An investigation on Electrorheological Fluid-assisted Polishing Process for Tungsten Carbide

Yunwei Zhao

Engineering Training Center, Beihua University,Jilin 132021, P.R. China
jluzyw@yahoo.com.cn

Dexu Geng* and Xiaomin Liu

Engineering Training Center, Beihua University,Jilin 132021, P.R. China
gengdx64@163.com, jlulxm@yahoo.com.cn

Abstract—The surface roughness and material removal is investigated in electrorheological (ER) fluid-assisted polishing of tungsten carbide die. In this study, the microstructure of fibrous columns formed by particles perpendicular to the electrodes is observed by CCD when the electrical field is applied. The distribution of the electric field strength on the surface of workpiece was analyzed by ANSYS and theoretical equation. The force acting on ER particles and abrasive particles is calculated in an electric field. According to *Preston*'s equation, a model for material removal of the polished conductive workpiece is derived. Polishing experiments with Al_2O_3 and diamond particles for tungsten carbide is conducted. The influential regularities of the polishing time, rotational speed of micro-tool, voltage, concentrations of abrasive particles and gap of electrodes on the surface roughness and material removal are obtained. The profile of machined area is measured by WYKO and the experimental results are compared with the theoretical predictions, which confirm the validity of the presented model.

Index Terms—Electrorheological fluid-assisted polishing, Surface roughness, Material removal, Electric field strength

I. INTRODUCTION

The size of the photoelectron equipment component is decrease with the development of the photoelectron communications technology. The demand for large numbers of micro-optical aspherical lenses with low surface roughness has prompted the investigation into new processing method [1]. The conventional polishing mainly using of small polishing pad or polishing wheel under computer control is not fit to finish a miniaturized part or die efficiently, as it is not place fine abrasive particles on the targeting area steadily, in addition to the manufacture of micro polishing tool is difficult [2]. As a result, losse abrasives processes using electric or magnetic fields are recommended [3-4].

Electrorheological(ER) fluid-assisted polishing process is the ultra precision finishing technologies has been presented to polish micro-aspherical lenses and dies, which is first proposed by Kuriyagawa[5] using the ER fluid which contains fine abrasives as the polishing medium in 1999. ER fluid-assisted polishing utilize field-assisted to control the action and pressure of abrasives similar to magnetic finishing, magnetorheological finishing (MRF), electrophoresis polishing. Compared to a MRF, ER-assisted polishing has advantage of homogeneity of an electric field and simple configuration of electrodes [6]. Surface roughness and material removal are the great concerns in the ER fluid-assisted polishing. Kuriyagawa et al. [7] observed the ER effect facilitates collection of abrasives at the tip of tool for the polishing of optical lenses and dies by CCD microscope. W.B Kim et al. [8] analyzed the friction characteristics of ER fluid and the behavior of the ER particles at interface with and without the application of an electric field and extend the ER fluid-assisted polishing method to the polishing of silicon wafer chip. Zhang et al. [9-10] develop the empirical models for evaluation of the effects of the process parameters on the material removal depth and surface roughness in the ER fluid-assisted polishing. Lu et al. [11] use Fe_3O_4 magnetic particles as solid particles of ER fluid in ER fluid-assisted polishing of optical glass.

In previous research, the machining principle is the ER effect generated by ER fluid which rheological properties and microstructure will be readily changed when the electric field is applied. The particles in the ER fluids are almost all polarized and then gathered to the tiny polishing area under electric field, and which load greater pressure on workpiece. And ER fluid-assisted polishing process can place fine abrasive particles on the targeting area steadily to overcome defects of convention fabrication technologies. Therefore the machining process of ER-assisted polishing has been recommended to polish extremely fine three dimensional geometries to achieve finer surface roughness, which has been expanded to polish nonconductive and conductive material. On the other hand, the polishing tool is designed to use a micro needle-like electrode in the ER fluid-assisted polishing process. Furthermore, it is facilitate to control the polishing action through adjusting the voltage

*Corresponding author.Tel.18604496886.
Email: gengdx64@163.com (D.X.Geng)

between the electrodes. And the material on the surface of workpiece is removed through the relative motion between the soft polishing pad and the surface of workpiece under the hydrodynamic pressure. Obviously the ER fluid-assisted polishing is developed to polish extremely fine three-dimensional geometries to achieve finer surface roughness.

II. ER POLISHING FLUID

ER fluid is among the many smart or intelligent materials, its rheological properties and micro structure can be readily changed, such as apparent viscosity and yield stress when the electric field is imposed.

