotational axis (cathode); (3) cylindrical tube (anode); (4) work-piece; (5) worktable

Figure 4(a) shows the polishing head without electric field, the diameter of polishing head which is cathode is 1.4 mm, and the distance between polishing head and the anode is 2 mm. Due to the symmetrical distribution of the tool, the electric field intensity was imitated by ANSYS using the 2D mode. In the simulation, the voltage between anode and cathode is 3000 V. Figure 4(b) illuminates that the maximum intensity of electric field (0.427×10^7 V/m) existence at the end of the integration electrodes tool. The electric field intensity decreases not only with the increases of the distance away from the centre line of the tool, but also with the increase of the distance from the end of the

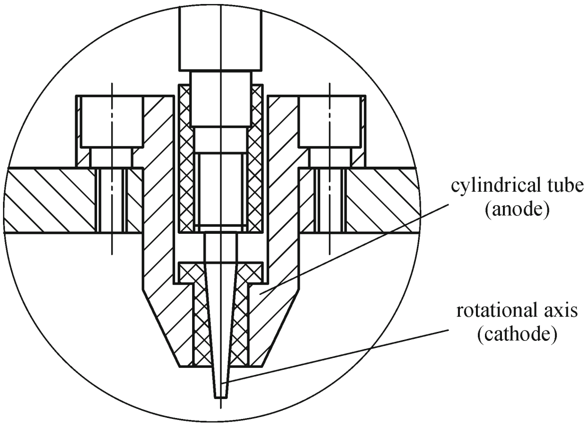
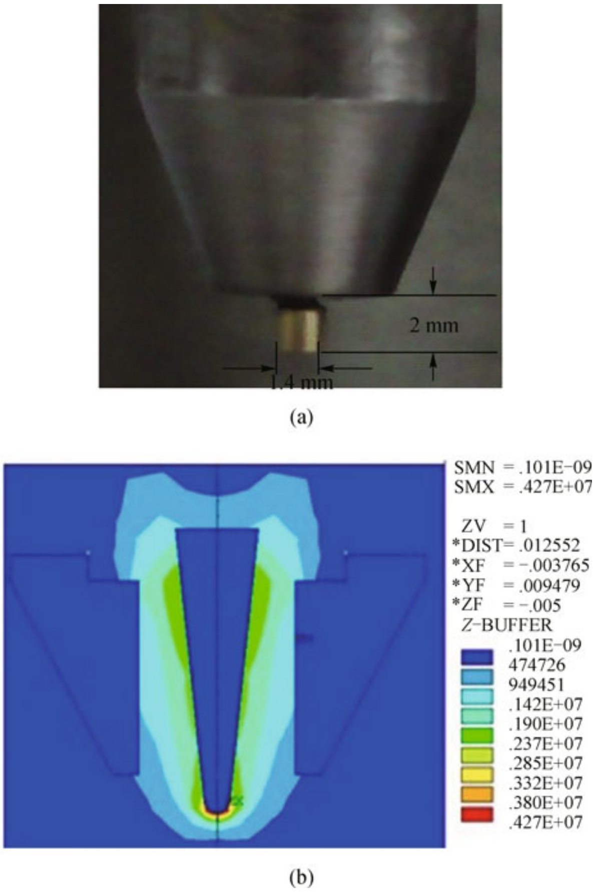


Fig. 3 Schematic diagram of the head of tool



(a)

(b)

Fig. 4 (a) Head of tool; (b) its electric field analysis by ANSYS

tool to work piece. The intensity distributing satisfied with the necessary condition of polishing.

Consider the tool axis is normal to the surface. Under high voltage, electric field lines are formed between the rod and the concentric tube in the radial direction. ER particles suspended in the fluid are polarized and form chains along the field line directions. Abrasive particles are also polarized and are adhered to the chains. Near the rod-tip one expects a high field line concentration. Tool rotation causes the chains of ER particles and abrasive particles to also rotate. An impression is left on the surface directly underneath the tool due to material removal caused by the rotating chains.

3 Experiment and discussion

In view of Preston equation [14] (see Eq. (1)), which is accepted as a traditional and fundamental principle of most abrasive processes.

$$R(x,y) = kp(x,y)v(x,y), \tag{1}$$

where, $R(x,y)$ is the abrasive wear; k is the coefficient of Preston; the parameters $p(x,y)$ and $v(x,y)$ are the functions of pressure and relative velocity, respectively; the coefficient of Preston k includes the influence of interacting materials (tool, glass, abrasive) into a single value.

