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A Study on the Surface Finishing Technique using Electrorheological Fluid

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ABSTRACT

The electrorheological(ER) fluid has been used to the ultraprecision polishing of single crystal silicon as new polishing slurry whose properties such as yield stress and particle structure changed with the application of an electric field. In this work, it is aimed to find the effective parameters in the ER fluid on material removal in the polishing system whose structure is similar to that of the simple hydrodynamic bearing. The generated pressure in the gap between a moving wall and a workpiece, as well as the electric field-induced stress of the mixture of ER fluid-abrasives, is evaluated experimentally, and their influence on the polishing of single crystal silicon is analyzed. Moreover, the behavior of abrasive and ER particles is described.

Key Words : Electrorheological fluid, Surface finishing, Shear stress, Bingham lubrication, Hydrodynamic pressure

1. Introduction

An electrorheological (ER) fluid is the complex fluid whose viscosity is altered by an electric field. It was founded in late 1940's by Winslow [1]. Similar materials to an ER fluid, a magnetorheological (MR) fluid and a ferrofluid are also the complex fluid whose viscosity is changed by a magnetic field. Such have been sometimes tried to use as a functional tool in ultraprecision polishing because liquid is transformed into semi-solid by external fields. Since a MR fluid and a ferrofluid can produce higher viscosity than an ER fluid, they were noticed as a good finishing tool. They do not contact directly with part surface but transmit the force required to remove material to part surface efficiently. And the process is easy to obtain super smooth finish and maintenance is relatively simple. In mid of 1990's, magnetorheological finishing process was developed by Kordonski et al. [2].

This process has been advanced to polish various optical materials such as ultraprecision spherical and aspherical lenses. A ferrofluid has also been explored to use as polishing slurry for diverse products in a few papers [3-5]. An ER fluid has been applied to the finishing of local area considering the finishing of three-dimensional micro products such as micro aspherical lens and molds by authors and other researchers [6,7]. Lee et al. [8] have introduced an ER fluid to polish single crystal silicon surface utilizing simple shear flow. Their results described that the shear stress of an ER fluid exerted on part surface is too weak to remove surface asperities because the simple shear flow of a present ER fluid gives the shear stress of a few kilo-Pascals at best. In this work, the hydrodynamic flow of an ER fluid is applied in a different way as Lee et al. did. Thus material removal is driven by complex effect of shear stress and hydrodynamic pressure. Since the principle of the hydrodynamic flow of an ER fluid is different with that

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of general Newtonian fluid, simple theoretical aspect is described. As a result of measurement of the pressure and the shear stress with respect to the applied voltage under certain operation conditions, material removal depends on shear stress more than pressure.

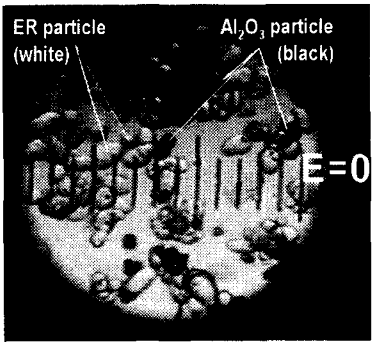
Compared to a MR fluid, an ER fluid has advantage of homogeneity of an electric field and simple configuration of electrodes. Moreover, some ER fluids reported recently are so noticeable that the yield stress is comparable to that of a commercial MR fluid. These will stimulate a study on the finishing techniques using ER fluids(electrorheological finishing). This study focuses on finding of efficient finishing principle using an ER fluid. Special application, ultimate surface roughness and other further considerations are not concerned.

2. ER fluid

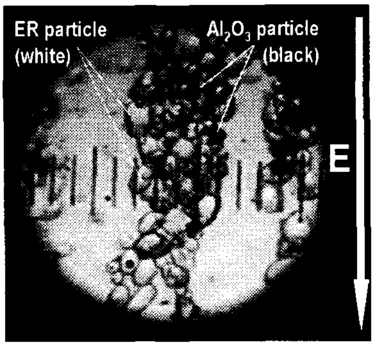
An ER fluid is suspension of 1 to 100mm of cornstarch, silica, or other semiconductors at volume fraction of 0.05~50 in a dielectric(electrically insulating) liquid such as silicone oil or mineral oil. For an electric field of 50~5000V/mm, the particles form chains that span the gap between the field-generating electrodes [8].

