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Surface Finishing Technique for Micro 3-Dimensional Structures Using ER Fluid

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ABSTRACT

In this study, the electrorheological (ER) fluid was used as finishing agent. Since the apparent viscosity can be controlled by an electric field, the ER fluid can be one of efficient materials in finishing processes. To finish small 3-dimensional structures such as the aspherical surface in optical elements, the possible arrangement of a tool, part and auxiliary electrode was described. We examined the influence of the addition of a few abrasive particles on the performance of the ER fluid by measuring yield stress and observed the behavior of abrasive particles in the ER fluid by a CCD camera, which had been also theoretically predicted from the electromechanical principles of particles. On the basis of the above results, the steady flow analysis around the rotating micro tool was performed considering the non-uniform electric field. Finally, borosilicate glass was finished using the mixture of the ER fluid and abrasive particles and material removal with field strength and surface roughness were investigated.

Key Words : Electrorheological fluid, Surface finishing, Particle behavior, Three dimensional structure, Steady flow analysis

1. Introduction

Recently, miniaturization and ultraprecision in the fabrication of optical, biomedical, and telecommunication products are required more and more. However, the present micro fabrication technologies are not enough to fulfill the increasing demands in the market because of various technical and scientific barriers to the development of micro fabrication.

Together with MEMS technologies, the investigation of the fabrication technology using the micro/nano-scale material removal processes is being expanded owing to the easier fabrication of three dimensional structures rather than that by MEMS techniques, the superior part accuracy (form and surface roughness), and etc. Especially, the surface finishing of three dimensional micro products such as mold parts and glass lens are hard to be performed without mechanical material removal. However, even with the traditional mechanical (including chemical) polishing methods, the finishing of above products is still difficult because the fabrication of the polishing tool suitable for such the tiny and curved surface and the maintenance of the abrasives for efficient and stable material removal are difficult. For example, the application of small grinding wheel for the finishing of a small aspherical lens will be inefficient due to its severe wear and chip loading.

In order to overcome those difficulties, field-assisted polishing method which can control the motion or the

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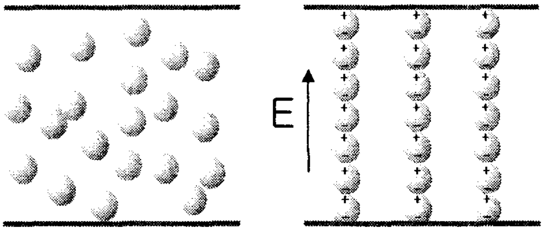
force of abrasives by electric and magnetic fields in very small area is recommended. The flat surface polishing utilizing electrophoresis of abrasives is one example of field-assisted polishing [1]. Recently, the surface finishing techniques using ER/MR fluids whose viscosity changes with the electric/magnetic fields were addressed [2-4]. The advantages of the field-assisted polishing are that there are no direct contact between a tool and a part surface and the material removal is controlled by the fields. However, there are a few points that should be changed for the better to apply for the finishing of micro parts. For instance, in case of the finishing with MR fluids and ferrofluids, the abrasives dispersed in those fluids are force to move away from the magnetized tool while the magnetic particles are strongly attracted by the tool. This is due to magnetic buoyant (levitation) and makes the process inefficient. Kuriyagawa et al.[4] introduced the finishing of a micro aspherical lens with the ER fluid and showed the feasibility of the ER fluid as finishing agent. However, they didn't explain clear explanation on the relation between ER particles and abrasives (i.e. behavior and role).

In this work, the behavior of the abrasives dispersed in the ER fluid under a non-uniform electric field which is formed around a tool is described. And the finishing principle is presented by analyzing the steady flow around the rotating tool. For this purpose, the influence of the addition of abrasives to the ER fluid on the performance of the pure ER fluid is examined and the in-situ observation of the particles is performed. The effect of the non-uniform electric field on the flow of the abrasive-mixed ER fluid is also presented. At last, as a result of the finishing of a small area on the Pyrex glass, material removal according to the field strength and surface roughness are reported.

