

Polishing performance of magnetorheological finishing with flocculated and deflocculated aqueous polishing fluid

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Abstract. We propose that a magnetorheological (MR) polishing fluid should be considered as a polydispersed suspension system due to its composition and appearance after sedimentation and that fluid can be divided into flocculated MR polishing fluid and deflocculated MR polishing fluid. Two kinds of MR polishing fluid are prepared using different additives, and removal function experiments are carried out on BK7 glass and a silicon modification layer on reaction-bonded silicon carbide, respectively. The performance of flocculated and deflocculated MR polishing fluid is investigated by removal function experiments. The experimental results demonstrate that performance of flocculated MR polishing fluid is superior to deflocculated MR polishing fluid in material removal rate, surface roughness, and removal function stability in long-term polishing processes. © 2019 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.58.2.025104]

Keywords: magnetorheological finishing; magnetorheological polishing fluid; material removal rate; surface roughness; stability.

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1 Introduction

Magnetorheological finishing (MRF) is the innovative practice of magnetorheological (MR) fluid in optical fabrication. The fluid used in MRF is called MR polishing fluid, which is also one of the key techniques of MRF.^{1,2} MR fluid can be classified into two types, aqueous and nonaqueous, which depend on the base fluid type. The base fluid of aqueous MR fluid is water and nonaqueous MR fluid is based on an organic solvent, such as silicon oil. Nonaqueous MR fluids are mainly used in mechanical, architecture, medical, and some water-soluble material polishing, such as potassium dihydrogen phosphate (KDP) crystal. However, aqueous MR fluids are widely used in optical fabrication. At present, there are many kinds of materials that can be polished with aqueous MR polishing fluid, such as glasses, silicon, silicon carbide, and some metals.^{3–6} Taking into consideration the material removal rate and application popularity of these two types of MR polishing fluid, aqueous fluid is more advantageous. Therefore, studying the preparation of MR polishing fluid is of great importance for the application of MRF. Due to the importance of MR polishing fluid for the actual fabrication, there are many researchers who propose different preparation methods of MR polishing fluid. QED developed a series of MR polishing fluids that are suitable for the fabrication of glass, ceramic, silicon, and other materials. However, the preparation methods of MR polishing fluid are closely guarded.^{7,8} Researchers at Rochester University studied the preparation of aqueous and nonaqueous MR polishing fluid.^{4,9} Moreover, they also explored zirconia-coated carbonyl iron powders (CIPs) via sol-gel synthesis, and the MR polishing fluid stability, material removal rate, and antirust ability using the coated CIPs were also studied.^{10,11} You et al.¹² proposed a preparation method of aqueous MR polishing fluid and the material removal rate was also investigated. Peng et al.¹³ explored a kind of nonaqueous MR polishing fluid and polishing

experiments were carried out on KDP crystal surface to eliminate the tool mark of single-point diamond turning.

Despite much research about the preparation and performance of MR polishing fluid being carried out, the relationship between the fluid dispersion property and polishing performance has not been investigated before. Therefore, in this work, we propose that the MR polishing fluid should be considered as polydispersed suspension according to the fluid composition. Two kinds of MR polishing fluids called flocculated MR polishing fluid and deflocculated MR polishing fluid based on the polydispersed suspension sedimentation behaviors are prepared. The polishing performance of the two kinds of MR polishing fluids was investigated via removal function experiments on BK7 glass and silicon modification layer on reaction-bonded silicon carbide (RB-SiC). The experimental results prove that the flocculated MR polishing fluid is superior to deflocculated MR polishing fluid in material removal rate, achievable surface roughness, and long-term material removal rate stability.