The simplest ER mechanism is the chaining of particles brought about by their polarization in an electric field. In principle, such field-induced chaining should occur whenever there is a mismatch between the bulk dielectric constant of the particle, ε_p, and that of the liquid ε_s. Usually $\varepsilon_p/\varepsilon_s>1$. In addition to true bulk polarizability, particles are also effectively polarizable if charged species can adsorb and migrate along particle surfaces, or if there are polarizable electric double layers around the particles [9].

Fig. 1 shows photographs of the chain-forming effect of an electric field on the abrasive(alumina)-mixed ER suspension. The white particle in the picture is an ER particle(starch). The black particle is alumina particle (#2000). Freely-dispersed particles without an electric field (a) align along the field direction making thick columns when a field is applied (b). It is known that abrasive shows same behavior with ER particles although the real electrostatic force on/by abrasive is smaller than between ER particles[7] because abrasive such as diamond, SiC and alumina satisfy the condition of bulk polarization.



(a) Without electric field



(b) With electric field

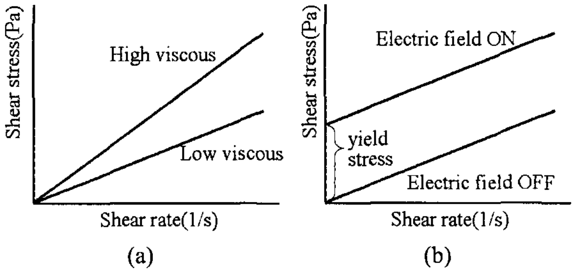
Fig. 1 Microscopic behavior of ER & alumina dispersed in silicone oil with and without electric field

2.1 Shear flow

The chains of particles in an electric field increase the shear stress τ_x in a sheared ER fluid. It is simply represented by the Bingham model [10,11] (See Fig. 2),

$$\begin{array}{ll} \tau_x(E,\dot{\gamma}) = \tau_Y(E) + \eta_{pl}\dot{\gamma} & \text{for } \tau_x \geq \tau_Y \\ \dot{\gamma} = 0 & \text{for } \tau_x < \tau_Y \end{array} \qquad (1)$$

where τ_Y is the yield stress according to electric field strength (E), $\dot{\gamma}$ is the shear rate, and η_{pl} is the plastic viscosity, which is nearly independent of the field.



(a) (b)

Fig. 2 Newtonian(a) and Bingham plastic behavior(b)

2.2 Hydrodynamic flow

Together with the shear stress, the hydrodynamic pressure is an important parameter concerning material removal. ER fluid flow caused by the rotating spindle located above the flat part surface is analogous to the classical problem commonly encountered in the theory and practice of hydrodynamic lubrication (See Fig. 3). If we consider the case when the shear flow, initiated by the rotating spindle with velocity U takes place in the gap at a given distance x along the gap and the shear stress magnitude $|\tau_x|$ is greater than the yield stress τ_Y for all y. For two-dimensional flow, the Bingham model in this case reduces to the conventional lubrication theory. The shear stress in the fluid film may not exceed in places the yield value. In this case, cores of unsheared material are formed near the stationary surface at the inlet to the gap ($dP/dx > 0$) and the rotating spindle at the outlet ($dP/dx < 0$) [2,12]. It is throttling action of the artificial boundary surfaces of theses cores that gives rise to new patterns in the flow. A theoretical consideration of this problem is based on the solution of the modified Reynolds' equation for pressure distribution. Under the conditions that are routinely used by lubrication theory, the basic equation is shown to be

$$\frac{dP}{dx}=\frac{d\tau_x}{dy} \qquad (2)$$

Equation (2) describes that pressure gradient depends on the shear stress as shown in equation (1).