2. Model of ER fluid

The ER fluid is suspension which consists of low conductive fine particles dispersed in dielectric liquid and the particles align across the gap between two electrodes along the applied field direction under the field strength of 0~5kV/mm as shown in Fig. 1. Since the particles become polarized and the attraction force is exerted between particles, they behave like bar magnets.



(a) E=0 (b) $E \neq 0$

Fig. 1 The structure of particles in ER fluid

These chain structures of the particles resist the fluid flow. Consequently, the apparent viscosity of the fluid increases. This is called ER effect. The response is very rapid and reversible.

The ER fluid is modeled as a Newtonian fluid in the absence of an electric field and as a Bingham fluid when an electric field is applied. The relation between shear stress, τ, shear rate, $\dot{\gamma}$, and the yield stress, τ_0, is

$$\tau = \tau_y(E) + \eta_{pl}\dot{\gamma} \tag{1}$$

for the Bingham fluid when it flows, with no flow occurring for $\tau < \tau_y(E)$; η_{pl} is the plastic viscosity and the viscosity is unaltered, $\eta_{pl} = \eta$. The yield stress of the Bingham fluid, $\tau_y(E)$, is proportional to the applied field strength [5-6].

$$\tau_y = \alpha E^{\beta} \tag{2}$$

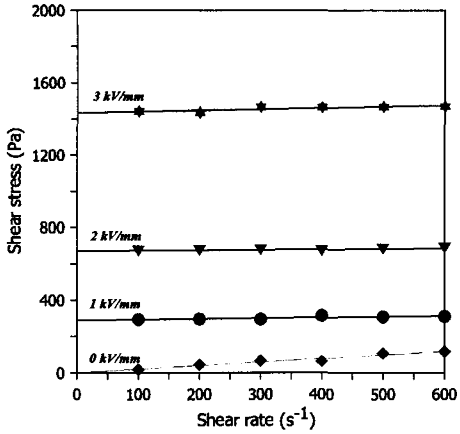
where α, β are constants from the measurements of the relation between the yield stress and the field strength.

The ER fluid which was used in this paper consisted of soluble starch (mean diameter 11.4μm) and silicone oil (absolute viscosity 0.096Pa·sec). The concentration of the starch particle was 30wt%. The yield stresses of the ER fluid obtained with a concentric electro-viscometer and the fitted data as Bingham fluid are shown in Fig. 2.

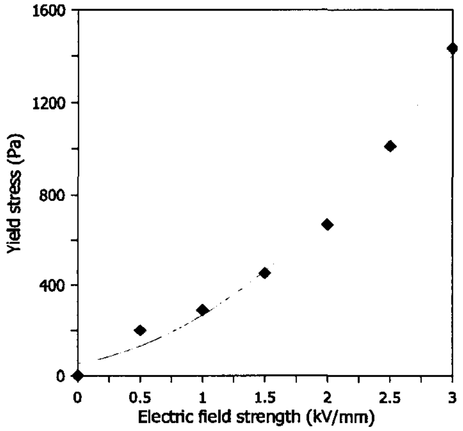
3. Relation between ER fluid and abrasive

3.1 Yield stress

A dielectric particle is polarized in an electric field and its polarizability depends on the conductivity, the permittivity, and interfacial properties of the particle and dispersing medium. Especially, the ER particles show strong electromechanical force in an electric field. Since