ER fluid which consisted of silicone oil and starch particles is used as the medium. The ER polishing fluid between the electrode and the workpiece is mixed from ER fluid and ultra-fine abrasives with a certain percentage. The ultra-fine abrasive particles suspended in ER fluid generally includes diamond, SiC and Al_2O_3. The ER particle and the addition of ultra-fine abrasive particles into ER fluids are dielectrically polarized with an electric field. The ER particles surrounding the abrasive particles form a chain-like structure and give bonding strength to the embedded abrasive particles. The microstructure formed by particles perpendicular to the electrodes is observed by CCD when the electrical field is 0.3KV/m in Fig 1. As can be seen in Fig 1, the chains formed by ER particles associate with each other into fibrous columns, in which the abrasive particles is embed. The mean diameter of fibrous columns is approximately 200μm, and the starch and SiC particle are the white and black particle respectively in the picture.
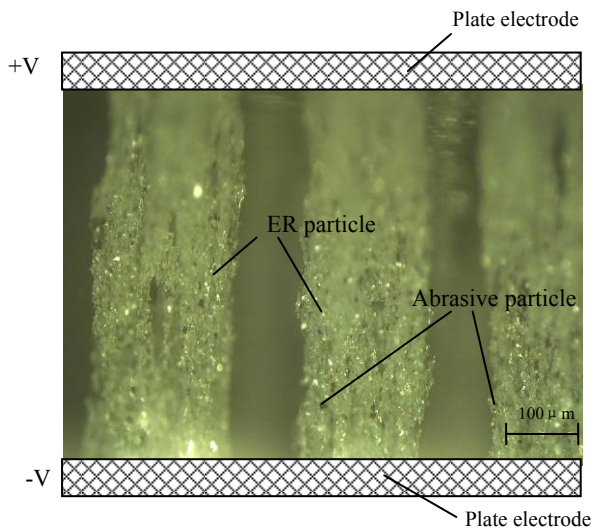

Fig.1. Microstructure of fibrous columns formed by particles in ER polishing fluid.

The yield stress increases with application of an external electric field as the fibrous columns structures restrict the movement of the ER polishing. Without the electric field, the ER particles disperse in the ER fluid which flow as Newtonian fluid. Otherwise, the ER polishing fluid flows under high-intensity electric field gradient, and the fluidity has the same physical character

as the medium of Bingham. The simplified model ER suspension uses the Bingham equation [12].

$$\tau = \eta_0\dot{\gamma} + \tau_0 sign(\dot{\gamma}) \qquad |\tau| \geq |\tau_0|$$
$$\dot{\gamma} = 0 \qquad |\tau| \leq |\tau_0| \qquad (1)$$

Where τ is shear stress, η_0 is pastic viscosity, $\dot{\gamma}$ is shear rate, τ_0 is yield stress. Here the expressions for yield stress are given as[13]

$$\tau_0 = kE^2 \qquad (2)$$

If τ is smaller than τ_0, the ER fluid forms rigid core, otherwise the ER fluid flows as a Newtonian fluid. The yield stress of ER polishing fluid is proportional to the square of the electric field intensity in Eq. (2). The detailed simulation and experimental conditions are listed in Table I.

The yield stress of ER polishing fluid is calculated by Eq.(2) and the experiments are conducted to measure the static shear yield stress of ER polishing fluid by the developed yield stress testing device. The simulation for yield stress for Eq. (2) and the measured ones are shown in Fig. 2. It can be seen that the yield stress is rise with the increase of electric field intensity. The theoretically calculated yield stress values are in close agreement with experimental results.
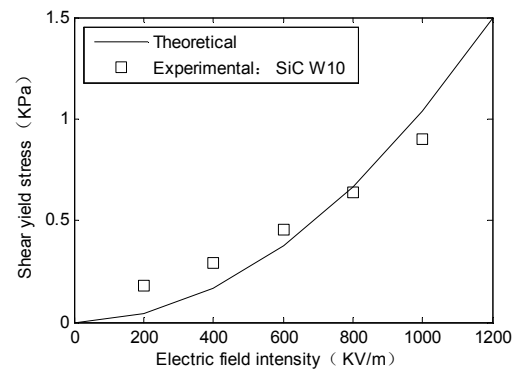

Fig.2. Relationship between shear yield stress and electric field intensity.

TABLE I.

SIMULATION AND EXPERIMENTAL CONDITIONS

Applied voltage	1-5KV
Amount of abrasives for ER fluid	15%
Volume percentage of starch particle	30%
Width of plate electrode	60mm
Length of plate electrode	90mm
Gap between plate electrodes	5mm
Material of plate electrode	copper

III. MACHINING PRINCIPLE

The principle of the ER fluid-assisted polishing of conductive materials is schematically shown in Fig.3. The micro copper tool electrode is positive pole, and workpiece of conductive material is used as negative pole, which retains narrow gap between electrodes. Meanwhile,

the mixture of abrasive particles and ER fluid is supplied to the gap between the tool and the workpiece. When the external electric field is applied, the ER particles and abrasive particles suspended in silicone oil are polarized in which ER particles strongly attract each other and aggregate into chain like structure aligned the electric field line, and the abrasive particles may adhere to the ER chain. When the chain of particles contact with workpiece surface with the rotation of the micro-tool, the abrasive particles indent into workpiece surface under normal pressure. And then the material is removed when the tangential force caused by ER-fluid on the abrasive particles is greater than the reaction force of the workpiece surface.

