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Investigation of the polishing mechanism of magnetorheological elastic polishing composites

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Abstract: Computer-controlled ultra-precision polishing technology is widely used for high-quality surface processing. However, its polishing tool has some shortcomings, such as limited adaptability to the complex surface and easy to cause surface damage. Therefore, a new smart material-based abrasive tool named magnetorheological elastic polishing composites (MREPCs) and its flexible polishing method are proposed. This study first prepared MREPCs and developed a polishing tool for MREPCs. Then, the material properties of MREPCs were obtained by theoretical and experimental analysis, and the tool influence function (TIF) of the hemispherical MREPCs was established according to the Hertz contact theory, the variable rheological theory and the Preston equation. Finally, the TIF and the polishing performance of MREPCs were verified by polishing experiments. The results show that the theoretical and the experimentally measured TIF models have a high coincidence, and the developed MREPCs can remove surface material with high precision. The above preliminary study indicates that MREPCs are promising for ultra-precision machining of small-sized parts with complex profiles.

Keywords: Magnetorheological elastomers; Magnetic field; Tool influence function; Flexible polishing

1. Introduction

Ultra-precision polishing technology and processes have always been hotspots of research. In order to quickly produce high-quality surfaces, many ultra-precision polishing methods have emerged in recent years, such as stress disc polishing [1], airbag polishing [2], magnetorheological polishing [3], electrorheological polishing [4], shear thickening polishing [5], and chemical mechanical polishing [6], etc. However, there are some problems in stress disc polishing, such as expensive equipment, complex processing technology, movement interference, and wear of abrasive tools. In the process of magnetorheological polishing, electrorheological polishing and shear thickening polishing, the polishing fluid is easy to settle, the material removal rate is low, and the removal function is difficult to control. Chemical mechanical polishing is difficult to process complex surface, and its polishing fluid will pollute the environment.

In order to solve the above problems to a certain extent, MREPCs [7, 8] with magneto-rheological elasticity as the binder and diamond powder as the abrasive was proposed in this paper. MREPCs have the following characteristics: 1) Flexible contact with the surface of the workpiece, less damage to the surface of the rigid polishing tool, and using magnetron variable stiffness characteristics of the magnetorheological elastomer can improve the polishing tool's adaptability to materials and shapes; 2) Adopt consolidated abrasive particle polishing method, the polishing removal function is more stable, and the polishing process is easier to control; 3) MREPCs carbonyl iron powder can isolate the abrasive particles, reduce agglomeration, and also help to dissipate heat. Combining MREPCs with computer-controlled polishing technology can achieve high-efficiency, high-precision and high-quality polishing of workpieces.

The material removal mechanism and characteristics of polishing tools are extremely important for obtaining high quality surfaces and automating the polishing process. Nowadays, there are many studies on

the establishment of the material removal function model of abrasive particle fixation or semi-fixation polishing tools, almost all based on the Preston's equation. For example, in the polishing process, some scholars used the finite element method to solve the pressure distribution in the polishing contact area [9–11], and some scholars used Hertz contact theory to analyze the material removal function in the polishing process and obtained the pressure distribution in the polishing contact area [12, 13]. In addition, PAN et al. took into account the influence of the friction coefficient between the polishing tool and the workpiece surface, and modified the existing material removal model [14]. CAO et al. established a multi-scale theoretical model of airbag polishing removal characteristics from the perspective of single abrasive particle wear, and studied the formation process of optical surface [15, 16]. MIRSA proposed a biaxial wheel magnetorheological polishing device and solved the material removal modulus according to the magnetic dipole moment theory of magnetic particles [17]. According to the previous research status, this study will also establish a material removal function model of MREPCs polishing tools based on the Preston's equation.

This article focuses on the material removal characteristics of the proposed MREPCs. First, MREPCs were prepared using magnetic field-assisted compression molding. Then, a polishing tool with an excitation structure was designed, and the magnetic field simulation analysis and optimization were performed on it. Finally, a material removal function model of MREPCs during fixed-point polishing was established based on the Preston's equation, Hertz contact theory, and magneto-rheological elastic material magnetogenic stiffness mechanism. Meanwhile, the model was verified by simulation and experiment, and the influencing factors of material removal were analyzed.