2 Flocculated and Deflocculated Suspension

The dispersion stability of MR fluid depends on the forces of interaction between the particles.¹⁴ DLVO theory (named after Boris Derjaguin and Lev Landau, Evert Verwey and Theodoor Overbeek) proposes that the stability of suspensions depends on the repulsion between particles arising from the osmotic effect produced by the increase in the number of charged species on overlap of the diffusion parts of the electrical double layer. The electrical potential gradient on the solid-liquid interface of the dispersed particles (electronegative for example) results in the formation of an electric double layer as shown in Fig. 1. The potential between the surface of a tightly bound layer and the electroneutral region of the solution is termed the zeta potential.¹⁵ To guarantee the stability of suspension, the absolute value of zeta potential commonly requires more than 30 mV. However, the particles

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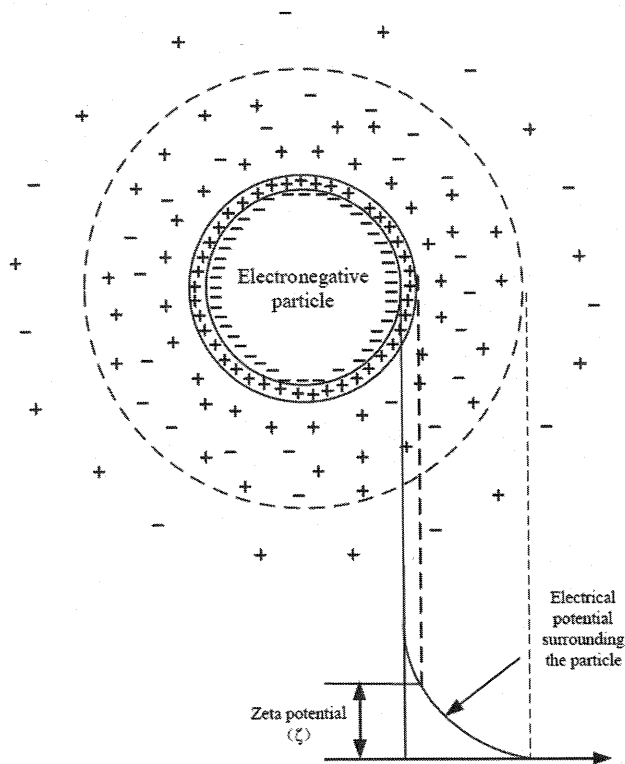


Fig. 1 Electric double layer and zeta potential of a charged particle.

exist not as individual particles but rather as aggregates in concentrated suspensions, such as MR fluid. Therefore, the high zeta potential is the basic stability requirement of concentrated suspension. The concentration of particles in MR fluid commonly is more than 30 vol. %, and sedimentation is inevitable.¹⁶ To slow down the sedimentation and increase the zeta potential, dispersants (ionic or nonionic) and wetting agents are indispensable in the fluid. The polymer organic ionic dispersants that are ordinarily used in the MR fluid can satisfy the long-term dispersion stability due to the steric and electrical repulsion force. However, the MR polishing fluid used for polishing contains abrasives that possess different size and chemical properties from CIPs and should be considered as a polydispersed suspension system.

Table 1 Comparison of flocculated and deflocculated suspension appearance after sedimentation.

Comparison	Flocculated system	Deflocculated system
Particles	Compressed of particles	In discrete units of particles
Size	Large due to aggregation	Small
Rate of settling	Rapid	Slow
Supernatant	Clear	Cloudy for appreciable
Nature of sediment	Loose flocs with high porosity	Compact

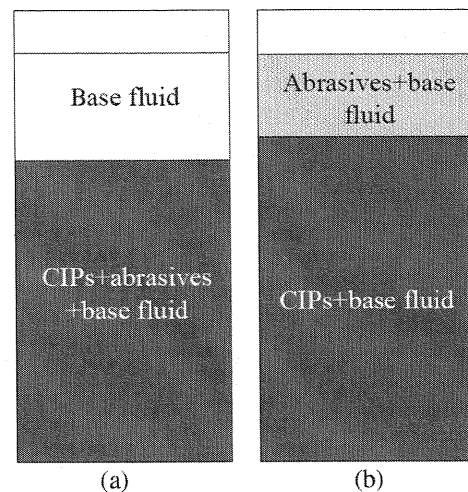


Fig. 2 Sedimentation behaviors of (a) flocculated and (b) deflocculated MR polishing fluid after several hours.

The sedimentation behavior of polydispersed suspension is complicated, especially for high-concentration suspensions. Generally, the sedimentation of polydispersed suspension presents two different features that are described as flocculated and deflocculated systems, depending on the additives used in the suspension. A comparison of flocculated and deflocculated suspension systems is shown in Table 1.¹⁷

Therefore, the MR polishing fluid will also be classified into two types according to the sedimentation behaviors as concluded in Table 1. The appearance of flocculated and deflocculated MR polishing fluid at given times after agitation is shown in Fig. 2.