In ER fluid-assisted polishing process, the necessary voltage is hundreds of volts when the gap distance of electrodes is 100μm, which is not exceed 700V to prevent the electrodes short-circuiting.
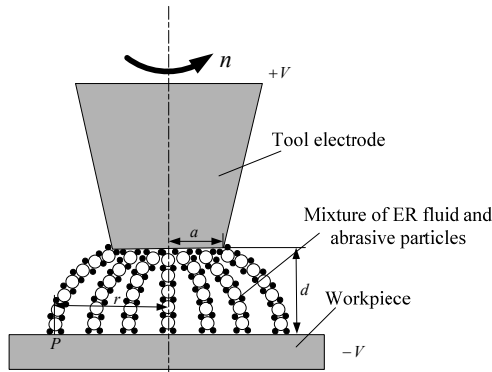

Fig.3. Mechanism of ERP

A. Analysis of Electric Field

When the voltage is loaded between electrodes, a non-uniform gradient electric field is generated between tool electrode and workpiece.

Fig.4a) indicates that there is a non-uniform gradient field between the tool electrode and the workpiece. The electric power line is most concentrated on around the tip of tool electrode and perpendicular to the surface of workpiece. Fig.4b) illustrates that the strongest electric field strength lie at the tip of the tool electrode as the electric power lines gathered there.
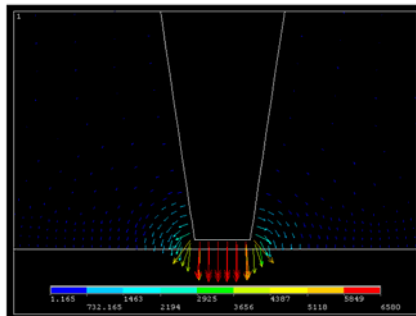
a) Distribution of electric lines
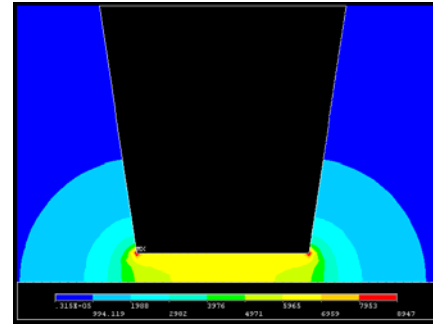
b) Distribution of electric field intensity

Fig.4. ANSYS simulation.

Since the area of tool electrode top is far less than that of workpiece, through the *mirror method* can obtain the electric field .The electric field E of the surface of workpiece is given as

$$E = \frac{c_1 U s}{2\pi \left(c_2 r^2 + d^2\right)^{3/2}} \qquad (3)$$

Where U is the voltage loaded between electrodes, S is the area of tool electrode top, r is the distance from point P to the centre line of the tool electrode, d is the gap of electrodes, c_1 and c_2 are the modified coefficients.

The electric field strength on the surface of workpiece decreases far away from the centre line of the tool electrode, as shown in Fig.5.
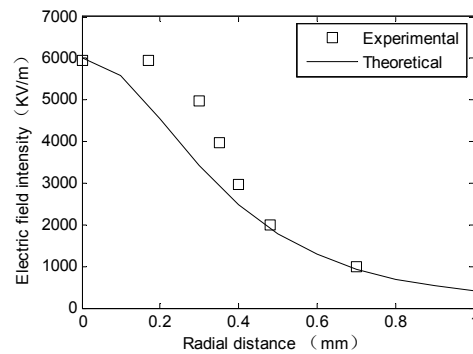

Fig.5. The distribution of electric field strength on the surface of workpiece

Because of the gap of electrodes is extreme small, the electric field between electrode electrodes is almost well-distributed. As a result, the electric field theoretical cases is lower than the ANSYS analytical values at the area less than radius of tool tip under tool. When beyond the radius of tool tip, the trend of theoretical curve of electric field is well identical with ANSYS analytical results.

B. Force Acting on ER Particles and Abrasive Particles in an Electric Field

1. Electric field induced attraction force between particles

When the electric field is applied, these dielectric particles will be polarized disperse in base medium which cause the attraction force among particles. The interaction of particles due to electric polarization is as shown in Fig.6.
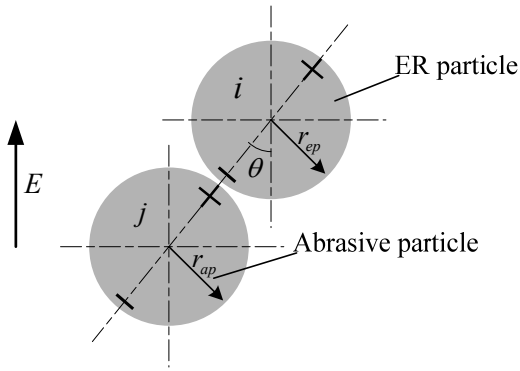
Fig.6. The interaction of particles due to electric polarization

Fig.7. Interacting force and dielectrophoretic force between ER and abrasive particle with radial distance from the micro tool.