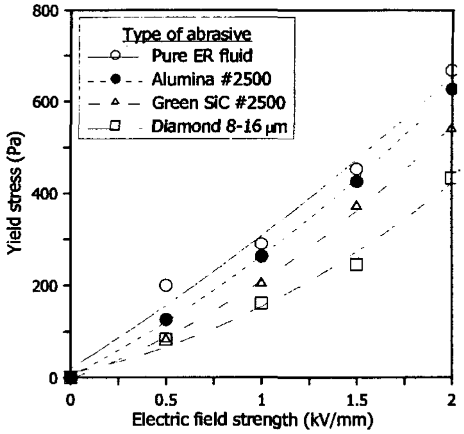


(a) Shear stress via shear rate according to field strength

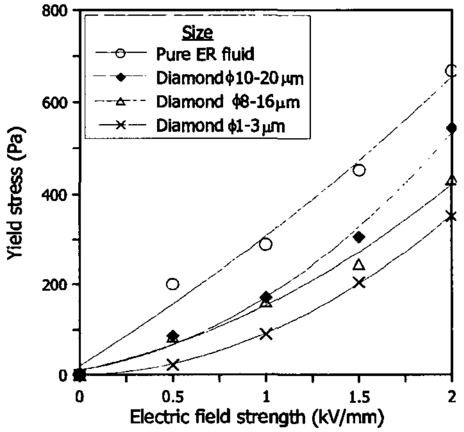


(b) Yield stress via electric field strength

Fig.2 Shear & yield stress graph of starch-based ER fluid



(a) Mixture of ER fluid and alumina, SiC, and diamond



(b) Mixture of ER fluid & diamond with different size

Fig. 3 Yield stress graph of abrasive-mixed ER fluid

some kinds of abrasives such as alumina and diamond are dielectric, they also show weak ER effect under certain conditions. If abrasives are added to the pure ER fluid, the shear and the yield stresses are altered. The stress characteristics of the abrasive-mixed ER fluid were measured with the electro-viscometer. Then, the mixed abrasives were alumina, silicon carbide, and diamond and each of them was added to the pure ER fluid by 4wt%. The yield stresses with the applied field strength of three kinds of abrasive-mixed ER fluid and pure ER fluid are shown in Fig. 3(a). The figure indicates that abrasive-mixed ER fluid has smaller yield stresses than that of the pure ER fluid. Among abrasives used in this experiment, diamond deteriorates most the original yield stress of the pure ER fluid. The effect of abrasive' size on the yield stress is described in Fig. 3(b) for diamond particles. Abrasive concentration was fixed at 4wt%. As abrasive' size becomes small the yield stresses of the fluid decreases. From Fig. 3, the influence of abrasive on the performance of the ER fluid is understood and the yield stress of the fluid to be used as finishing agent can be modeled numerically by Eq. (2).

3.2 Behavior of particles

In this section, the behavior of the abrasives which are mixed in the ER fluid is described. As described in Chapter 2, the ER particles span the gap between two electrodes and make chain-like structures. Abrasives show similar behavior. The polarizability of abrasives is weaker than the ER particle's polarizability. For two dielectric particles in dielectric medium, the inter-particle force between the particles in an electric field can be described on the assumption that both particles are spherical and mono-disperse, and their properties are represented by electric permittivity[6]. This force is

$$F(R,\theta)=\frac{3}{16}\pi\varepsilon_0\varepsilon_l d^2\beta^2E^2\left(\frac{d}{R}\right)^4\left[\left(3\cos^2\theta-1\right)e_r+\sin 2\theta e_\theta\right] \tag{3}$$

where ε_0 and ε_l are the permittivity of free space and fluid, respectively. d is the diameter of the particle, E is electric field, R is the distance between the centers of two particle, θ is the alignment angle of the two particles from the field direction, e_r and e_θ are the unit vector in $r-\theta$ coordinates, and $\beta=(\varepsilon_p-\varepsilon_l)/(\varepsilon_p+2\varepsilon_l)$, called as the Clausisus-Mossotti function, provides a measure of the strength of the effective polarization of a particle as a function of ε_p. If two dielectric particle are aligned in the direction of the field, two particles attract each other ($F>0$). If two particles are placed normal to the field direction, they repulse each other. Even though Eq. (3) can be applied to two particles whose properties are assumed to be same, it is also natural that the inter-particle force between the abrasive and the ER particle shows a similar tendency compared with the force between two ER particles because the value of β in Eq. (3) of both the abrasive and the ER particle are positive (the permittivity of alumina, SiC, and diamond are lager than that of fluid). Consequently, the motion of the abrasives dispersed in the ER fluid is identical to that of the ER particles in an electric field. Fig. 4 proves this mechanism. It shows the chain-like structures of both the ER (starch) and the abrasives (diamond) in the direction. of an electric field. It was taken by an optical microscope. The white particle in the picture is the ER particle. The black particle is diamond (#2000). Freely-dispersed particles without an electric field align along the field direction making thick columns when the field is applied. As can be seen in Fig. 4, it is known that abrasives shows almost same behavior with ER particles, although the acting force on/by abrasives is theoretically smaller than between ER particles [7]. That is, the ER fluid plays a role of a finishing tool which holds abrasives electromechanically. As the performance of the ER fluid increases, the holding force on abrasive increases.

