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RESEARCH ARTICLE

Investigation of electrorheological fluid for optical finishing

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Abstract Electrorheological (ER) finishing is a promising technique for polishing optical mirrors lenses. Silicone oil-based ER finishing fluid with ceria particles as abrasive was developed, whose dispersed phase was alumina, titanium dioxide, silica, and starch, respectively. Experiments were performed in detail under the voltage of 3000 V, after 25 min of polishing a K9 glass. By using the ER fluid developed in this paper, with 47.62% starch, 47.62% silicone oil, and 4.76% ceria, the surface roughness of the K9 glass was reduced from 8.46 nm R_a to 3.45 nm R_a. The result verifies the validity of the developed ER fluid.

Keywords electrorheological fluid, polishing slurry, shear stress

1 Introduction

Electrorheological (ER) fluid is a high-tech smart material that can be converted from fluid to solid within milliseconds by the effect of the electric field. Also, the transformation process is reversible, continuous, and consumes low energy [1]. The ER finishing technique utilizes these performances of the ER fluid, that is, the ER finishing technique is based on the ER effect. When an electric field is applied, ER particles form an array of stable chains of particles along the electric field, gather at the polishing tool, and polish the workpiece. Kuriyagawa et al. first utilized ER fluid to finish an optical micro-aspherical lens in 1999 [2]. Kim used the diamond-mixed ER fluid and obtained average surface roughness of 2.8 nm after polishing a borosilicate glass surface, whose initial surface roughness was 28 nm [3]. Yan and Zhang et al. [4–8] also studied ER finishing in China, and achieved some results. Today, ER finishing is a cutting-edge technology; however, some key practical problems remain to be solved for ER to meet practical applications. The ER fluid for optical finishing is the foundation of ER finishing; thus, it is important for us to study the ER polishing slurry.

The paper based on the performance of ER fluid and its polishing mechanism. Silicone oil-based ER fluid was developed, whose dispersed phase was alumina, titanium dioxide, silica, and starch, respectively, and the polishing abrasive used was ceria. The paper also tested the performance of ER fluid with different formulas, and obtained a kind of ER fluid that is suitable for polishing.

2 ER finishing principle

Good rheological properties and the ability to remove material are important for ER polishing slurry. By mixing polishing abrasive in the ER fluid, the efficiency of material removal can be increased without affecting the ER effect. ER polishing slurry is composed of ER fluid and a certain percentage of polishing abrasive. When an external electric field is applied, the ER effect of the polishing slurry around the tool occurs. Particles concentrate at the tip of the tool, and the polishing slurry is converted from fluid to solid immediately. It forms a flexible tiny grinding wheel, which has high apparent viscosity and large shear stress. When the grinding wheel contacts with the workpiece, and makes the tool rotate, the surface material of the workpiece is removed, and the polishing of the workpiece surface is achieved. The principle of ER finishing is shown in Fig. 1.

3 Configuration of ER polishing slurry

The ER polishing slurry is mainly composed of dispersed phase, basal fluid (continuous phase), polishing abrasive, and additives. The dispersed phase is usually some solid particles with high permittivity, so it is easy to generate ER

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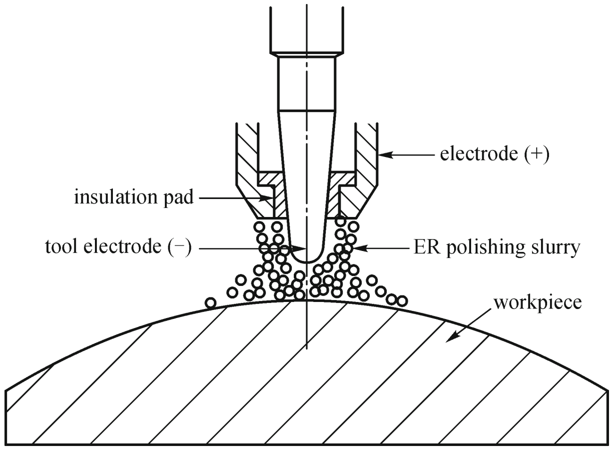

Fig. 1 Principle of ER finishing

effect under an electric field. Alumina, silica, titanium dioxide, and starch meet the requirements, so they are selected as the dispersed phase of ER fluids. The basal fluid is usually non-conducting liquid with low permittivity, low conductivity, and high breakdown voltage. Also, in order to make sure that the ER effect has flexible adjustment range, it must have low viscosity. Therefore, silicone oil with good chemical and physical stability is chosen as basal fluid. The polishing abrasive of the ER polishing slurry is ceria in this experiment, which plays a major role in the polishing process. Additives mainly include a surfactant for promoting the ER effect, a dispersing agent for preventing particle cohesion, and a stabilizer for preventing particle sedimentation, etc.