2. Experimental methods

2.1 Materials

The diamond powder (the average size is W5) was produced by Taizhou Haojing Abrasives Company of China. The carbonyl iron powder with the size of W2.5 was brought from BASF Company of German. 704B silicone rubber was support by Osborne Company of the United States. The dimethyl silicone oil was purchased from Shandong Yousuo Chemical Technology Company of China.

2.2 MREPCs preparation

The preparation process of MREPCs includes mixing, pouring, excitation, compression molding, deep curing, and stripping [8]. Before the preparation of MREPCs, a set of forming molds for the preparation of hemispherical anisotropic MREPCs was designed. The overall structure is shown in Fig. 1(a), which is a typical three-stage structure, including upper mold, middle frame, and lower mold. All of them are stainless steel without magnetic permeability. The excitation method uses two permanent magnets (rubidium iron boron, brand N35) placed up and down to add magnetization.

When using the mold to prepare MREPCs, the raw material diamond powder, carbonyl iron powder, 704 silicone rubber, and dimethyl silicone oil are weighed in order according to the mass ratio of 10wt%, 40wt%, 45wt%, and 5wt%. First, mix them evenly until they appear viscoplastic, and then pour the mixture into a mold, put it in a 300mT magnetic field, and heat it to 30°C, meanwhile, press it for 60 minutes under 10N pressure and cure at room temperature for three days, then the mold was demolded, and solid MREPCs with a diameter of 10 mm were finally obtained.

Figs. 1(b), (c), and (d) show the MREPCs physical objects and local microstructures after demoulding. From the surface microstructure of MREPCs, it can be seen that in the direction perpendicular to the axis, diamond and iron powder are randomly distributed in the matrix with good dispersion; in the direction parallel to the axis, iron powder distributed in chains [18, 19].

Fig. 1. MREPCs: (a) MREPCs forming mold; (b) Physical map; (c) The end face microstructure of an MREPCs; (d) Axial microstructure of MREPCs.

The X-ray diffraction pattern of MREPCs and its composition is shown in Fig. 2. The pure carbonyl iron powder exists obvious characteristic peaks at 44.67° and 65.02° . Diamond powder has obvious characteristic peaks at 43.92° and 75.30° . The X-ray diffraction pattern of silicone rubber shows many small peaks, which are also determined by its composition. These characteristic peak at 23.02° , 29.41° , 35.96° , 39.40° , 43.15° , 47.12° , 48.51° , 57.40° and 63.06° are very obvious, and we can find that the components of the characteristic peak is mainly CaCO_3 by comparing with the standard card. The characteristic peaks of the X-ray diffraction pattern of MREPCs are marked by the numbers J (Diamond), T (Carbonyl iron) and G (Silicone rubber) in Fig. 2. Through comparison, we found that the characteristic peaks of MREPCs correspond to the characteristic peaks of carbonyl iron powder, diamond and silicone rubber, which further shows that MREPCs retain the properties of each component during the synthesis

process.

Fig. 2. X-ray diffraction pattern of MREPCs and its components.

2.3 MREPCs polishing tool design

According to the requirements of the computer-controlled small grinding head polishing process, an MREPCs polishing tool with an excitation structure was designed. The physical and overall structure is shown in Fig. 3. The overall size of the polishing tool is $\Phi 22\text{mm}$ in diameter and 82mm in total length. It consists of MREPCs, chucks, sleeves, clamping rods, cocks, magnets, and M3 screws. The chucks and MREPCs here directly use the demolding MREPCs described in Fig. 1. In order to facilitate the polishing of precision parts, chip removal and heat dissipation, the bottom working surface of the prepared MREPCs was further trimmed into a spherical surface with a spherical diameter $\Phi 14.5\text{mm}$; the chuck and the sleeve was connected by two symmetrically distributed M3 set screws; the excitation part was a permanent magnet with a size of $\Phi 10 \times 20\text{ mm}$. The magnet was bonded to the lower surface of the cock. The cock and the sleeve's inner wall were connected by threads, which could be raised and lowered by the thread to realize

the continuous adjustment of the magnetic field strength, thereby control the stiffness change of MREPCs in the magnetic field; the clamping rod and the sleeve were also connected by two symmetrically distributed M3 set screws, and the upper end could be fixed by the motor spindle.