If only the attraction of the pair of particles are considered, and the angle θ of two nearly touching particles along the electric field is zero. Then the interacting force between the ER particle and abrasive particle is given as follows [13],

$$F_{ij} = \frac{3 p_i p_j}{2\pi\varepsilon_0 \varepsilon_f R_{ij}^4} \qquad (4)$$

Where p_i and p_j are the dipole moments of two interacting particles, respectively, ε_0 is the permittivity of free space, ε_f is the relative permittivity of dielectric fluid, and R_{ij} is the distance between two interacting particles.

$$p_{ap} = \frac{\pi\varepsilon_0\varepsilon_f \beta_{ep} d_{ap}^3 E \left(1 + \beta_{ep} d_{ep}^3 / 4R^3\right)}{2\left[1 - \left(\beta_{ap} d_{ap}^3 / 4R^3\right)\left(\beta_{ep} d_{ep}^3 / 4R^3\right)\right]} \qquad (5)$$

$$p_{ep} = \frac{\pi\varepsilon_0\varepsilon_f \beta_{ep} d_{ep}^3 E \left(1 + \beta_{ap} d_{ap}^3 / 4R^3\right)}{2\left[1 - \left(\beta_{ep} d_{ep}^3 / 4R^3\right)\left(\beta_{ap} d_{ap}^3 / 4R^3\right)\right]} \qquad (6)$$

Where d_{ap} and d_{ep} are the diameter of the abrasive particle and that of the ER particle, respectively.

$$\beta_{ep} = \frac{\varepsilon_{ep} - \varepsilon_f}{\varepsilon_{ep} + 2\varepsilon_f} \qquad (7)$$

$$\beta_{ep} = \frac{\varepsilon_{ap} - \varepsilon_f}{\varepsilon_{ap} + 2\varepsilon_f} \qquad (8)$$

Where ε_{ap} and ε_{ep} are the relative permittivity of the abrasive particle and that of the ER particle, respectively.

2. Dielectrophoresis

The dielectrophoretic force will attract the abrasive particles from the weaker field to strong field, which is found with the following eqution[14].

$$F_{DEF} = \frac{\pi}{4}\varepsilon_0\varepsilon_f \beta d_p^3 \nabla E^2 \qquad (9)$$

Where d_p is the spherical grain diameter.

All parameters considered in the calculations are summarized in Table II and Table III. Fig.7 shows the pair attraction force between particles in ER-fluid.
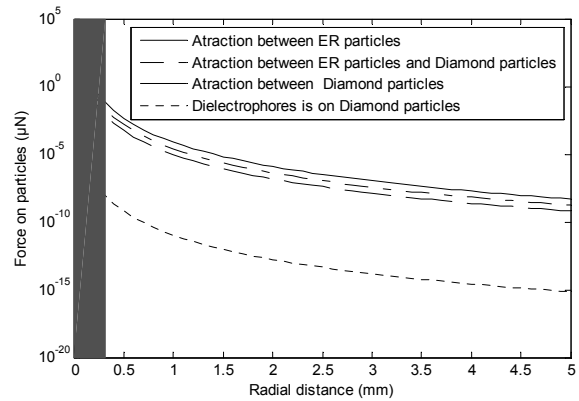
All forces decrease with radial distance due to the electric field strength in the polishing area on the surface of workpiece. The attraction force between ER particles is highest, secondary between ER particles and between diamond particles and the electrophoretic forces on diamond particles is negligible.

TABLE II.

GEOMETRIES AND PROPERTIES OF THE EMPLOYED MATERIALS

Relative permittivity of starch particle	50
Relative permittivity of silicone oil	2.7
Relative permittivity of diamond particle	5.7
Relative permittivity of Al$_2$O$_3$ particle	9.0
Coefficient of c_1	0.022
Coefficient of c_2	0.008
Diameter of starch particle	10μm
Diameter of diamond particle	10μm

TABLE III.

SIMULATION AND EXPERIMENTAL CONDITIONS

Diameter of tool	1.2mm
Diameter of tool tip	600 μm
Gap between tool and workpiece	100μm
Applied voltage	600V
Volume percentage of starch particle	30%

C. Model for Material Removal

According to *Preston*'s equation[15], the material removal rate is calculated from the following equation.

$$\frac{dV}{dt} = C_p F_N v_s \qquad (10)$$

Where C_p is Preston coefficient, F_N is the normal force and v_s is the relative speed between the tool and workpiece.

$$F_N = \frac{\tau_y}{\mu} \qquad (11)$$

Where μ is the friction coefficient by measured through the yield stress testing device.

The relative speed between the tool and workpiece may be calculated approximation as follows:

$$v = k\omega r \qquad (12)$$

Where k is the coefficient, ω is the angular velocity of tool electrode.

Substituting Eqs. (11)- (12)into Eq. (10) yields

$$\frac{dV}{dt} = kC_p \frac{\omega}{\mu} \tau_y r \qquad (13)$$

In Eq. (13), τ_y can be calculated in Eq. (2).

With Eq. (13) the material removal rate can be calculated. Hence, we can get the material removal rate in polishing area by varying the yield stress acting on abrasive particles (τ_y), because the yield stress is a function of the distance far away from the centre line of the tool electrode (r).