Based on the performance of ER fluid and its polishing mechanism, four kinds of ER polishing slurry in this study are developed, as shown in Table 1.

Table 1 ER polishing slurry with different dispersed phases

formula	basal liquid	dispersed phase	polishing abrasive
A	silicone oil	alumina	ceria
B	silicone oil	titanium dioxide	ceria
C	silicone oil	silica	ceria
D	silicone oil	starch	ceria

4 Performance investigation of ER polishing slurry

The CV20 torque and rotational speed sensor measurement system is used in this experiment [9]. Performances of ER fluids are tested in two cases: a) the content of the dispersed phase and the basal liquid is fixed, and the content of the polishing abrasive is increased gradually; b) the percentage between the dispersed phase and the base liquid is changed gradually, and the polishing abrasive is added to different ER polishing slurry.

4.1 Silica and titanium dioxide are used as dispersed phase

Similarly, 7 g of silicone oil, 3 g of titanium dioxide, and silica are used as the dispersed phase respectively. Ceria is still used as the abrasive for the ER polishing slurry. As shown in Fig. 2, when the dispersed phase is silica, the shear stress is small and the stress does not show significant increase after ceria is added. Meanwhile, the breakdown voltage is low. When the dispersed phase is titanium dioxide, the shear stress of the fluid increases steadily as the electric field strength increases, and the breakdown voltage reaches 2100 V. The stress is slightly increased after ceria is added, but the shear stress remains at about 500 Pa in general. Thus, when the dispersed phase is silicon dioxide and titanium dioxide respectively, the shear stress is too small to be used for polishing.

4.2 Starch is used as dispersed phase

When starch is used as dispersed phase, its advantage is that the particle hardness is very low. Ceria is chosen for

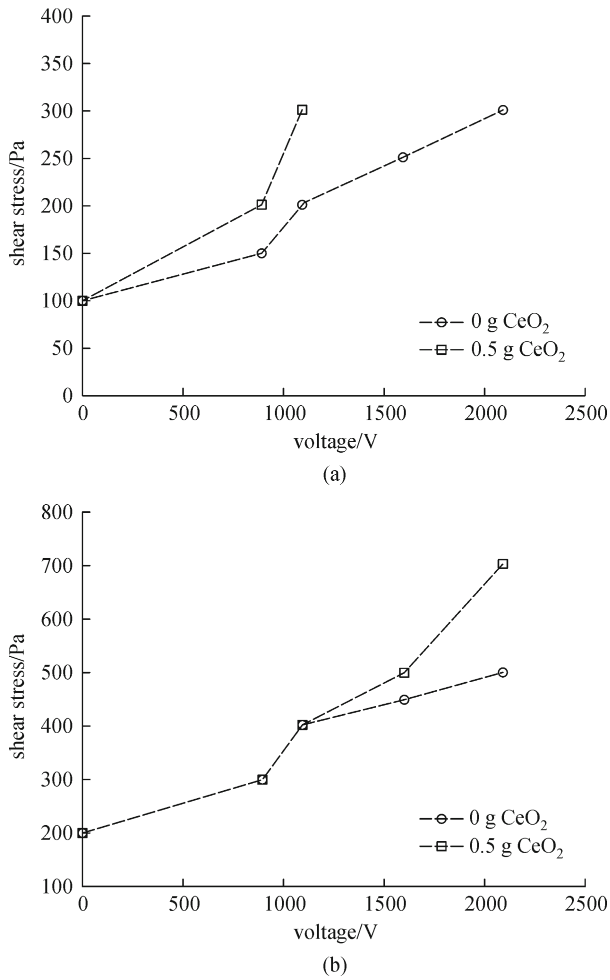

Fig. 2 Shear stress according to applied voltage for fluid with and without ceria. (a) Dispersed phase is silicon dioxide; (b) dispersed phase is titanium dioxide

polishing abrasive, and it becomes a key factor for material removal. In the beginning, this experiment tests the performance of the ER polishing slurry without ceria. Then it compares performance changes of the fluid after ceria is added by a certain percentage. The ER polishing slurry is configured as shown in Table 2.

Table 2 Dispersed phase is starch, ER polishing slurry with different formulas

	number	dispersed phase starch/g	basal liquid silicone oil/g	polishing abrasive ceria/g
F	1	3 (30.0 wt.%)	7 (70.0 wt.%)	
	2	3 (25.6 wt.%)	7 (66.7wt.%)	0.5 (4.7wt.%)
	3	3 (27.3 wt.%)	7 (63.6wt.%)	1.0 (9.1 wt.%)
	4	3 (26.1 wt.%)	7 (60.9 wt.%)	1.5 (13 wt.%)
G	1	4 (40.0 wt.%)	6 (60.0 wt.%)	
	2	4 (38.1 wt.%)	6 (38.1 wt.%)	0.5 (4.8 wt.%)
	3	4 (36.4 wt.%)	6 (54.4 wt.%)	1.0 (9.1 wt.%)
	4	4 (34.8 wt.%)	6 (34.8 wt.%)	1.5 (13 wt.%)
H	1	5 (50.0 wt.%)	5 (50.0 wt.%)	
	2	5 (47.6 wt.%)	5 (47.6 wt.%)	0.5 (4.8 wt.%)
	3	5 (45.5 wt.%)	5 (45.5 wt.%)	1.0 (9.0 wt.%)
	4	5 (43.5 wt.%)	5 (43.5 wt.%)	1.5 (13.0 wt.%)