Fig. 3. Schematic diagram of MREPCs polishing tool.

To clarify whether the magnetic field generated by the MREPCs polishing tool meets the polishing process requirements, Finite Element Magnetic Field Simulation Software was used to conduct magnetic field simulation analysis. As shown in Fig. 4(a), the distribution of magnetic field lines through the working surface (lower end surface) of MREPCs is relatively sparse, and few magnetic field lines perpendicular to the surface. Most of the magnetic field lines diverge to both sides. As shown in Fig. 4(b), the cloud image near the surface is light in color and fluctuates greatly in color difference, the magnetic field strength is weak and not a uniform magnetic field. The above phenomena are not conducive to magnetron flexible polishing. Thus, the excitation structure needs to be optimized.

Fig. 4. Simulation results of internal magnetic field of polishing tool (a) Distribution of magnetic field lines (b) Distribution of magnetic field strength.

In order to make the polishing in a uniform magnetic field environment, this paper added a permanent magnet with a size of $\Phi 20 \times 20$ mm below the MREPCs, which is coaxial with the upper magnet and has opposite magnetic poles. Fig. 5 shows the results of magnetic field simulation analysis of the improved polishing tool. In Fig. 5(a), it can be seen that the magnetic field lines passing through the working surface of the MREPCs are concentrated and perpendicular to the surface. In Fig. 5(b), the cloud image near the working surface of the MREPCs and between the opposite magnetic poles are darker in color and the color difference is not obvious, indicating that the magnetic field intensity is strong, the vertical excitation effect is good, and the magnetic field intensity exceeds 500mT, which meets the polishing process requirements.

(a)

(b)

Fig. 5. Magnetic field simulation results after polishing tool optimization (a) Distribution of magnetic field lines (b) Distribution of magnetic field strength.

3. Material removal function model establishment

3.1 Theoretical background

Preston's equation can be written as:

$$m \frac{dz}{dt} = kvp \quad (1)$$

where dz/dt is the amount of material removed per unit time, k is the Preston coefficient which is related to multiple factors such as polishing medium and workpiece characteristics, v and p are the relative polishing speed and pressure at the contact point. When performing the fixed-point polishing process, the amount of material removal $R(x, y)$ at a certain point $Q(x, y, z)$ of the workpiece per unit time can be calculated by measuring the pressure, relative speed and the dwelling time:

$$R(x, y) = \frac{1}{T} \int_0^T kv(x, y) p(x, y) dt \quad (2)$$

3.2 Velocity distribution solution

When the polishing head is in vertical contact with the workpiece, there will be a speed zero point at the intersection of the axis of the polishing head and the surface of the workpiece, which is not conducive to the removal of the material. Therefore, when the polishing removal function was established, the workpiece was tilted at a fixed angle and the polishing head rotated at a fixed point. Fig. 6 is a schematic diagram of fixed-point polishing of MREPCs. The center of the contact area on the workpiece surface was used as the origin to establish a three-dimensional rectangular coordinate system. O_1 is the center of the

MREPCs with a radius r . The axis of the polishing head's main axis intersects the Y axis at Q and the angle with the Z axis is θ . The angular velocity of the spindle movement of the polishing head is expressed by a vector as:

$$\vec{\omega} = \omega(0, -\sin \theta, \cos \theta) \quad (3)$$

The polishing contact area is a circular surface with radius a . Point $P(x, y, z)$ is any point in the polishing contact area, then point $O_1(0, 0, h)$ to point P is represented by a vector $\vec{l}$ as:

$$\vec{l} = \vec{O_1P} = (x, y, -h) \quad (4)$$

$$h = \sqrt{r^2 - a^2} \quad (5)$$

According to the definition of linear velocity, the linear velocity of the polishing head in the polishing contact area can be solved as a vector cross product as:

$$\begin{aligned} \vec{v} &= \vec{\omega} \times \vec{l} = \omega(0, -\sin \theta, \cos \theta) \times (x, y, -h) \\ &= \omega((h \sin \theta - y \cos \theta), x \cos \theta, x \sin \theta) \end{aligned} \quad (6)$$

Since the polishing contact area is in the X-Y plane of the three-dimensional coordinate system, the velocity in the Z direction is discarded, and the relative linear velocity at any point in the polishing contact area is:

$$v = \omega \sqrt{(h \sin \theta - y \cos \theta)^2 + (x \cos \theta)^2} \quad (7)$$

Fig. 6. Schematic diagram of MREPCs fixed-point polishing movement.