IV. RESULS AND ANALYSIS

A. Polishing Equipment

A five-axis ER fluid-assisted polishing equipment with an integrated electrode is developed. As shown in Fig.8, the equipment is designed with X, Y, Z, B and C axes, and the workpiece is mounted on a table, which can rotate along the Z-axis, and move along the X-axis and Y-axis, respectively. The tool electrode is mounted on another table which can rotate along Z-axis; both two tables are driven by Panasonic AC servo motor.
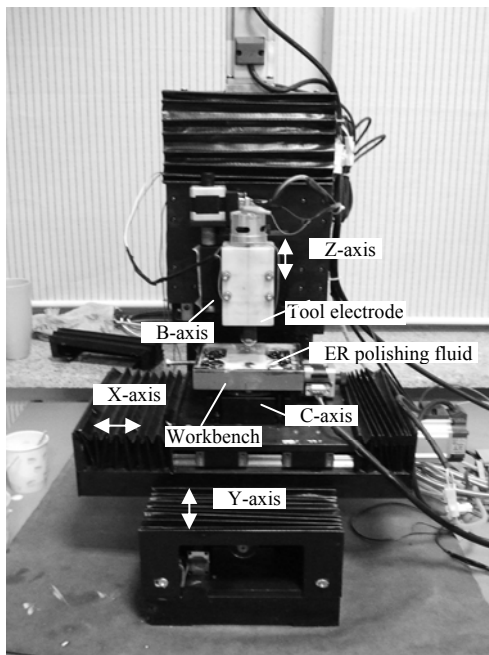

Fig.8. Whole view of the machine.

B. Polishing Experiment

A series of basic experiments of polishing tungsten carbide have been made which aim to find out the influential regularities of process parameters on the surface roughness. All experiments were performed in table Ⅲ. Fig.9-Fig.12 shows the relation among voltage, the density of abrasives in ER fluid, rotational speed of micro-tool and polishing time with the surface roughness.

The surface roughness gradually decreases with the increase of the polishing time is depicted in Fig.9. Fig.9 shows that the surface roughness gradually decreases with the increase of the polishing time. When polishing

tungsten carbide, the surface roughness gradually decreases in the first 40 minutes, after that, the surface roughness has no significant change with the increase of the polishing time. AS the indentation of the cutting edge of abrasives into workpiece under shear stress, the surface roughness only has slight change exceed necessarily polishing condition[16].
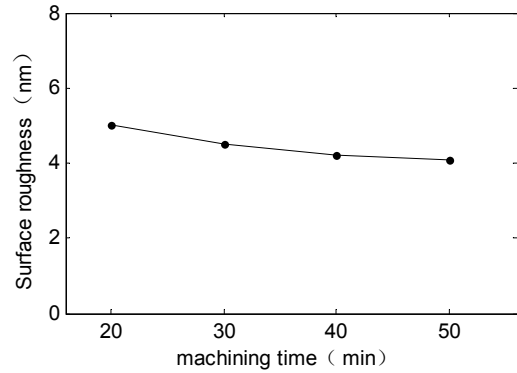

Fig.9. Relationship between surface roughness and machining time

Fig.10 reflects the effect of voltage on the surface roughness. It indicates that the surface roughness decreases with the increase of the voltage. The ER effect increase with the electric field strength result in the attraction force between particles and shear yield stress of ER fluid increase too. It is clear from Fig.10 that the electric field strength is one of the most important factors in ER fluid polishing.
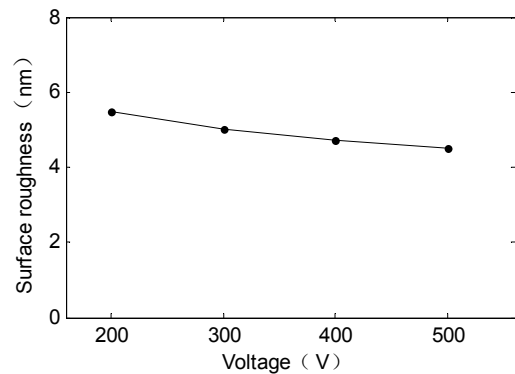

Fig.10.   Relationship between surface roughness and voltage

It is illustrated in Fig.11 that the surface roughness decreases with the increase of the rotational velocity of micro tool. Moreover, the tendency to decline of the surface roughness slows down when the rotational velocity of micro tool up to 2000rpm. Consequently, the surface roughness does not mainly depend on the rotational velocity of micro-tool.
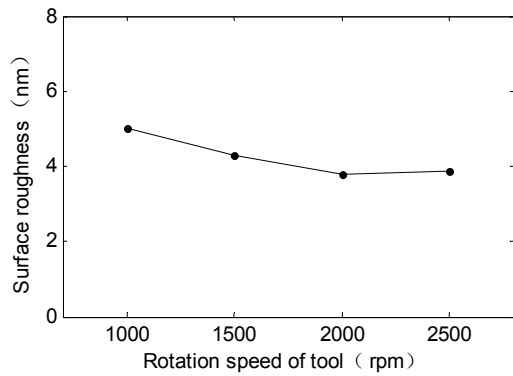
Fig.11.   Relationship between surface roughness and rotation of tool