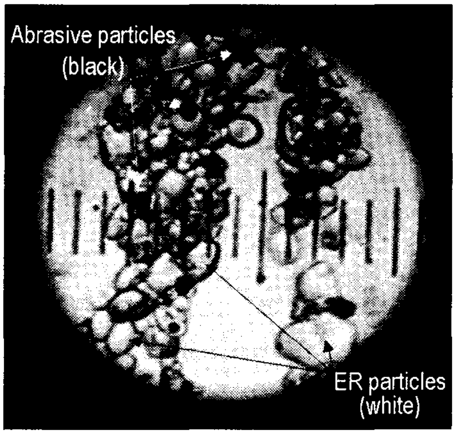


Fig. 4 Structure of ER particles and abrasives in an electric field

4. Flow characteristics in finishing system

4.1 Finishing structure

The structure of a finishing machine for the surface finishing of three-dimensional parts such aspherical lens is shown in Fig. 5. The tool can move along surface, not contacting with surface. This tool becomes one electrode and the other electrode is formed auxiliary around the tool. The part under the tool is polished when it rotates after the supply of the abrasive-mixed ER fluid and the application of high voltage. The shape of the auxiliary electrode is thin circular film surrounding the tool and it is adhered to the surface as shown in Fig. 6. This circular outer electrode makes the electric field concentrate to the conductive tool. That is, the electric field strength is high as close as the tool in radial direction. Even though the position of the tool may not be the center of the auxiliary electrode during finishing, the electric field can be modeled acceptably by using the formula for a coaxial cylindrical electrode system as follows,

$$E=\frac{V}{r\ln(R_2/R_1)} \tag{4}$$

where V is applied voltage and r is the radial position in Fig. 6. Accordingly, as the location of a particle become close to the tool, the inter-particle force between particle increases. This non-uniform electric field makes the spatial variation of the ER fluid flow when the electric field is applied.

4.2 Steady flow analysis of ER fluid

Shear stress of in the fluid is directly related with the force on surface transmitted by abrasives. For the finishing process with the ER fluid, the higher yield stress the ER fluid has, the larger abrasive force is transmitted to surface. In other words, the highest electric field strength makes the yield stress maximize at the tool in the machining system. Thus, the highest stress acts on the surface below or around the tool in the flow between the tool and the auxiliary electrode. In order to investigate the flow characteristics in the finishing system as shown in Fig. 6, steady flow analysis was performed for the mixture of ER fluid and abrasives assuming that the tool and the auxiliary electrode compose a concentric cylindrical system and the mixture is continuous Bingham fluid. The analysis was performed along the radial direction and the flow underneath the tool is not considered. This is because the flow underneath the tool can be considered as the radius the tool becomes small. Since the vertical gap between the tool and surface is similar to the diameter of the ER particle and when the tool diameter is about a few decades of microns, the flow underneath the tool contributes little to material removal. Moreover, the analysis including the flow under the tool is too complex. For this reason, the flow under the tool is not included in the analysis.

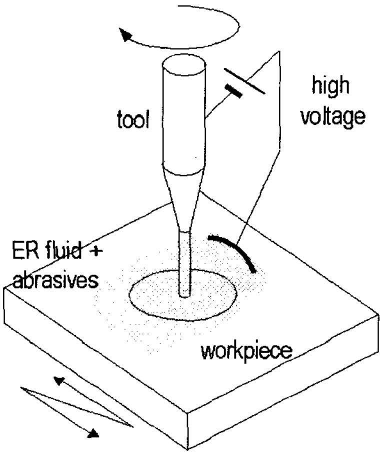


Fig. 5 Schematic of finishing structure

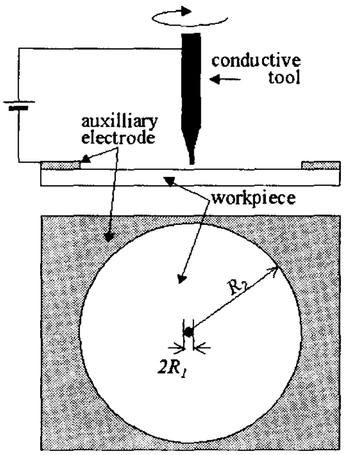


Fig. 6 Geometry of tool and auxiliary electrode to be identical to the flow close side of the tool