3.3 Solution of contact pressure distribution

(1) Analysis of force on polished contact area

In the polishing process of the polishing tool, the force of the hemispherical MREPCs on the workpiece is more complicated, including the normal pressure P of the polishing body on the surface of the workpiece and the shear stress τ along the speed direction. When an external magnetic field exists around the MREPCs, the polishing body will also generate magneto-compressive stress σ_m and magnetic shear stress τ_m on the workpiece surface, as shown in Fig. 7.

Due to the Preston's equation is solved only by polishing area contact pressure, here we just need to obtain the normal load F of the polished body to the workpiece, which includes the load F_N corresponding to normal pressure P and the magneto-compressive force F_m corresponding to the magneto-compressive stress σ_m :

$$F = F_N + F_m \quad (8)$$

Fig. 7. Stress analysis of the workpiece in the polishing contact area.

(2) Solution of magneto-compressive force F_m

The F_m of magnetorheological elastic materials is generally caused by the material's own magneto-compressive elastic modulus, which can be derived from the magnetic dipole model. According to the magnetic dipole model [20], a single soft magnetic particle after magnetization can be regarded as a magnetic dipole, whose direction is the same as the direction of the applied magnetic field, and the magnetic dipole moment is:

$$m = 3\mu_0\mu_1 \frac{\mu_p - \mu_1}{\mu_p + 2\mu_1} VH \quad (9)$$

where μ_0 is the vacuum permeability; μ_1 is the relative permeability of the base material; μ_p is the relative permeability of the soft magnetic particles; V is the volume of the single soft magnetic particles; H is the applied magnetic field strength. The interaction energy of two magnetic dipoles (magnetized soft magnetic particles) [21] is:

$$E_{12} = \frac{1}{4\pi\mu_0\mu_1} \left[\frac{m_1 g m_2 - 3(m_1 g_d)(m_2 g_d)}{|d|^3} \right] \quad (10)$$

where m_1, m_2 are the magnetic dipole moments of the two particles; e_d is the direction vector; d is the

center distance vector of the two particles. After simplifying this formula (10), E_{12} can be obtained as follows:

$$E_{12} = 4\pi\mu_0\mu_1 \left(\frac{\mu_p - \mu_1}{\mu_p + 2\mu_1} \right)^2 a_1^3 a_2^3 \frac{1 - 3\cos^2 \theta}{d^3} H^2 \quad (11)$$

where a_1 and a_2 are the radius of the two particles; d is the center distance between the particles; θ the angle between the particle centerline and the direction of the applied magnetic field. Derivation of Eq. (11) for d and θ , respectively, we can get the magnetic field force of particle interaction as:

$$F_{12} = 12\pi\mu_0\mu_1 \left(\frac{\mu_p - \mu_1}{\mu_p + 2\mu_1} \right)^2 \frac{a_1^3 a_2^3}{d^4} H^2 \left[(1 - 3\cos^2 \theta) \mathbf{e}_d + \sin 2\theta \mathbf{e}_\theta \right] \quad (12)$$

where $\mathbf{e}_d$ is the direction vector in the direction of the particle centerline, and $\mathbf{e}_\theta$ is the direction vector perpendicular to the direction of the particle centerline. Treat the radius of soft magnetic particles as equal, all of which are a , because μ_p is much larger than μ_1 ; thus, equation (12) can be simplified as:

$$F_{12} = 12\pi\mu_0\mu_1 \frac{a^6}{d^4} H^2 \left[(1 - 3\cos^2 \theta) \mathbf{e}_d + \sin 2\theta \mathbf{e}_\theta \right] \quad (13)$$