The variation of the surface roughness according to the density of abrasives in ER fluid on is described in Fig.12. The effect of the density of abrasives in ER fluid on the surface roughness is complex that there is optimal value is 5%.
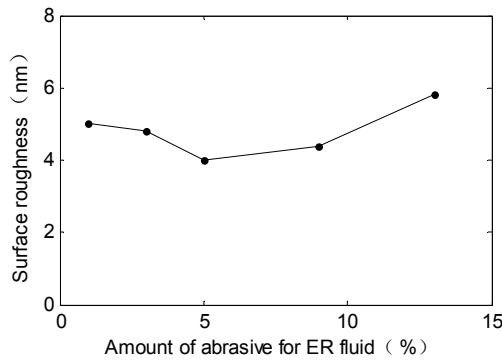

Fig.12.   Relationship between surface roughness and amount of abrasives for ER fluid

Fig.13 shows the topological images of tungsten carbide surface from WYKO N100. Fig.13a) and Fig.13 b) show the surface roughness of workpiece before polishing and after polishing, respectively. It can be seen from Fig.13a) that the initial surface roughness is approximately 5.39 nm, and the polished surface roughness is 1.45 nm. It indicates that the surface roughness of workpiece is greatly improved after polishing process.
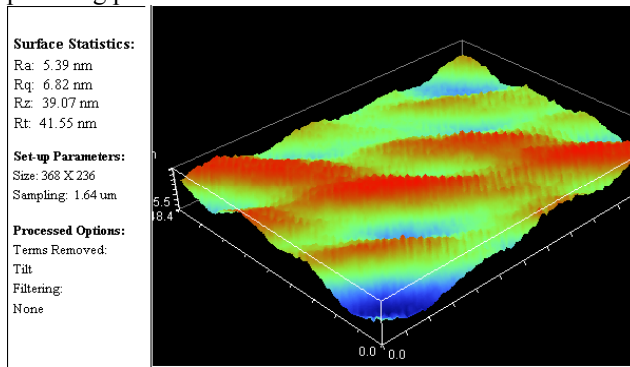
a) Initial surface roughness
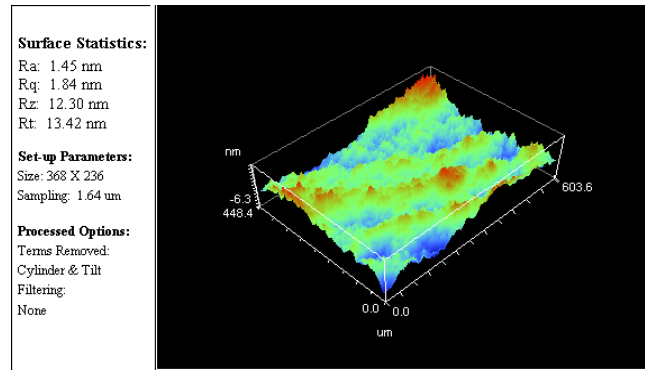
b) Polished surface roughness

Fig.13.   The surface roughness of workpiece.

C. Material Removal Experiment

The experiments of ER fluid-assisted polishing of tungsten carbide are conducted. And the abrasive particles mixed into the ER fluid are Al_2O_3 and diamond and the amount of abrasive particles for ER fluid is 5wt%. The polishing time is 5 min and the applied voltage is 5V. The coefficient of k is 0.2 which is calculated by Reynolds equation and the friction coefficient of μ is 0.5547 measured by the yield stress testing device. The microstructure and profile of the polishing area is measured by WYKO NT 1100 optical profiling system.

In ER fluid-assisted polishing process, the materials of workpiece surface obtained great amount of removal due to the smaller gap of electrodes. The microstructure of workpiece surface machined at various gaps with the voltage of 5V after 5min are shown in Fig.14. Fig.14 a) depicts the ring type distribution of groove by abrasive particles on the workpiece surface in ERP with the gap of 30μm. The microstructure of the machined surface becomes increasingly blurred with the increase of gap as shown in Fig.14 b) and Fig.14 c). As a result, the gap of electrodes is key parameter of ER-assisted polishing of conductive materials.

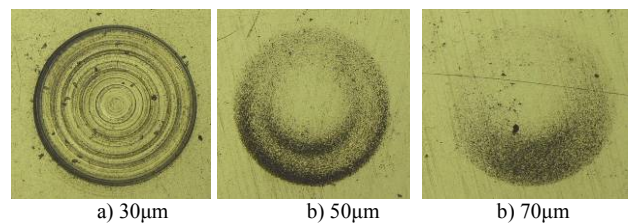a) 30μm   b) 50μm   b) 70μm

Fig.14.   The microstructure of workpiece surface machined.

Fig.15 shows the variation of depth of material removal with the gap. It can be seen that the depth of material removal decreases with the increase of the gap. As the gap of electrodes is gradually increased, the electric field intensity will sharply decrease from Eq.(1). Hence, the attraction force between particles in ER-fluid is reduced, which lead to the decrease of depth of material removal.
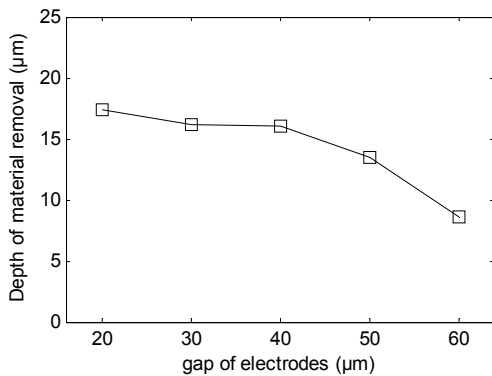
Fig.15.   Depth of material removed changing with the gap of electrodes.