3 Polishing Performance Comparison

3.1 Material Removal Rate

The MR polishing fluid is circulating in a loop and stirred in container during polishing process. Both the flocculated and deflocculated MR polishing fluids can satisfy dispersion stability requirements for long-term polishing process. We prepared two types of fluids using different dispersants and stabilizers to investigate the polishing performance. The major composition of flocculated and deflocculated MR polishing fluid is listed in Table 2. The diameter and concentration of CIPs used in the fluid are 4 μm and 38% in volume, respectively. The diameter and concentration of abrasives

Table 2 Main composition of flocculated and deflocculated MR polishing fluid.

Fluid type	Dispersant	Stabilizer	Other additives	Abrasive
Flocculated	PMMA	Carboxylate and chelator	Antirust Buffer agent	Cerium oxide
Deflocculated	Glycerin	Cellulose derivatives	Antirust Buffer agent	Cerium oxide

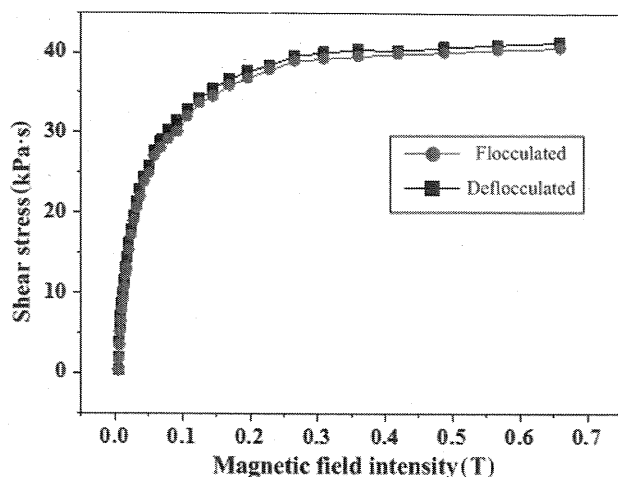


Fig. 3 Rheological property of flocculated and deflocculated MR polishing under a magnetic field.

Table 3 Experiment parameters.

Parameters	Wheel diameter (mm)	Rotation speed (r/s)	Dwell time (s)	Penetration depth (mm)
Values	160	2	10	1.0

(cerium oxide) used in the fluid are 3 μm and 1% in volume, respectively. The additives and concentration of dispersants and stabilizers are optimized to keep the suspension stability and antirust property by our previous investigation.¹

The rheological properties of flocculated and deflocculated MR fluid were tested with Anton Paar MCR 302 to compare the shear stress under the magnetic field, and the results are shown in Fig. 3.

From the results shown in Fig. 3, the shear stress of deflocculated fluid is slightly higher than that of flocculated MR fluid due to the addition of cellulose derivatives in the fluid. Based on the material removal mechanism of MRF, material removal rate can be expressed as

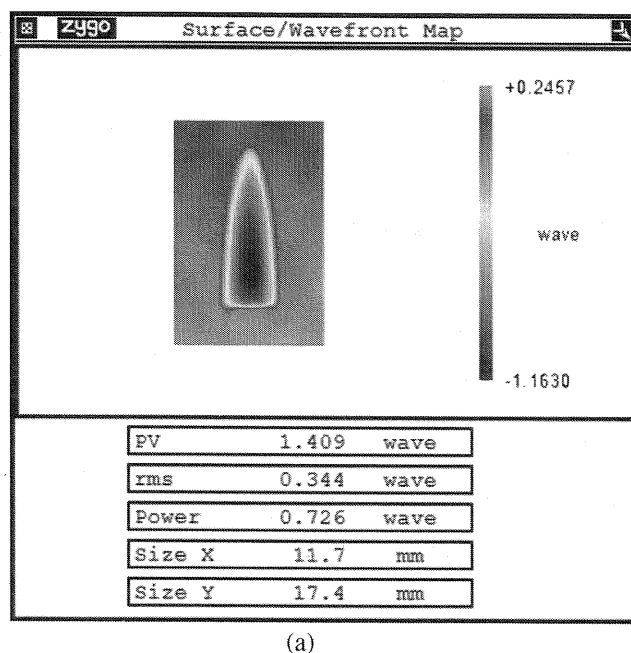
$$\text{MRR} = K \cdot \tau \cdot V, \quad (1)$$

where K is the coefficient that depends on fluid ingredient, such as particles concentration, fluid pH, etc., τ is the shear stress, and V is the rotation speed of wheel.