When the flow of the abrasives-ER fluid mixture is caused by the rotating of one of electrode (inner or outer cylinder), from the equation of continuity and motion, the governing equation of Bingham fluid flow between the tool and the outer circular electrode can be expressed as follows,

$$\tau_{r\theta} = \tau_e \operatorname{sgn}\left(\frac{d\omega}{dr}\right) + \eta r \frac{d\omega}{dr} = \frac{T}{2\pi L r^2} \tag{5}$$

where T is applied torque the internal cylinder (tool), τ_e is the yield stress, and L is length of the tool. The length has no concern with the flow.

Combining the non-uniform electric field in Eq. (4) and the governing equation in Eq. (5) and applying the boundary conditions $\omega(R_1)=\Omega$ and $\omega(R_2)=0$ in Fig. 6 gives [8]

$$\eta\omega(r) = \frac{T}{4\pi L}\left(\frac{1}{R_1^2} - \frac{1}{r^2}\right) + \frac{\alpha}{\beta}\left[\frac{V}{\ln(R_2/R_1)}\right]^{\beta}\left(\frac{1}{R_1^{\beta}} - \frac{1}{r^{\beta}}\right) \tag{6}$$

with

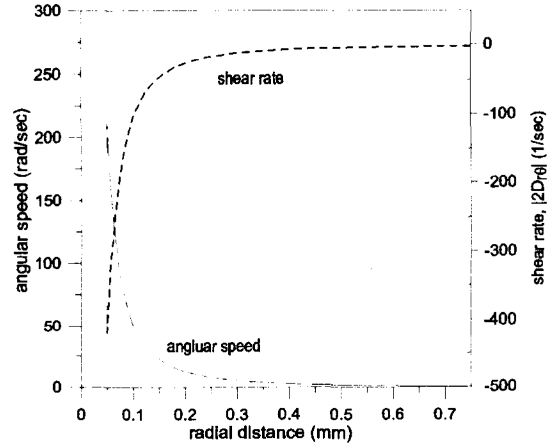
$$T = \frac{4\pi L R_1^2 R_2^2}{R_2^2 - R_1^2}\left[-\eta\Omega - \frac{\alpha}{\beta}\left(\frac{V}{\ln(R_2/R_1)}\right)^{\beta}\left(\frac{1}{R_1^{\beta}} - \frac{1}{R_2^{\beta}}\right)\right] \tag{7}$$

The shear stress is obtained from Eq. (6), (7) and the relation of $\dot{\gamma} = r\partial\omega(r)/\partial r$ as follows.

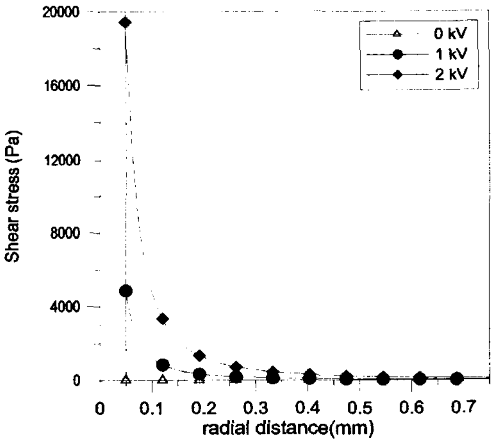
$$\tau_{r\theta} = \frac{2R_1^2 R_2^2}{R_2^2 - R_1^2}\frac{1}{r^2}\left[-\eta\Omega - \frac{\alpha}{\beta}\left(\frac{V}{\ln(R_2/R_1)}\right)^{\beta}\left(\frac{1}{R_1^{\beta}} - \frac{1}{R_2^{\beta}}\right)\right] \tag{8}$$

In order to determine the constants α, β in Eq. (2), polynomial approximation was performed for the yield stress as a function of the field strength of the diamond-mixed ER fluid in Fig. 3(a). As a result, α=85 and β=1.9 were obtained. Next, the shear stress is calculated. Considering the experimental conditions, rotating speed of the tool Ω, radius of the tool R_1 and R_2 are chosen to be 2000rpm, 0.05mm and 0.75mm, respectively. Applying these to Eq. (6)~(8), the shear rate, the angular speed and the shear stress are calculated along the radial direction from the tool and the outer electrode. They are presented in Fig. 7.