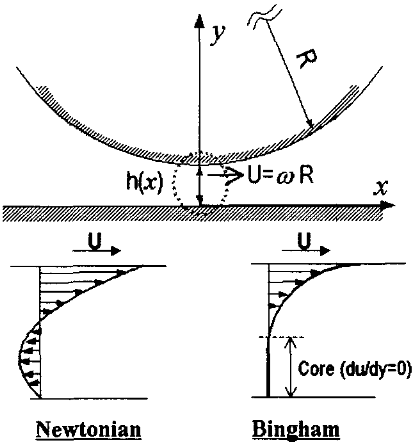


Fig. 3 Geometry of the gap between rotating spindle & workpiece, and possible velocity profile at *dP>dx* in Newtonian and Bingham fluids

This leads to too complicate algebraic expressions to describe them in this paper.

We examined the pressure variation with respect to applied voltage by direct measurement of the pressure of the ER fluid employed in this study.

3. Finishing structure

As described above, simple steady shear flow can not transmit enough force to remove material on flat surface. Thus both shear stress and hydrodynamic pressure must be applied. For this, the finishing structure shown in Fig. 4 was suggested. The ER fluid flowing the gap between a rotating cylinder and part surface makes hydrodynamic pressure which may be affected by the field-induced yield stress. Another advantage of this structure is that material removal can be homogeneous spatially compared to a structure of CMP or general polishing process where workpiece path is cycloid motion.

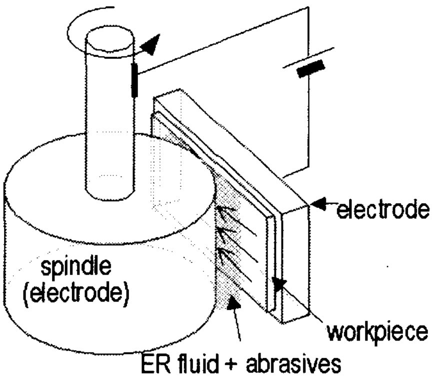
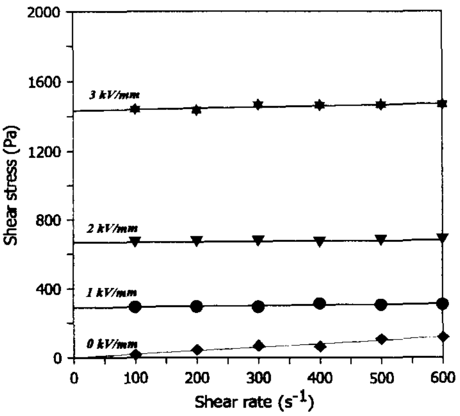


Fig. 4 Schematic of finishing structure using ER fluid

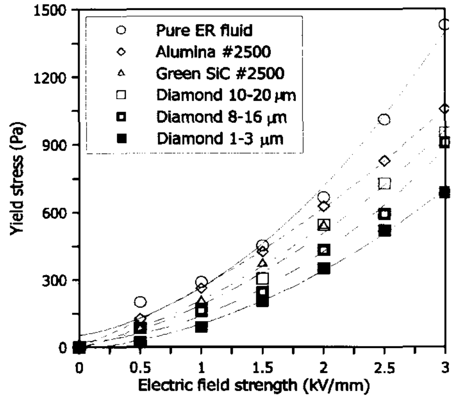
4. Measurement of shear stress and hydrodynamic pressure

4.1 Shear stress

The shear stress is a typical parameter which is controllable in an ER fluid. Also, it governs the friction on part surface by abrasive slurry. The measurements of the shear and yield stress were performed in concentric cylindrical viscometer. Fig. 5(a) shows relationship between the shear stress and electric field strength (0~3kV/mm) at shear rates from 0 to 600s^{-1} for the ER fluid containing 40wt% starch particles in 50cSt silicone oil. The averaged shear stresses at each shear rates were dotted with different shapes and they are fitted linearly. This ER fluid has the yield stress about 1.4kPa under 3kV/mm. The relation is consistent with Bingham model. Fig. 5(b) shows the yield stress τ_Y with field strength of the mixture of different kinds and types of abrasive. Abrasive concentration was 4wt%. The mean diameter of abrasives is ϕ6μm. Among the abrasives whose size are same, influence of diamond is most significant. In the diamond-mixed ER fluids, the yield stress decreases as diamond's size decreases. The yield stress of the mixture and diamond ϕ1-3μm at 3kV/mm is about half of that of the pure ER fluid. Generally, the yield stress increases exponentially along the field strength ($\tau_Y \propto |E|^{\alpha}$).