When the electric field is imposed, the abrasive particles are concentrated in the vicinity of the tool tip to form flexible polishing pad and produce the removal region on the workpiece surface with the rotation of the tool electrode. The size of polishing area is important to plan the polishing path. Fig.16 illustrates that the diameter of the polishing area changing with different rotation speed of tool. As the abrasive particle suspending in ER fluid will not effective participate in polishing action when the interface force is stronger than the centrifugal force on abrasive particle, the size of the polishing area decreases with increasing of the tool rotation speed owing to the abrasive particles break away from polishing area under the centrifugal force. The diameter of the polishing area of ER polishing fluid mixed with Al_2O_3 is larger than it mixed with diamond at different tool rational speed due to the interface force between ER particle and Al_2O_3 particle is much stronger than the interface force between ER particle and diamond particle.
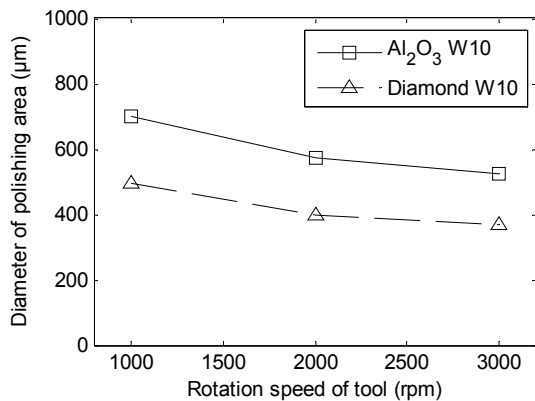

Fig.16.   Diameter of the polishing area with different rotation speed of tool.

The microstructure of workpiece surface after polishing by abrasive particles when the gap between tool and workpiece is 30μm and the tool rotational speed is 1000 rpm, as shown in Fig.17. The machined region is similar to a shape of letter W. It indicates that the removal volume first increases and then decreases far away from the centre of removal region. The radius of the removal region is 300μm, the lowest removal volume is

in the center of polishing area under the tip of the micro-tool electrode.

According to Eq.(13), the material removal rate in the removal region is calculated and the Preston coefficient of C_p is 1.02e-7 obtained by comparing the theoretical and experimental results, as shown in Fig.18. It can be seen that the trend of the material removal rate first increases and then decreases in accordance with removal volume. Although both the electric field strength are strongest under the tip of the micro-tool electrode, the removal volume is the lowest there as result of the lower shear velocity of ER polishing fluid on material surface. The electric field strength decreases far away from the centre of removal region, but the material removal rate increases owing to the increase of the shear velocity of ER polishing fluid. Then the electric field strength sharply, which is almost zero on the edge of the removal region. Hence, the material removal rate will gradually decrease.
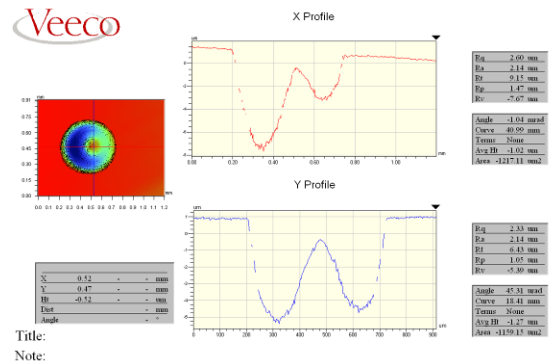

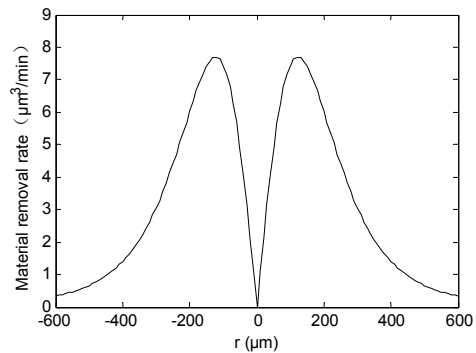Fig.17.   Profile of the polishing area.

Fig.18.   The material removal rat.

V. CONCLUSIONS

In this paper, we have investigated a new ER fluid-assisted polishing method on tungsten carbide. The results obtained are summarized as follows:

1) ER fluid mixed fine abrasive particles may appear ER effect, which yield stress increases with application external electric field. Thus the surface roughness is improved after ER fluid-assisted polishing. Analysis on the electric field using ANSYS when conductive material is used as electrodes, and found that the electric power lines gathered at the tip of the tool electrode and the electric field strength is strongest here.