As shown in Fig. 7(a), there is a chain structure in anisotropic MREPCs. When the MREPCs are in a compressed state, the particle chain will bend with the deformation of the matrix, as shown in Fig. 8(b). Two adjacent particles are analyzed, and only the magnetic effect is considered, as shown in Fig. 8(c). The expression of each component in the figure can be obtained from formula (13). Since the two particles are next to each other, the center distance d of the two particles is approximately $2a$, it can be seen that the forces F_{12t} and F_{21t} will form a magnetic moment, which makes the particle chain tend to rotate in the direction of the angle θ decreasing, the size is:

$$M_m = \frac{3}{2} \pi\mu_0\mu_1 a^3 H^2 \sin 2\theta \quad (14)$$

In the entire particle chain, every two adjacent particles will produce such a moment. The moment on

the particle chain can be regarded as a continuous distribution. The torque distribution density can be obtained as:

$$M_{m\rho} = \frac{3}{4} \pi \mu_0 \mu_1 a^2 H^2 \sin 2\theta \quad (15)$$

From the mobility of the torque, the magnitude of the balance torque M_{ms} in Fig. 8(d) is:

$$M_{ms} = R \int_0^\varphi M_{m\rho} d\theta = \frac{3}{4} \pi \mu_0 \mu_1 a^2 H^2 R (1 - \cos^2 \varphi) \quad (16)$$

The moment M_{ms} has a tendency to straighten the particle chain. When the compressive strain is constant, the magneto-compressive force F_m needs to be balanced with it, and its size is:

$$F_m = \frac{3}{4} \pi \mu_0 \mu_1 a^2 H^2 R (1 + \cos \varphi) \quad (17)$$

Fig. 8. Magnetic dipole model of anisotropic MREPCs.

It can be known from Eq. (17) that under the condition that the compressive strain of MREPCs is constant, its magnetic compressive force F_m is proportional to the square of the applied magnetic field strength H . The magnetostrictive process of magnetorheological materials is not yet clear, and the above solution process is based on a variety of assumptions; thus, the existing theoretical calculations can only be used as a basis for qualitative analysis. For the accuracy of modeling, the compression test of MREPCs under different magnetic fields is actually needed to determine the mapping relationship $F_m(H)$ between the magnetic compressive force F_m and the magnetic field strength H under a certain compressive strain.

In this study, the magneto-compressive mechanical properties of MREPCs were tested on a universal

electronic testing machine. Because the commercial testing machine is not easy to excite [22], a compression device with an exciting structure was designed. Fig. 9(a) shows the uniaxial compression test system. Fig. 9(b) shows the overall structure of the compression device, which consists of a support frame, a pressure member, a support plate, magnets at the upper and lower ends, and screw nut fasteners. By adjusting the position of the support plate and changing the distance between the two magnets, the magnetic field strength can be changed, and the magnetic attraction between the two strong magnets can be transferred to the support table without acting on the MREPCs. The size of the test sample is $\Phi 10 \times 6 \text{ mm}$, and the curve of magnetocompressive force with magnetic field strength under different compressive strains can be obtained. As shown in Fig. 10(a), the corresponding magneto-induced compression force F_m can be determined by determining the compression strain and the applied magnetic field strength. At the same time, according to Hooke's law, the magneto-elastic modulus of the magneto-rheological elastic polishing body can be calculated in combination with the experiment, as shown in Fig. 10(b).

Fig. 9. Compression test equipment.

Fig. 10. Magneto-compression performance of MREPCs: a) Relationship between MREPCs magnetic force and magnetic field intensity; b) The relationship between MREPC Young's modulus and magnetic field intensity.