(a) Relation between shear rate & stress of pure ER fluid



(b) Yield stress of pure ER fluid and mixture with alumina, SiC(#2500), and diamond (three kinds of size)

Fig. 5 Shear stress characteristics of ER fluid and mixture with abrasives [13]

4.2 Pressure

Experimental setup and specification for the measurements of the hydrodynamic pressure generated in the gap between the rotating spindle and part surface as depicted in Fig. 4 is shown in Fig. 6 and Table 1. The composition of the ER fluid was same as that in Section 4.1.

The measured pressures with respect to revolution speed of the spindle, gap, and applied voltage are described in Fig. 7. Fig. 7(a) shows the relation between hydrodynamic pressure and spindle rotating speed under different gap thicknesses. At this time, 200 volt is applied between the spindle and conductive dummy block. Naturally, pressure increases linearly with spindle rotating speed. Also pressure increases as the gap thickness decreases. Fig. 7(b) shows pressure variation according to applied voltage for the rotating speed 500, 1000, and 1500rpm. As applied voltage increases up to 200~250 volt, hydrodynamic pressure increases slightly. After 200~250 volt, the pressure decreases and this is thought to be due to dielectric breakdown (300volt at the gap 30μm corresponds to 10kV/mm).

The increase of pressure with applied voltage is coincident with the result of Bingham lubrication theory on the flow between a rotating spindle and a flat wall when it is compared to other works [2,12]. However, it cannot be stated positively that the pressure increases is owing to core formation.

With the present ER fluid, hydrodynamic pressure cannot be controlled effectively on material removal process.

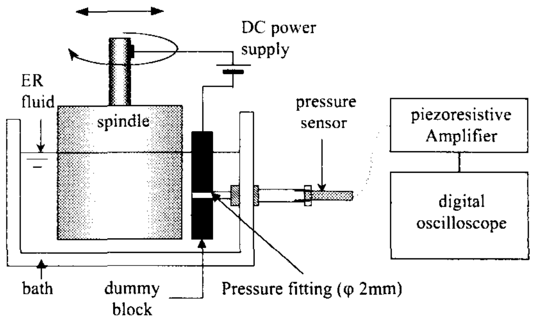
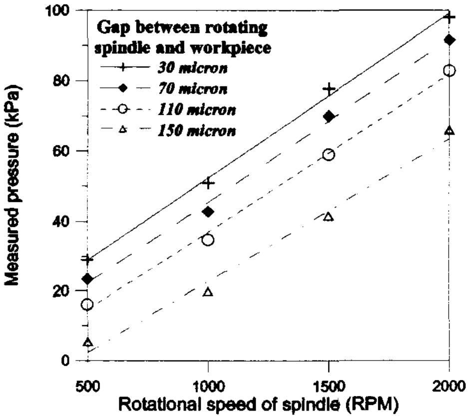


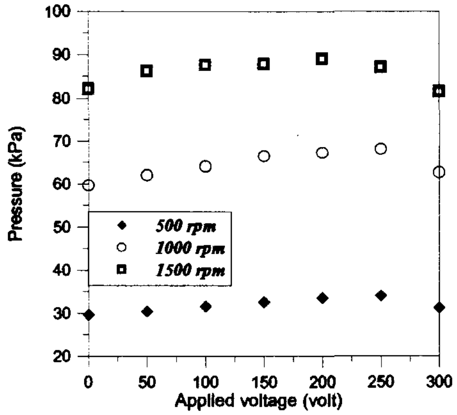
Fig. 6 Schematic of the pressure measurement apparatus