We have finished a K9 glass work-piece using the ER finishing technique. The experiment began by proper selection of the parameters which mainly involve the applied electric voltage, the spin rate, the polishing time, the gap between the tool and the work-piece, and the viscosity of the ER fluid. The ER fluid is composed of starch particle as the disperse phase and silicone oil as the continuous phase. We used cerium oxide (CeO_2) particle as the abrasives mixed into the ER fluid [15]. Volumetric component ratios of the fluid in the present study are 35.2% starch particles, 52.8% silicone oil, 12% CeO_2 particles. The spin rate was controlled to reach 1500 r/min. The gap between the tool and the work-piece is 0.5 mm. The applied voltage is 3000 V. The parameters used in the experiments were listed in Table 1.

Using a Wyko NT1100 optical interferometer, we evaluated the surface roughness of the K9 glass polished by ER finishing. Figure 5 shows surface roughness of the K9 glass decreases along with the increasing of the polishing time.

Three-dimensional (3D) plot of the polished surface is shown in Fig. 6, and the original surface roughness of

Table 1 Experimental parameters

dispersed phase (starch particle)	continuous phase (silicone oil)	abrasive (CeO_2)	rotational speed /($r\cdot min^{-1}$)	polished gap /mm	voltage /V	time /min
35.2%	52.8%	12%	1500	0.5	3000	30

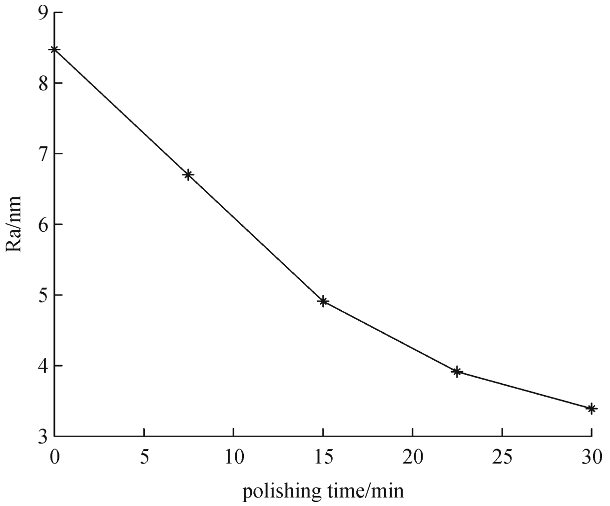


Fig. 5 Relationship between surface roughness with polishing time

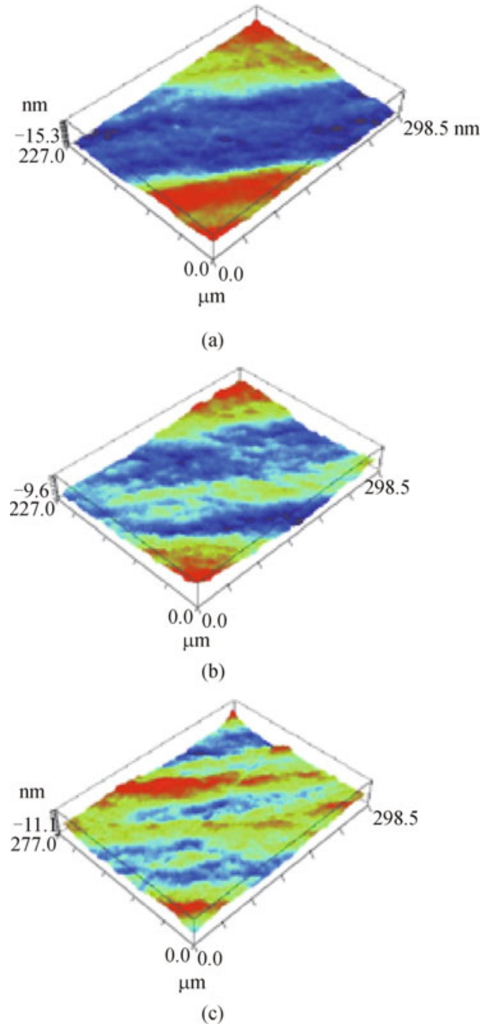


Fig. 6 Surface roughness microstructure of finishing area. (a) Initial Ra = 8.46 nm; (b) after finishing Ra = 3.38 nm; (c) after finishing Ra = 2.53 nm

8.46 nm is decreased to 3.38 nm after 22 minutes ER finishing, and the 3D microstructure of the finishing region exhibits a shape of the letter U before polishing and becomes nearly a shape of the letter W. After 30 minutes ER finishing, the surface roughness is decreased to 2.53 nm, and the 3D microstructure of the finishing region becomes more smooth. The results show that a better smoothing quality for non-conductive work-piece can be achieved with our technique compared with that ER finishing conductive work-piece by virtue of a tip-to-plate tool.

4 Conclusions

We have extended the ER finishing to non-conductive glass by using the developed integration-electrodes ER tool, and a finishing accuracy of 2.53 nm Ra is achieved. The result verified the validity of the integrated-electrodes tool for non-conductive optical glasses. It is believed that this technique can also be used to polish conductive materials with a nanometer accuracy demands.

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