(3) Contact domain pressure distribution

When the elastic deformation of MREPCs and the workpiece is small, consider using Hertz contact theory to model the pressure distribution of the polishing contact area [23, 24]. Fig. 11 shows the three-dimensional and two-dimensional Hertz contact theoretical model. The relevant calculation formula for the pressure $p(x, y)$ can be obtained as follows:

$$\left\{ \begin{array}{l} p(x, y) = \begin{cases} \left(\frac{3F}{2\pi a^2} \right) \left(1 - \frac{x^2 + y^2}{a^2} \right)^{\frac{1}{2}}, & \sqrt{x^2 + y^2} \leq a \\ 0, & \sqrt{x^2 + y^2} > a \end{cases} \\ a = \left(\frac{3FR^*}{4E^*} \right)^{\frac{1}{3}} \end{array} \right. \quad (18)$$

In the above formula, F is the normal load of the polishing body on the workpiece, and the calculation method is shown in formula (8); a is the radius of the contact area between the MREPCs and workpiece; R^* is the equivalent radius, and the calculation method is shown in formula (19), because the radius of the planar workpiece can be regarded as infinity; thus, R^* is equal to the radius of the curved surface of the

elastic body r ; E^* is the equivalent elastic modulus, and the calculation method is shown in formula (20),

where E_1 and E_2 are the elastic modulus of the MREPCs and the workpiece, respectively; ν_1 , ν_2 are the

Poisson's ratio of the MREPCs and the workpiece, respectively; $p(x, y)$ is the stress at the Q point.

$$\frac{1}{R^*} = \frac{1}{r} + \frac{1}{R} \quad (19)$$

$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad (20)$$

Fig. 11. Hertz contact theory model.

From formulas (8), (18), (19), (20) and $F_{mi}(H)$, the calculation formula of the pressure distribution of the

polishing contact area is:

$$p(x, y) = \left[\frac{3(F_N + F_m^i(H))}{2\pi \left(\frac{3(F_N + F_m^i(H))r}{4} \cdot \frac{E_1 + E_2 - E_1 \cdot \nu_2^2 - E_2 \cdot \nu_1^2}{E_1 \cdot E_2} \right)^{\frac{2}{3}}} \right]^{\frac{1}{2}} \cdot \left[1 - \frac{x^2 + y^2}{\left(\frac{3(F_N + F_m^i(H))r}{4} \cdot \frac{E_1 + E_2 - E_1 \cdot \nu_2^2 - E_2 \cdot \nu_1^2}{E_1 \cdot E_2} \right)^{\frac{2}{3}}} \right]^{\frac{2}{3}} \quad (21)$$

3.4 Material removal modeling

The velocity and pressure distribution functions of the removal model have nothing to do with time,

so from Eq. (2), combined with the polishing contact area velocity distribution function (7) and pressure distribution function (21), the polishing contact point $Q(x, y)$ is obtained. The material removal amount expression is as follows:

$$R(x, y) = kv(x, y)p(x, y) \quad (22)$$

4. Simulation and experiment

4.1 Experiment

The polishing device required for the material removal characteristic verification experiment of the flexible polishing of the MREPCs is shown in Fig. 12, which mainly includes a numerical control slide table, a speed regulating motor, a spindle chuck, MREPCs and its polishing tool, excitation Fixtures, and dynamometers. The CNC sliding table can realize three-axis linkage, with a movement accuracy of $1\mu\text{m}$; the speed of the speed-adjustable motor can be adjusted from 0 to 2800rpm; the excitation fixture is a non-magnetic aluminum alloy structure with a flat upper surface for fixing the workpiece. The magnets are placed in the excitation fixture and polishing tool, respectively, which can provide a continuously adjustable magnetic field with a magnetic field strength exceeding 500mT; the fixed-point polishing experiment scheme and parameters are shown in Table 1. The experiment adopts single factor method to explore the influence of compression amount, spindle speed and magnetic field conditions on the material removal function of MREPCs.

Fig. 12. Fixed-point polishing experiment device.

Table 1 Experimental parameters of fixed-point polishing.

Describe objects	Size (mm)	(MPa)	ν	δ (mm)	ω (rpm)	θ (°)	H (mT)	t (s)
MREPCs	r : 7.25	E_I : 1.05	ν_1 : 0.47	--	--	--	--	--
Workpiece	15×15×1	E_2 : 1.3×10^5	ν_2 : 0.28	--	--	--	--	--
Work condition	--	--	--	0.1	1500	20	0, 500	120

4.2 Simulation and experimental results of fixed-point polishing

4.2.1 Material removal analysis

When the MREPCs on the polishing tool presses 0.1mm under zero magnetic field (that is, its compressive strain is 2%), the positive pressure F_N measured by the dynamometer is 1.65N; when a 500mT magnetic field is applied, from the data in Fig. 10, the corresponding F_m value is 0.167N.