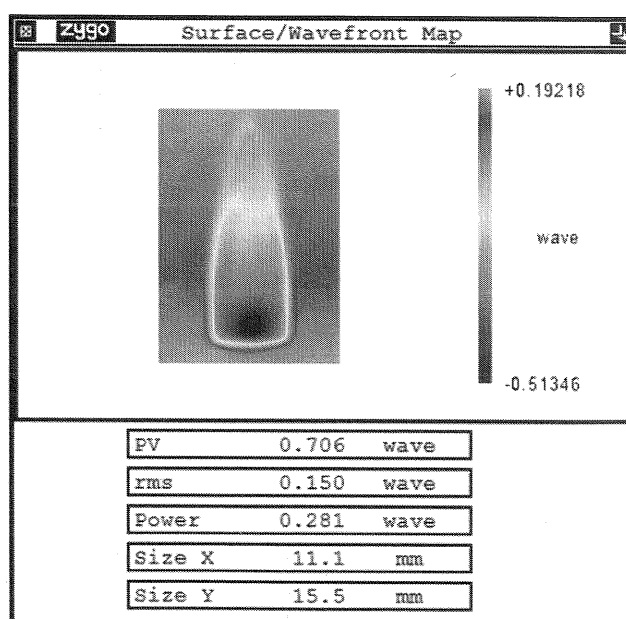
According to Eq. (1), the material removal rate of deflocculated MR fluid should be not less than the material removal rate of flocculated MR fluid without consideration of the interaction of abrasives and CIPs. Therefore, to investigate the performance of the prepared two types of MR polishing fluids, removal function experiments were carried out on the prepolished BK7 glass part. The experiment parameters used for BK7 and silicon modification layer on RB-SiC are listed in Table 3.

The removal function spots after polishing are shown in Fig. 4. The removal function spots were measured with Zygo interferometer.

As shown in Fig. 4, the removal function spot obtained using flocculated MR polishing fluid has greater symmetry and plumpness in comparison with the spot obtained under usage of deflocculated MR polishing fluid. It can also be seen that the resulting removal function spot tip under usage of flocculated MR polishing fluid possesses a higher removal rate than the one using deflocculated MR fluid. Then, after changing the composition of the two types of MR polishing fluid by replacing the cerium oxide with nano-diamond and adjusting the concentration to 0.03 vol. %, another removal function experiment was carried out on a prepolished silicon modification layer on RB-SiC part to study the performance of flocculated and deflocculated



(a)



(b)

Fig. 4 (a) Spot with flocculated MR polishing fluid on BK7 glass and (b) spot with deflocculated MR polishing fluid on BK7 glass.