Table 1 Specifications of device for pressure measurement device and conditions

Pressure sensor	piezoresistive
Manufacturer / model	KISTLER / 4073A
Range	0~20Mpa
Amplifier	
Manufacturer / model	KISTLER / 4630B
Input range	±0.1 ... 1 volt
Spindle	
Rotational speed	0~2000 rpm
Material	brass
Diameter	75mm
Run-out	±5μm
Gap between spindle and Workpiece	30~150 μm
Applied voltage	0~300 volt



(a) Pressure with spindle rotating speed for different gap



(b) Pressure with voltage for different rotating speeds

Fig.7 Measured hydrodynamic pressure of ER fluid in gap between spindle and dummy block

5. Finishing test

5.1 Experimental conditions

The finishing quality of the present ER fluid was examined for a single crystal silicon wafer chip. The machining structure was already described in Fig. 4 and Fig. 6. The wafer chip was fixed on a block using vacuum pressure. The mixed abrasive into the ER fluid was alumina (ϕ0.3 and 1μm). The wafer chip had been lapped with SiC #1200 before experiments and initial surface roughness was Ra 0.2μm and Rmax 1.3μm. The whole experimental conditions are summarized in Table 2 After finishing, surface roughness was measured using stylus surface profiler at different three points in the wafer chip and averaged.

Table 2 Experimental conditions for the polishing test

Workpiece	Single crystal silicon
Size	20x20mm
Surface roughness	Ra 0.2 / Rmax 1.3μm
Abrasives	Al_2O_3 (ϕ0.3, 1μm)
Concentration	5wt%
Rotational speed	~2000 rpm (~7.8m/sec)
Gap between spindle and workpiece	30μm
Applied voltage	0~300 volt
Machining time	~10min
Feed length	5mm

5.2 Results

Fig. 8 shows surface roughness of silicon after finishing with the alumina (ϕ1μm)-mixed ER fluid during 480sec. when applied voltage varied from 0 to 300 volt. Spindle rotating velocity was 2000rpm and gap was 30μm. Maximum surface roughness decreases significantly as applied voltage increases while average roughness decreases slowly. Along with the result of pressure measurement in Fig. 7(b), surface roughness does not decrease over 200 volt. The ER fluid was out of work due to electric breakdown.

Fig. 9 shows the variation of surface roughness with respect to spindle rotating speed when 0 and 200volt were applied. Surface roughness decreases as rotating speed increases. It is thought that the rise of hydrodynamic pressure of the ER fluid due to the increased rotating speed of the spindle makes material removal fast. It is remarkable that surface roughness becomes significantly different according to applied voltage even under the same voltage conditions. From this result, the shear stress is more effective than hydrodynamic pressure on the control of material removal with electric field strength.

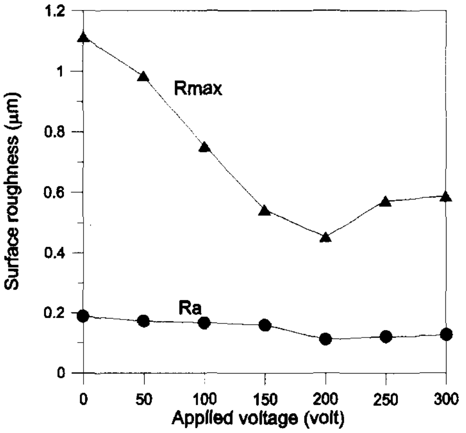


Fig. 8 Influence of applied voltage on surface roughness (2000rpm, alumina ϕ1μm, gap 30μm, 8min)