The simulation results and experimental results of the polishing tool on the workpiece surface material removal under the presence or absence of magnetic field are shown in Fig. 13. As can be seen from these pictures, the simulated data and the experimental data are similar in the color distribution of the polished contact area, the deepest color deviates from the symmetry center of the contact area. It can be seen from

the two-dimensional curve data graph that the XX contour curve of the removal function is axisymmetric, the trend is to decrease first and then increase, the YY contour curve is asymmetric trend, and the extreme point deviates from the origin, which is caused by the asymmetric distribution of the velocity in the polished contact area. In addition, whether it is the X-X direction or the Y-Y direction graph, it can be seen that the amount of material removal under the magnetic field condition is greater than zero magnetic field.

In any case, under the same magnetic field conditions, the XX and YY directions of the simulation and experimental contour curves are very consistent, indicating that the established removal function model can reflect the magneto-rheological elastic polishing body polishing tool to a certain extent distribution of actual material removal.

Fig. 13. Simulation and experimental results of fixed-point polishing material removal.

4.2.2 Magnetic field analysis

Fig. 14(a) shows the process of micro-removal of materials by the MREPCs under zero magnetic field.

It can be seen that the abrasive particles in the MREPCs are wrapped with carbonyl iron powder distributed

in a chain. When the cutting edge of the prominent abrasive particle contacts the roughness peak of the workpiece surface, due to the elasticity of the polished body, carbonyl iron powder and abrasive particles will be deformed with the matrix, and "elastic concession" (the abrasive particles move under the block of the peak or even cross the obstacle) phenomenon will occur to the abrasive particles. Therefore, only a small part of the top of the roughness peak or no material is abrasive cut away. In Fig. 14(b), under the action of an external magnetic field, the carbonyl iron powder in the particle chain will produce an interaction force, which makes the polished body less likely to deform, and the particle chain will tightly clamp the abrasive particles when the abrasive particles are close to the rough peak, the iron powder chain will hinder the "elastic yield" phenomenon of the abrasive particles, resulting in larger cutting chips on the roughness peak. Therefore, the external magnetic field will increase the material removal rate.

Fig. 14. Schematic diagram of material removal: (a) Off magnetic field; (b) On magnetic field.

4.3 MREPCs plane polishing

To verify the actual polishing ability of the MREPCs, a plane polishing experiment was carried out. Under the conditions of zero magnetic field and 500mT magnetic field, the device shown in Fig. 12 was

used to polish the single-crystal silicon wafer after grinding pretreatment, the polishing tool was pressed into the depth of 0.1mm, the translation speed was 300mm/min, and the polishing time was 30 minutes, and other parameters are consistent with the data in the previous section. The polishing results are shown in Fig. 15 and Fig.16. Fig. 15 is a micrograph of the surface morphology of the single crystal silicon wafer before and after polishing. There are a large number of obvious wear scars on the silicon wafer before polishing. After zero magnetic field polishing, the wear scars are effectively reduced, and only shallower Traces and spots, and after 500mT magnetic field polishing, the wear marks on the surface of the silicon wafer completely disappeared, only a small amount of spots can be seen, and a better surface quality is obtained. Then compare the roughness profile curves of the workpiece surface before and after polishing as shown in Fig. 16, It can be seen that the number of peaks and troughs of the workpiece surface profile curve after grinding is relatively small, the amplitude of the fluctuation is large, the ripple period is long, and the roughness value is $R_a\ 0.192\mu\text{m}$. However, the workpiece surface profile curve after polishing under zero magnetic field shows the peaks and troughs are uneven, but the overall amplitude is reduced, and the roughness value is reduced to $0.041\mu\text{m}$. The peak and trough of the workpiece surface profile curve after polishing under 500mT magnetic field increase, but the amplitude is small, the fluctuation is relatively stable, and the roughness value decreases to $0.024\mu\text{m}$. Similar to the previous simulation analysis and the experimental analysis, the polishing performance of the magnetorheological elastomer has been improved correspondingly under the condition of the magnetic field.