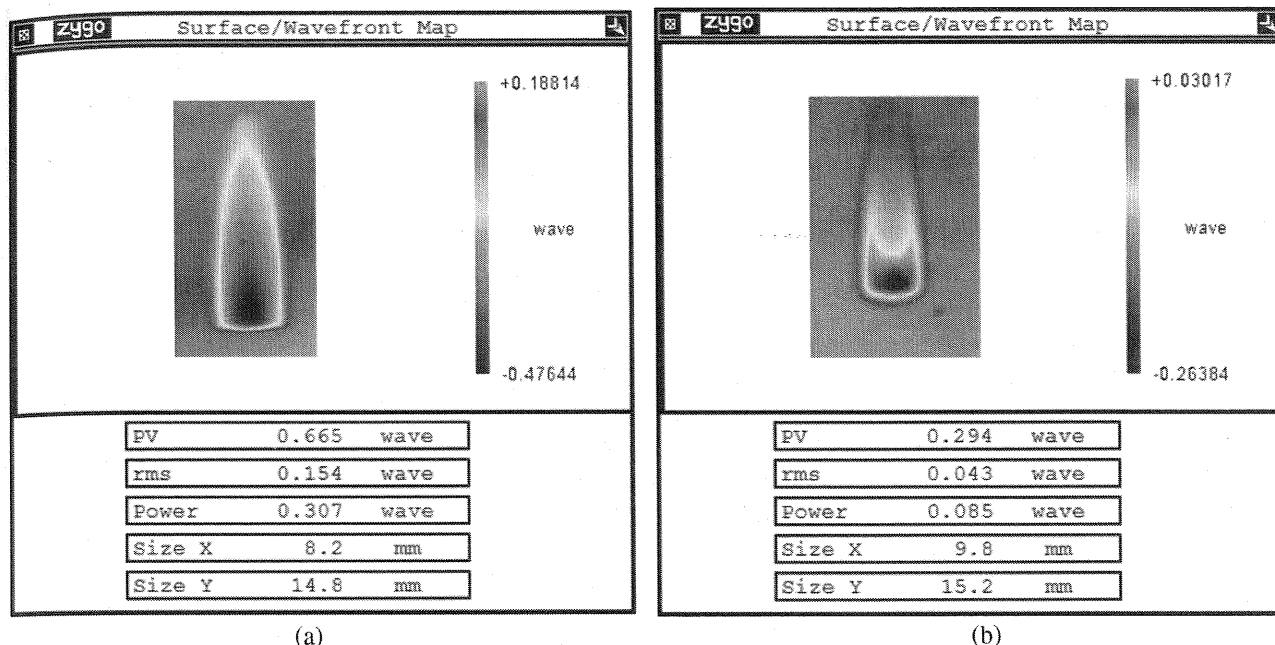


Fig. 5 (a) Spot with flocculated MR polishing fluid on silicon modification layer on RB-SiC and (b) spot with deflocculated MR polishing fluid on silicon modification layer on RB-SiC.

Table 4 Material removal rate on BK7 glass and on silicon modification layer on RB-SiC with flocculated and deflocculated MR polishing fluid.

Fluid type	BK7 glass		Silicon modification layer	
	PRR ($\mu\text{m}/\text{min}$)	VRR (mm^3/min)	PRR ($\mu\text{m}/\text{min}$)	VRR (mm^3/min)
Deflocculated	2.4	0.05	1.05	0.014
Flocculated	4.85	0.12	2.45	0.058

MR polishing. The experiment parameters are the same as that listed in Table 3. The experimental results are shown in Fig. 5.

As shown in Fig. 5, the performance of flocculated MR polishing fluid also shows an advantage over deflocculated MR polishing fluid when polishing the silicon modification layer on RB-SiC, which is similar to the results obtained in polishing BK7 glass. Then, the material removal rates, including peak removal rate (PRR) and volume removal rate (VRR), of the two types of MR polishing fluids as polishing BK7 glass and silicon modification layer on RB-SiC