2) A series of experimental results indicate that the surface roughness decreases with the increase of the polishing time, rotational speed of micro-tool and voltage. The effect of the density of abrasives in ER fluid on the surface roughness is complex that there is an optimal value. Obviously, the surface roughness is obviously improved after ER fluid-assisted polishing.

3) A theoretical model for material removal is derived on the basis of *Preston*'s equation. The effect of the electric field strength and shear velocity of ER polishing fluid on material removal rate is revealed. According to the simulations and experiments, the material removal rate first increases and then decreases far away from the centre of the removal region.

REFERENCES

[1] S. Jha, V.K. Jain,"Design and development of the magnetorheological abrasive flow finishing (MRAFF) progress," *International Journal of Machine Tools & Manufacture*, vol. 44, 2004, pp. 1019–1029.

[2] K. Shimada, Y. Wu, Y.C. Wong, "Effect of magnetic cluster and magnetic field on polishing using magnetic compound fluid (MFC)," *Journal of Magnetism and Magnetic Materials*, vol.262 ,2003, pp. 242–247.

[3] S. Jha, V. K. Jain, "Modeling and simulation of surface roughness in magnetorheological abrasive flow finishing (MRAFF) process, "*Wear* , vol.261,2006, pp.856-866.

[4] M. Das, V. K. Jain, P. S. Ghoshdastidar, "Fluid flow analysis of magnetorheological abrasive flow finishing (MRAFF) process," *International Journal of Machine Tools and Manufacture*, vol. 48, 2008, pp.415- 426.

[5] T. Kuriyagawa, K. Syoji, "Development of electrorheological fluid assisted machining for 3-dimensional small parts ," *Journal of Japan Society for Precision Engineering* , vol.65 (1), 1999,pp. 145-149.

[6] Y. Akagami, N. Umehara, "Development of electrically controlled polishing with dispersion type ER fluid under AC electric field," *Wear* , vol. 260,2006,pp. 345-350.

[7] T. Kuriyagawa, M. Saeki, K. Syoji, "Electrorheological fluid-assisted ultraprecision polishing for small three-dimensional parts," Journal of the International Societies for Precision Engineering and Nanotechnology, vol. 26, 2002, pp. 370–380.

[8] W.B. Kim,S. J. Park,B.K.Won,S.J. Lee, "Surface finishing technique for small parts using dielectrophoretic effects of abrasive particle," Journal of Materials Processing Technology, vol. 147, 2004, pp. 377-384.

[9] L. Zhang, T. Kuriyagawa, T. Kaku, J. Zhao, "Investigation into electrorheological fluid-assisted polishing," International Journal of Machine Tools & Manufacture, vol. 45 ,2005, pp. 1461– 1467.

[10] L. Zhang, X. S. He, H. R. Yang, Y. Zhang, "An integrated tool for five-axis electrorheological fluid-assisted polishing," *International Journal of Machine Tools and Manufacture* , vol. 50 ,2010,pp. 737-740.

[11] J.B. Lu, Q.S. Yan, H. Tian, L.Y. Kong, "Polishing properties of tiny grinding wheel based on Fe_3O_4 electrorheological fluid," *Journal of Materials Processing Technology*, vol. 209, 2009, pp. 4954–4957.

[12] Young Gun Ko, Ung Su Choi, Yong Jin Chun, "Influence of particle size on behavior of amine-group-immobilized polyacrylonitrile disperised suspension under electic field," *Journal of Colloid and Interface Science*, vol. 335,2009,pp.183-185.

[13] C. G. Wei, *Electrorheological Technology*. Beijing: Beijing Institute of Technology Press, 2000.

[14] T. Kaku, T. Kuriyagawa, N. Yoshihara, *Electrorheological fluid-assisted polishing of WC micro aspherical glass molding dies*,7th International Symposium on Advances in Abrasive Technology, Bursa, TURKEY, 2004, pp. 17-19.

[15] Sha Tong, S.M. Gracewski, P.D, "Funkenbusch, Measurement of the Preston coefficient of resin and bronze bond tools for deterministic microgrinding of glass," Precision Engineering, Vol. 30,2006, pp. 115–122.

[16] Rajendra K. Jain, Vijay K. Jain, "P.M. Dixit. Modeling of material removal and surface roughness in abrasive flow machining process," *International Journal of Machine Tools & Manufacture*, 1999,vol. 39, pp. 1903–1923.

Yunwei Zhao was born in 1978 in Jilin, China. He received the M.S.degree in Mechanical Manufacture in 2007 from Jilin University. He has been working at the Beihua University as a lecturer. His research interests include intelligent precision manufacturing, electrorheological (ER), and micro- and nanofluidic control, microsphere fabrication.

Dexu Geng was born in 1964 in Jilin, China. He received the M.S. degree and Ph.D. degree in Mechanical E Manufacture in1994 and 2010 from Tianjin University and Jilin University, respectively. He has been working at the Beihua University as a professor. His research interests include intelligent precision manufacturing, dynamics of mechanical system.

Xiaomin Liu was born in 1980 in Jilin, China. She received the M.S.degree in Mechanical Manufacture in 2007 from Jilin University. She has been working at the Beihua University as a lecturer. Her research interests include intelligent precision manufacturing and CAD/CAM.