In Fig. 3, the relationship between the shear stress of the fluid and the electric field strength for different percent of starch and ceria are shown. The shear stress of the fluid increases as the content of the starch increases, within a certain range. However, when the applied voltage reaches a certain degree, fluctuations in shear stress curve are larger. As shown in Fig. 4, the breakdown voltage of the fluid without ceria is 1600 V. Within a certain range, the breakdown voltage of the fluid increases as the content of ceria increases, and the maximal breakdown voltage is 3000 V. It indicates that the breakdown strength of the fluid is enhanced because of the addition of ceria. When the dispersed phase is 5 g of starch, the basal liquid is 5 g of silicone, the polishing abrasive is 0.5 g (4.7 wt.%) and 1.0 g (9.1 wt.%) of ceria respectively, the applied voltage is 2100–2550 V approximately, the shear stress of the fluid reaches to about 2000 V, and its rheological property is relatively strong under low shear rate.

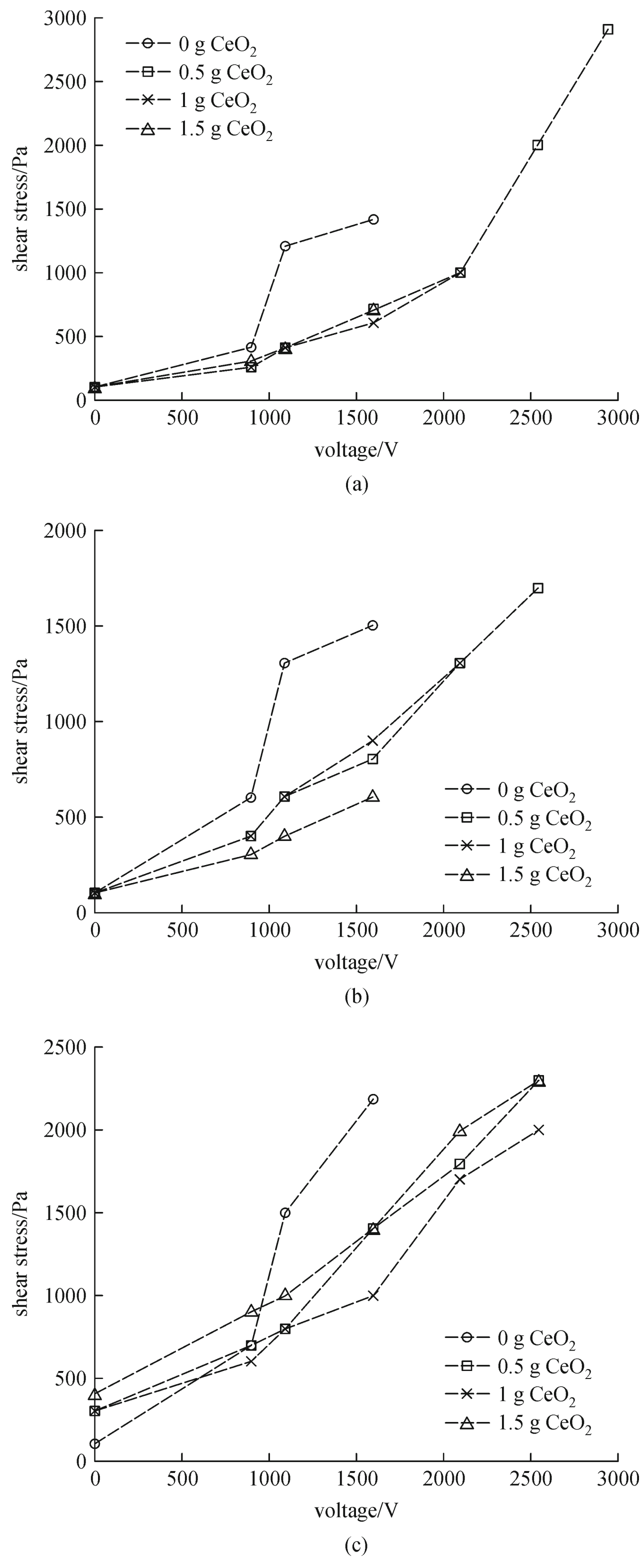

Fig. 3 Shear stress according to applied voltage for formula. (a) 3 g of starch; (b) 4 g of starch; (c) 5 g of starch