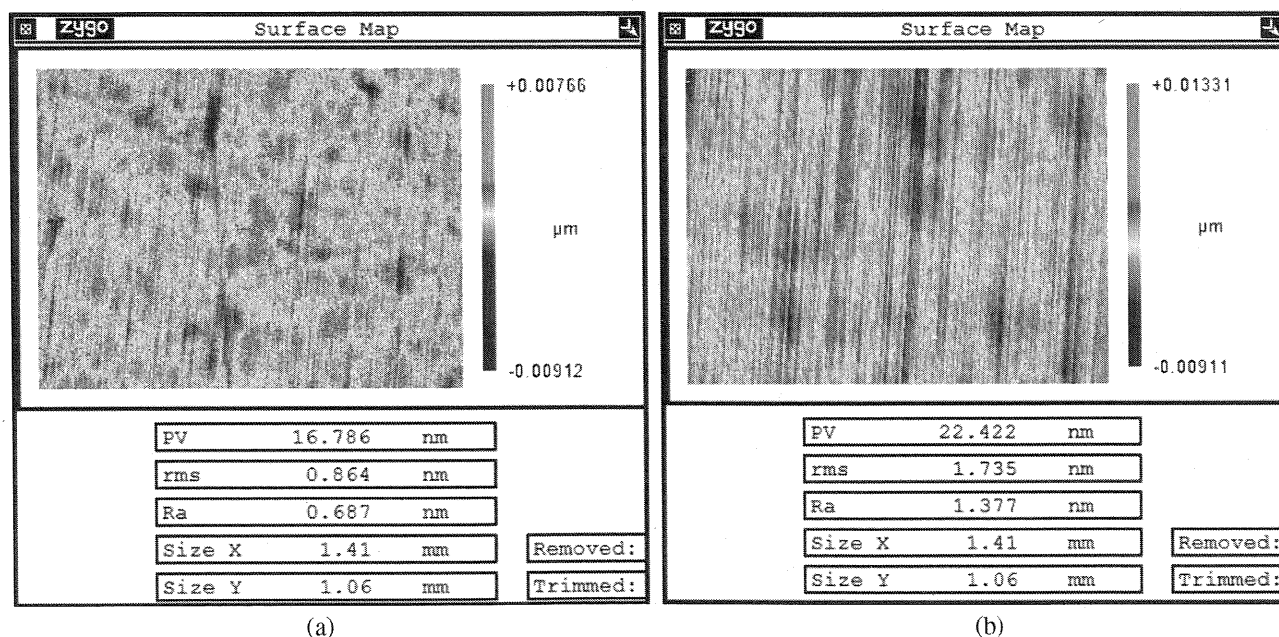


Fig. 6 Surface roughness of BK7 after polishing with (a) flocculated and (b) deflocculated MR polishing fluid.

are calculated based on the testing results, which are shown in Table 4.

The calculation results in Table 4 show that, when polishing BK7 glass with flocculated MR polishing fluid, the PRR and VRR is 2 times and 2.4 times greater than using deflocculated MR polishing fluid, respectively. As for polishing of the silicon modification layer on RB-SiC, the PRR and VRR is 2.3 times and 4.14 times greater than using deflocculated MR polishing fluid, respectively.

3.2 Surface Roughness

The roughness of the deepest area in removal function spots was measured with Zygo New View 7200 white-light interferometer to investigate the surface quality after polishing. The surface roughness results of BK7 glass and silicon modification layer on RB-SiC after polishing with flocculated and deflocculated MR polishing fluid are shown in Figs. 6 and 7,

respectively. It can be seen that surface roughness (R_a) of BK7 glass after polishing with flocculated and deflocculated MR polishing fluid is 0.864 and 1.377 nm, respectively. The surface roughness (R_a) of silicon modification on RB-SiC after polishing with flocculated and deflocculated MR polishing fluid is 0.937 and 1.69 nm, respectively. In consideration of the depth of the removal function in this paper, the roughness will not be higher than the roughness measured in the removal function as the corresponding flocculated MR polishing fluid is used for polishing mirrors.

3.3 Long-Term Polishing Stability

The material removal rate stability of flocculated MR polishing fluid and deflocculated MR polishing fluid in long-term polishing processes was also investigated by means of removal function stability under the condition of 8 h of continuous processing, which means that the fluids were in use