The angular speed and the shear rate are highest at the side of the rotating tool. The shear stress of the abrasive-mixed ER fluid which is modeled as Bingham body dramatically increases around the tool with the applied voltage due to the non-uniform electric field. To sum up, the significant increase of the rheological properties of the ER fluid around the micro tool due to the non-uniform electric field is effective in finishing process because very high shear force can be applied to surface with abrasives.



(a) Distribution of angular speed and shear rate



(b) Distribution of shear stress

Fig. 7 Flow characteristics of the diamond-mixed ER fluid around tool in radial direction

The behavior of the mixture of the ER fluid and diamond around the tool in center of the circular outer electrode is presented in Fig. 8. The applied voltage was DC 0.6kV and rotation of the tool was 1500rpm. Chain-like structures are formed and the particles become highly crowded around the tool. With rotation of the tool, each chains break near the outer electrode and instantly reform again or slip at boundary of the electrode.

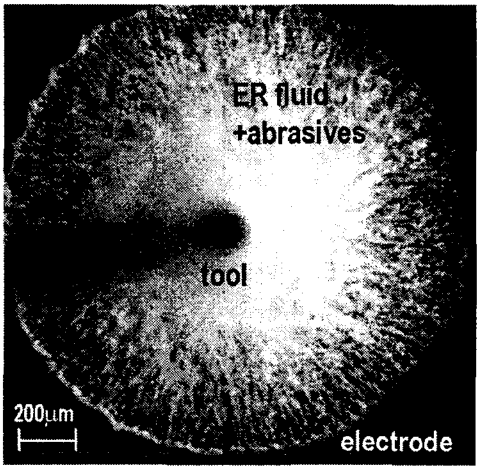


Fig. 8 Photograph of mixture of ER fluid and abrasives around tool (rotation 1500rpm, applied voltage DC 0.6kV)

5. Experiments

5.1 Conditions

Finishing experiments were performed in the structure described in Fig. 5 and 6 in order to evaluate material removal according to the applied voltage and surface roughness. The experimental setup consists of a three axis motion table and a precision spindle. However, there was no motion of the table during finishing for simplicity. Only the spindle rotated at constant speed. Borosilicate glass was prepared as a specimen. The abrasive to be mixed with the starch-based ER particle was two types; one is diamond (ϕ2μm) for the evaluation of material removal with respect to the voltage and the other is alumina (ϕ0.3μm) considering surface roughness. Other experimental conditions are summarized in Table 1.

Table 1 Experimental conditions

ER fluid	30wt% starch particles dispersed in 0.096Pa·s silicone oil
Abrasive	diamond ϕ2μm alumina ϕ0.3μm
Abrasive concentration	4wt%
Diameter of tool	100μm
Diameter of outer electrode	1.5mm
Thickness of outer electrode	45μm
Tool rotation speed	1500~2500rpm
Gap between tool and finished surface	10mm
Finishing time	~15min
Applied voltage	~2kV
Workpiece	Borosilicate glass
Hardness	418kgf/mm^2

5.2 Results

Fig. 9 shows the relation between material removal and the applied voltage when the diamond-mixed ER fluid was used. Material removal was obtained by measuring the removed depth from initial glass surface with a surface profiler. The finishing time was 5 minutes. As the applied voltage increases, material removal increases. The depth of material with respect to the applied voltage is similar to the relation between the field strength and the yield stress as described in Fig. 2. As a result of many experiments under different conditions, material removal can be controlled from 0 up to about 0.7μm/min. The gap from surface to the tip of the tool was also effective parameter on material removal. As the gap decreases, material removal rises. However, the gap must be larger than the size of abrasive. The complicate description of the process characteristics will be reported later.