5 Polishing experiment

This experiment is based on the tested performance rules of the ER polishing slurry for the above formulas, selects ceria as the polishing abrasive, silicone oil and starch as the base fluid and the dispersed phase, respectively. Also, the ER polishing slurry is configured according to a certain proportion. The polishing experiment is carried out with the ER fluid having 47.62% starch, 47.62% silicone oil, and 4.76% ceria. The rotation speed of the tool is controlled to reach 1500 rpm. The gap between the tool

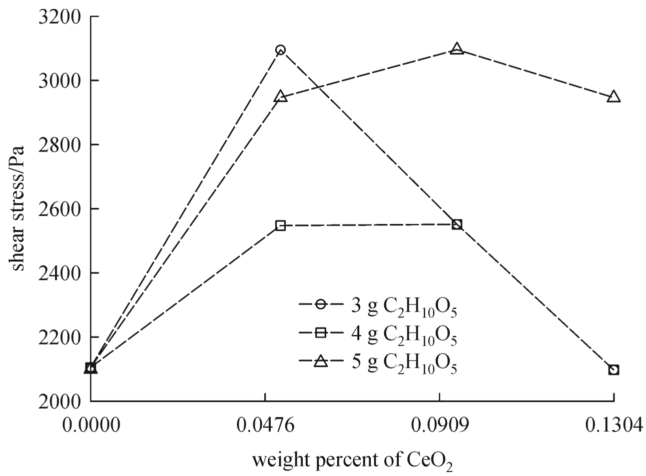

Fig. 4 Breakdown voltage versus percent of ceria for content of starch

and the workpiece is 0.5 mm. The applied voltage is 3200 V. Using a Wyko NT1100 optical interferometer, we evaluate the surface roughness of the K9 glass polished by ER finishing. After 25 min polishing, the surface roughness is reduced from 8.46 to 3.45 nm R_a. As shown in Fig. 5, the surface images of before and after finishing the glass are investigated by the optical interferometer.

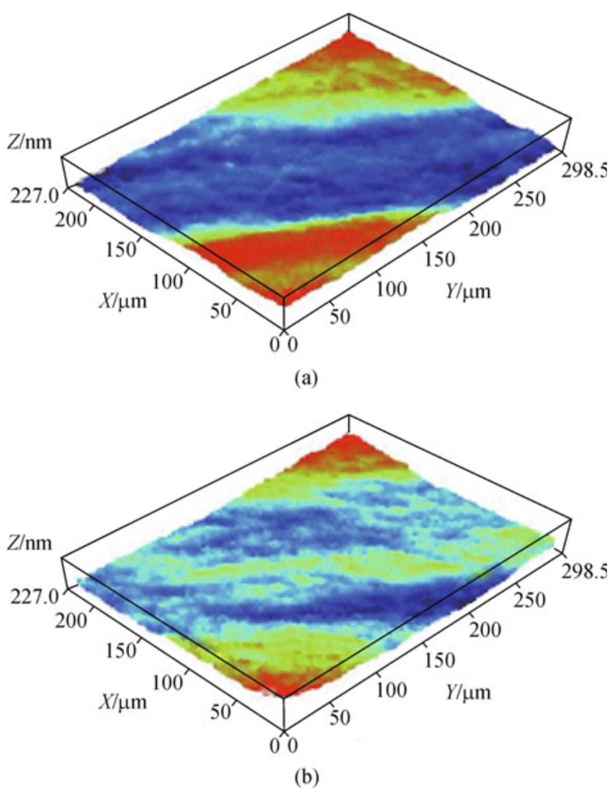

Fig. 5 Surface roughness (R_a) of K9 glass after polishing with ER fluid. (a) Before polishing; (b) after polishing

6 Conclusion

This paper is based on the principle of the ER finishing. Silicone oil is chosen as basal fluid, alumina, titanium dioxide, silica, and starch are used as dispersed phase respectively, and ceria is used as polishing abrasive. Four kinds of ER polishing slurry are configured and their performances are tested. The experimental results show that when the dispersed phase is alumina, the shear stress is very small, but when the dispersed phase is silica or titanium dioxide, the shear stress is too small to be used for polishing. When the ER fluid is composed of 47.62% starch, 47.62% silicone oil, and 4.76% ceria, the shear stress, under the voltage 2100–2550 V, reaches 2000 Pa. which is stronger and more stable and thus suitable for optical polishing. An ER polishing slurry is developed, whose dispersed phase is starch, then the polishing experiment is carried out. Results show that the surface roughness of the K9 glass polished by ER finishing is reduced from 8.46 to 3.45 nm R_a after 25 min polishing.

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