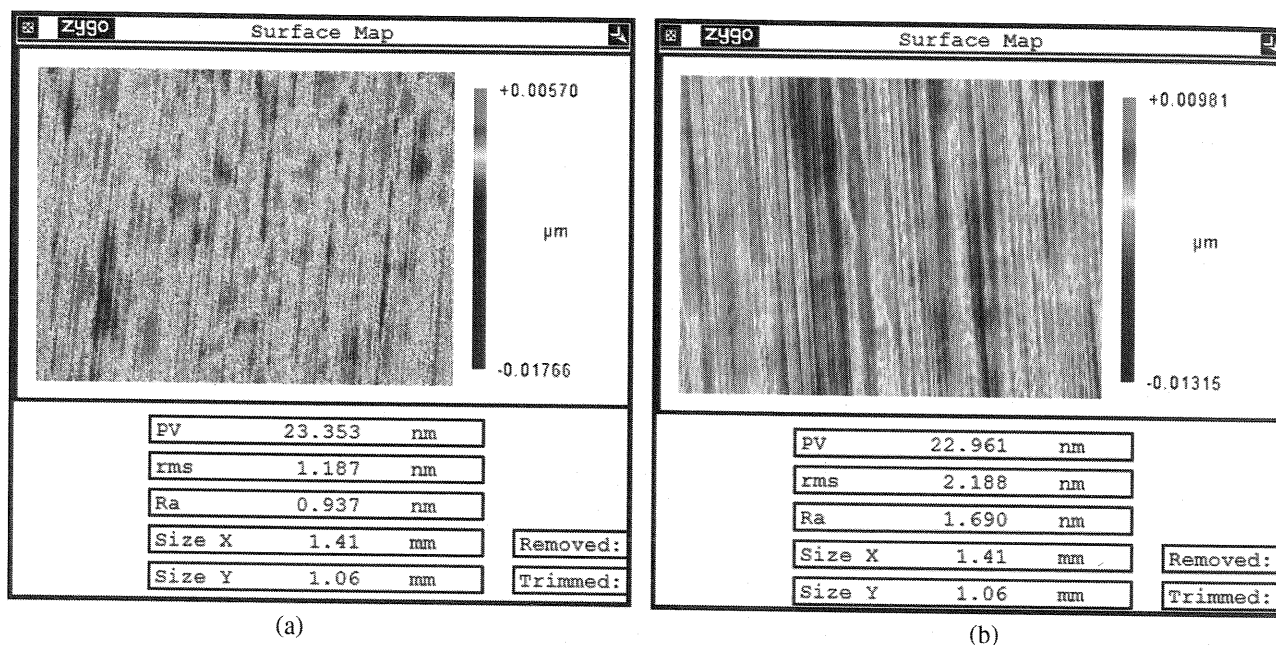


Fig. 7 Surface roughness of silicon modification layer on RB-SiC after polishing with (a) flocculated and (b) deflocculated MR polishing fluid.

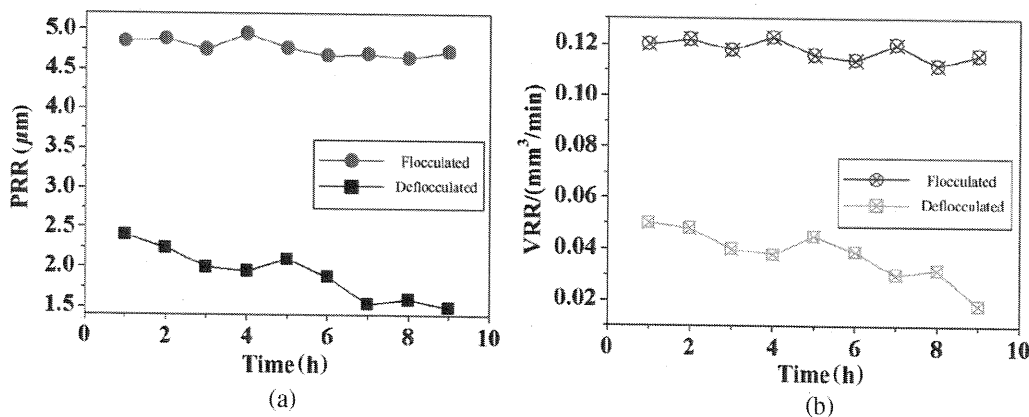


Fig. 8 Material removal rate comparison of BK7 glass with flocculated and deflocculated MR polishing fluid in 8 h of continuous polishing: (a) PRR and (b) VRR.