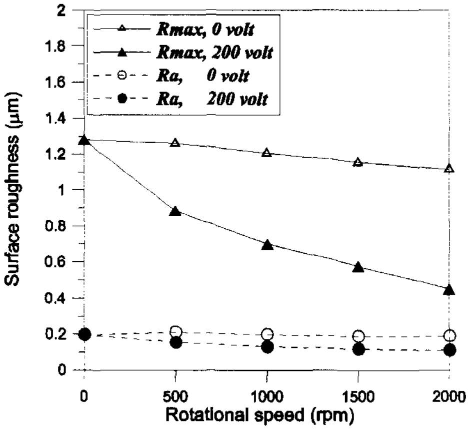


Fig. 9 Influence of rotating speed on surface roughness (200volt, alumina ϕ1μm, gap 30μm, 8min)

Fig. 10 describes the variation of surface roughness with finishing time to 600sec when 200volt was applied. Roughness improves remarkably before about 5min, which becomes dull after 5 min. The shear stress may not enough to make surface smooth further, which is shown in Fig. 11. It depicts topological images of the silicon surface from AFM device before and after the ER finishing. Alumina ϕ0.3μm was used as abrasive, applied voltage 200volt, gap 30μm, and finishing time was 10min. From this figure, small asperities in the initial surface are removed well while apparent waviness remains even after finishing. It can be known that the shear stress of the present ER fluid is too low as described above. Therefore, more advanced and stronger ER fluid would be required in order to establish the finishing and polishing process with an ER fluid as ultraprecision manufacturing process.

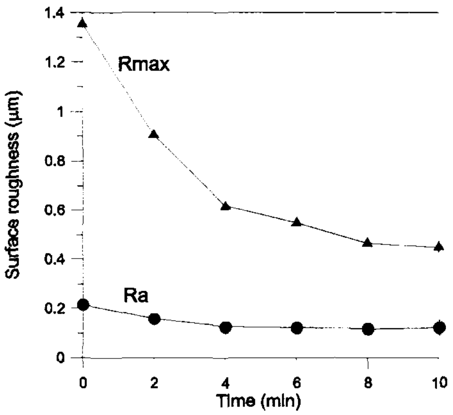
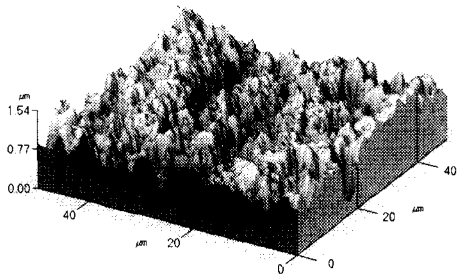
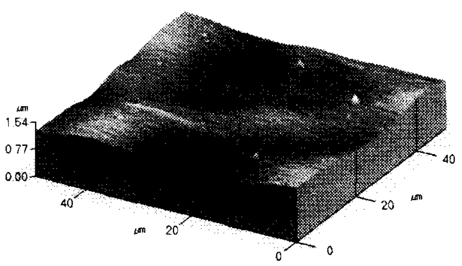


Fig. 10 Surface roughness with machining time (200volt, alumina ϕ1μm, gap 30μm)



(a) Initial surface (Ra 0.217μm, Rmax 0.947μm)



(b) Polished surface with ER fluid & Al_2O_3 ϕ0.3μm (Ra 0.026μm, Rmax 0.127μm)

Fig. 11 AFM image of surface before and after polishing

6. Conclusion

In this study, it was investigated how an ER fluid must be applied in a surface finishing technique. For this, the behavior of particles under an electric field and the shear stress and hydrodynamic lubrication characteristics are described theoretically and experimentally. And the influence of the shear stress and hydrodynamic pressure on material removal was examined comparatively. In result, the following conclusion was obtained.

Since the yield stress of an ER fluid can be controlled by electric field strength and the shear yield stress is exerted on surface like friction force, machining force can be controlled in the finishing with an ER fluid. Thus surface roughness decreases linearly with applied voltage to an ER fluid.

Also the hydrodynamic pressure varies with electric field strength. However, it affects material removal less than the shear stress because the influence of field strength on the hydrodynamic pressure was insignificant. It is thought that the yield stress of the present ER fluid is too low to form core in lubrication region. If the stronger ER fluid can be introduced, the hydrodynamic pressure can accelerate material removal even with low electric field strength. By every reason, the stress performance of an ER fluid is very important.

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