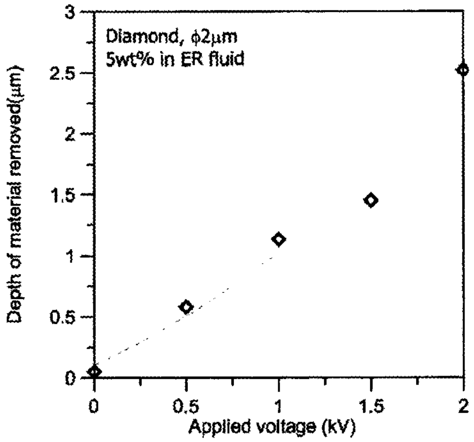
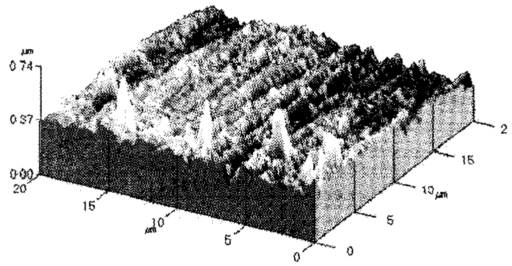


Fig. 9 Depth of material removed with applied voltage

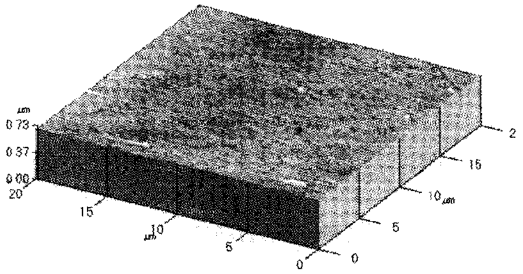
Fig. 10 shows the surface topography of glass viewed from AFM (Atomic Force Microscope) device before and after the finishing with the mixture of the ER fluid and alumina. Glass surface was lapped by SiC particles (#8000) before finishing and Rmax 0.15μm was obtained. The rotating speed of the tool was 2000rpm and finishing was performed for 10 minutes. As a result of finishing, Ra 3nm and Rmax 18nm were obtained and roughness was reduced down to 1/10 compared to that of initial surface.

6. Conclusion

In this paper, we presented theoretical models and a few experimental results using the ER fluid (electrorheological finishing). The shear and yield stress of the mixture of the ER fluid and a few types of abrasive were measured with electro-viscometer and the behavior of the particles (the relation between ER particles and ab-



(a) Initial surface (Ra : 28nm, Rmax : 0.15μm)



(b) Finished surface using ER fluid & 0.3μm alumina (Ra : 3nm, Rmax : 18nm)

Fig. 10 Surface topography by AFM before and after finishing with alumina-mixed ER fluid rasives) was described. The flow of the mixture of the ER fluid and abrasives was analyzed around the rotating tool in the electric field. As a result, the shear stress of the fluid could be obtained. It was intended to develop the electromechanical effect of fine particles for the precision finishing of small and curved surface. The method and principle are different with the established other finishing processes. The conclusion of this study can be summarized as follows.

The role of the ER fluid in the surface finishing of small parts can be explained from two points of view. Firstly, the ER fluid can supply and maintain the mixed abrasives to/at the area where material is removed. That is, since abrasives and ER particles attract each other along field direction, the abrasives embedded in the chain-like structures of ER particles can be placed around the finishing micro tool constantly. Secondly, as the yield stress of the ER fluid and electromechancial performance increase, the holding force on the abrasives increases. The ER fluid plays a role of the smart tool such as grinding wheel and material removal can be controlled with an applied voltage.

The finishing with the micro tool generates a non-uniform electric field and the field plays an important role on the finishing mechanism. The electric field emitted from the outer circular electrode concentrates on the tool located around the center of the circular electrode. This makes the spatial difference of the properties of the ER fluid. The yield and shear stress of the ER fluid maximizes as close as the tool. The numerical density of the abrasives dispersed in the ER fluid also increases near around the tool because of the concentration of the particle strands.

The finishing method described in this study may be suitable to the fabrication process of three dimensional micro parts made of glass or ceramics such as a micro lens and a mold. If stronger ER fluid rather than the present is applied in the finishing, this electrorheological finishing would be very useful as one of micro fabrication techniques.

Acknowledgement

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