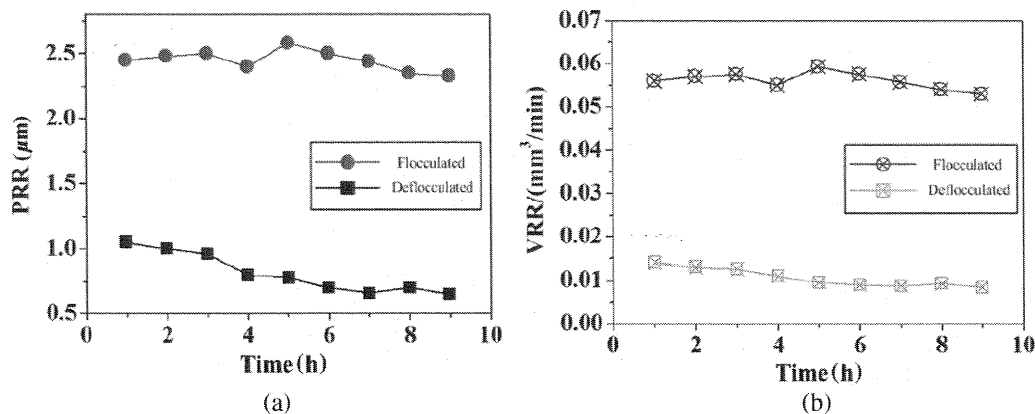


Fig. 9 Material removal rate comparison of silicon modification layer with flocculated and deflocculated MR polishing fluid in 8 h of continuous polishing: (a) PRR and (b) VRR.

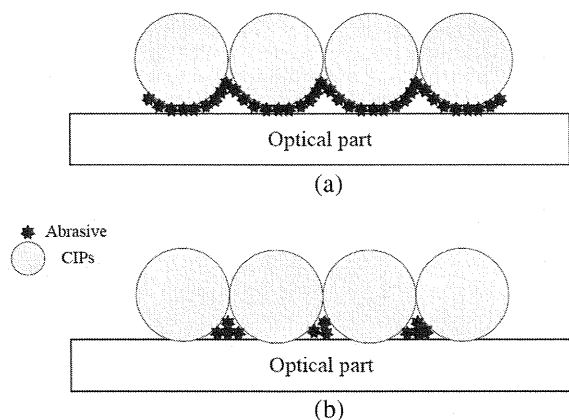


Fig. 10 Contact characteristic of CIPs and abrasives with optical part in the polishing process using (a) flocculated and (b) deflocculated MR polishing fluid.

for polishing other parts of the same materials (BK7, silicon modification layer on RB-SiC) during the interval. The experimental results are shown in Figs. 8 and 9.

Only water was added in this polishing process to keep the viscosity stable. Four different kinds of fluids were prepared as mentioned earlier, and removal rate stability was investigated for polishing the BK7 glass and silicon modification layer on RB-SiC.

As shown in Figs. 8 and 9, the material removal rate of flocculated MR polishing fluid is more stable than of the deflocculated MR polishing fluid's removal rate in long-term polishing processes. To verify the polishing performance, three similar experiments were also carried out by change the stabilizers of flocculated and deflocculated MR polishing fluids and using the same conditions as in this paper; similar results were obtained. This manifests that the results of the paper are universally applicable. Therefore, the results of this study will be of great significance to improve the efficiency and accuracy of MRF of large-aperture optical elements.

4 Discussion and Conclusions

Recent research proposes that the material removal of MRF is attributed to the collision of CIPs and abrasives in contact

area under high shear rate.¹⁸ Therefore, the association of CIPs and abrasives appears to be very important. The interaction of flocculated and deflocculated MR polishing fluid in the polishing area can be illustrated as Fig. 10. The abrasives disassociate from CIPs and gather between CIPs in polishing area using deflocculated MR polishing fluid. As a result, the abrasives do not fully participate in the polishing process, and the shear force derived from sheared CIPs will not be transmitted to abrasives, which determines that the material removal rate is comparatively low using deflocculated MR polishing fluid. However, the abrasives are bonded with CIPs in flocculated MR polishing fluid, and the interaction between abrasives and CIPs will be enhanced during the polishing process. Therefore, the abrasives will fully participate in polishing process and disperse uniformly in the polishing area, which explains the high material removal rate and good roughness using flocculated MR fluid compared with deflocculated MR polishing fluid. Furthermore, the abrasives will not decrease with the loss of base liquid, and the material removal rate will maintain stable during polishing process as the abrasives are bonded with CIPs.

Therefore, we propose that MR polishing fluid should be considered as polydispersed suspension system due to the existence of CIPs and abrasives in composition. Flocculated and deflocculated MR polishing fluids were prepared, and the material removal rate and surface roughness of the two types of MR polishing fluids were investigated by carrying out removal function experiments. The results show that the performance of flocculated MR polishing is superior to deflocculated MR polishing fluid in removal rate, surface roughness, and long-term material removal rate stability. The results will provide references and guidance for the preparation of MR polishing fluids and technology optimization of MRF, especially for the ultraprecision fabrication of large-aperture mirrors.

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