Fig. 15. Surface morphology of single crystal silicon wafer: (a) Before polishing; (b) Zero magnetic field polishing; (c) 500mT magnetic field polishing.

Fig. 16. Workpiece surface profile curve.

The above phenomenon shows that as a new type of abrasive tool, the MREPCs can improve the surface quality of the workpiece, especially the flexible contact between the elastic body and the surface reduces the normal stress applied by the polishing tool to the surface [25], but it cannot be said that the stronger the magnetic field the better the surface quality. In fact, the better the polishing effect under the magnetic field is reflected in the polishing efficiency problem, that is, in a unit time, the external magnetic field polishing makes the surface roughness drop to a lower value first. The machining accuracy of the workpiece surface is related to various factors such as initial roughness, abrasive grain size, and magnetic

field strength. Often the magnetic field strength is too large but it will cause new scratches on the surface [26]; thus, under which conditions high polishing accuracy needs further in-depth the study.

5. Conclusions

In this study, a flexible polishing method based on MREPCs was proposed, and the performance of the MREPCs was analyzed through experiment and simulation. The conclusions are as follows:

(1) The experimental results show that the external magnetic field can change the stiffness of MREPCs, which is mainly manifested as the increase of young's modulus of MREPCs with the increase of magnetic field and the increase of magneto-compression force required under the same strain compression.

(2) The results of experiments and simulations show that the distribution of the material removal depth of the polished contact area is ellipsoidal, and that the maximum removal amount deviates from the center of the release area. Meanwhile, the external magnetic field can increase the amount of material removal of the workpiece by the polishing tool.

(3) The plane polishing experiment shows that the polishing of the MREPCs under the zero magnetic field can reduce the surface roughness of the workpiece to $0.041\mu\text{m}$, while the polishing under the 500mT magnetic field can reduce the surface roughness to $0.024\mu\text{m}$. The smooth surface can be obtained by polishing with MREPCs, and the external magnetic field can improve the polishing effect. Therefore, the flexible polishing method based on the MREPCs is a potential ultra-precision machining method.

Author contribution Zhiqiang Xu, Jun Wang, Qiuliang Wang and Heng Wu contributed to the preparation of materials, including material research, grinding tool design, and experimental simulation. Gaofeng Zhang and Shengqiang Jiang contributed to the injection molding process, including the concept of curing process and experimental test results.

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Declarations

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Availability of data and material All relevant data are available on reasonable request.

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Figures

Figure 1

MREPCs: (a) MREPCs forming mold; (b) Physical map; (c) The end face microstructure of an MREPCs; (d) Axial microstructure of MREPCs.

Figure 2

X-ray diffraction pattern of MREPCs and its components.

Figure 3

Schematic diagram of MREPCs polishing tool.

Figure 4

Simulation results of internal magnetic field of polishing tool (a) Distribution of magnetic field lines (b) Distribution of magnetic field strength.

Figure 5

Magnetic field simulation results after polishing tool optimization (a) Distribution of magnetic field lines (b) Distribution of magnetic field strength.

Figure 6

Schematic diagram of MREPCs fixed-point polishing movement.

Figure 7

Stress analysis of the workpiece in the polishing contact area.

Figure 8

Magnetic dipole model of anisotropic MREPCs.

(a) Uniaxial compression test system

(b) Compression device structure

Figure 9

Compression test equipment.

(a)

(b)

Figure 10

Magneto-compression performance of MREPCs: a) Relationship between MREPCs magnetic force and magnetic field intensity; b) The relationship between MREPC Young's modulus and magnetic field intensity.

Figure 11

Hertz contact theory model.

Figure 12

Fixed-point polishing experiment device.

Figure 13

Simulation and experimental results of fixed-point polishing material removal.

Figure 14

Schematic diagram of material removal (a) Off magnetic field; (b) On magnetic field.

Figure 15

Surface morphology of single crystal silicon wafer: (a) Before polishing; (b) Zero magnetic field polishing; (c) 500mT magnetic field polishing.

Figure 16

Workpiece surface profile curve.