**Investigation of the polishing mechanism of magnetorheological elastic polishing composites**

Zhiqiang Xu 1,2 · Jun Wang 1 · Qiuliang Wang 1 · Heng Wu 1 · Gaofeng Zhang 1 · Shengqiang Jiang 1

Received: 9 March 2021 / Accepted: 20 August 2021 / Published online: 5 September 2021
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

**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 and more surface damage to the complex surface. Therefore, a new smart material-based abrasive tool named magnetorheological elastic polishing composites (MREPCs) and its flexible polishing method is 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 MRPECs 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. The grinding process often results in grinding hardening, which leads to residual stresses. Sun et al. established a new model for predicting residual stress in grinding workpieces, which optimized the residual stress in manufacturing processes [7].

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 hard 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, MREPCs [8–10] with magnetorheological 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) 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.
In addition, the material removal mechanism and characteristics of polishing tools are also 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 of them 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 [11–13], 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 [14, 15]. 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 [16]. 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 [17, 18]. MIRSA proposed a biaxial wheel magnetorheological polishing device and solved the material removal modulus according to the magnetic dipole moment theory of magnetic particles [19]. 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 magnetorheological 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 5μm) was produced by Taizhou Haojing Abrasives Company of China. The carbonyl iron powder with the size of 2.5μm was brought from the BASF Company of German. 704B silicone rubber was support by the Osborne Company of the USA. The dimethyl silicone oil was purchased from the 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 [9]. 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. 1a, 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 were weighed in order according to the mass ratio of 10wt%, 40wt%, 45wt%, and 5wt%. First, mixed them evenly until they appear viscoplastic, and then poured the mixture into a mold, put it in a 300mT magnetic field, and heat it to 30°C; meanwhile, pressed it for 60 min under 10N pressure and cured at room temperature for 3 days, then the mold was demolded, and solid MREPCs with a diameter of 10 mm was finally obtained.

Fig. 1b, c, and d show the MREPCs physical objects and local microstructures after demolding. 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 is distributed in chains [20, 21].

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 CaCO3 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.
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

Fig. 1. MREPCs: a MREPCs forming mold; b physical map; c the end face microstructure of an MREPCs; and d axial microstructure of MREPCs.

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

Fig. 3. Schematic diagram of MREPCs polishing tool.
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.

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. 4a, the distribution of magnetic field lines through the working surface (lower end surface) of MREPCs is relatively sparse, and few magnetic field lines are perpendicular to the surface. Most of the magnetic field lines diverge to both sides. As shown in Fig. 4b, 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.

In order to make the polishing in a uniform magnetic field environment, this paper added a permanent magnet with a size of Φ20×20 mm below the MREPCs, which was coaxial with the upper magnet and had opposite magnetic poles. Fig. 5 shows the results of magnetic field simulation analysis of the improved polishing tool. In Fig. 5a, 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. 5b, 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.

3 Material removal function model establishment

3.1 Theoretical background

Preston’s equation [22] can be written as:

\[ m \frac{dz}{dt} = kvp \]  

where \( \frac{dz}{dt} \) 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:

\[ R(x, y) = \frac{1}{T} \int_{T_0}^{T} kv(x, y)p(x, y)dt \]

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 is established, the workpiece is 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 is used as the origin to establish a three-

Fig. 4. Simulation results of internal magnetic field of polishing tool. a Distribution of magnetic field lines. b Distribution of magnetic field strength.
The polishing contact area is a circular surface with radius $a$. Point $P(x, y, z)$ is any point in the polishing contact area, and then point $O_1(0, 0, h)$ to point $P$ is represented by a vector $\vec{l}$ as:

$$\vec{l} = \vec{O_1P} = (x, y, -h)$$  \hspace{1cm} (4)

$$h = \sqrt{r^2 - a^2}$$  \hspace{1cm} (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:

$$\vec{v} = \vec{\omega} \times \vec{l} = \omega(0, -\sin \theta, \cos \theta) \times (x, y, -h)$$

$$= \omega((h\sin \theta - y\cos \theta), x\cos \theta, x\sin \theta)$$  \hspace{1cm} (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:

$$v = \omega \sqrt{(h\sin \theta - y\cos \theta)^2 + (x\cos \theta)^2}$$  \hspace{1cm} (7)

### 3.3 Solution of contact pressure distribution

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 $\tau$ along the speed direction. When an external magnetic field exists around the MREPCs, the polishing body will also generate magneto-compressive stress $\sigma_m$ and magnetic shear stress $\tau_m$ on the workpiece surface, as shown in Fig. 7.

Due to the Preston’s equation that is solved only by polishing area contact pressure, here we only 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 $\sigma_m$:...
\[ F = F_N + F_m \]

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 [23], 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:

\[ m = 3 \mu_0 \mu_1 \frac{\mu_p - \mu_1}{\mu_p + 2 \mu_1} VH \]

where \( \mu_0 \) is the vacuum permeability; \( \mu_1 \) is the relative permeability of the base material; \( \mu_p \) is the relative permeability of the soft magnetic particles; \( V \) is the volume of the single soft magnetic particles; and \( H \) is the applied magnetic field strength. The interaction energy of two magnetic dipoles (magnetized soft magnetic particles) [24] is:

\[ E_{12} = \frac{1}{4 \pi \mu_0 \mu_1} \left[ \frac{m_1 \cdot m_2 - 3(m_1 \cdot e_d)(m_2 \cdot e_d)}{|d|^3} \right] \]

where \( m_1 \) and \( m_2 \) are the magnetic dipole moments of the two particles; \( e_d \) is the direction vector; and \( d \) is the center distance of the two particles. After simplifying this formula (Eq. (10)), \( E_{12} \) can be obtained as follows:

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

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

\[ F_{12} = 12 \pi \mu_0 \mu_1 \left( \frac{\mu_p - \mu_1}{\mu_p + 2 \mu_1} \right)^2 \frac{a_1^3 a_2^2}{d^3} H^2 \]

\[ \cdot \left[(1 - 3 \cos^2 \theta) e_d + \sin 2 \theta e_o \right] \]

where \( e_d \) is the direction vector in the direction of the particle centerline and \( e_o \) 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 \( \mu_p \) is much larger than \( \mu_1 \); thus, Equation (12) can be simplified as:

\[ F_{12} = 12 \pi \mu_0 \mu_1 \frac{a^6}{d^3} H^2 \cdot \left[(1 - 3 \cos^2 \theta) e_d + \sin 2 \theta e_o \right] \]

As shown in Fig. 8a, 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. 8b. Two adjacent particles are analyzed, and only the magnetic effect is considered, as shown in Fig. 8c. 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 \( F_{12} \) and \( F_{21} \) will form a magnetic moment, which makes the particle chain tend to rotate in the direction of the angle \( \theta \) decreasing; the size is:

\[ M_m = \frac{3}{2} \pi \mu_0 \mu_1 a^3 H^2 \sin 2 \theta \]

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:

\[ M_{m_0} = \frac{3}{4} \pi \mu_0 \mu_1 a^2 H^2 \sin 2 \theta \]

From the mobility of the torque, the magnitude of the balance torque \( M_{m_0} \) in Fig. 8d is:

\[ M_{m_0} = R \int_0^\theta M_{m_0} d\theta = \frac{3}{4} \pi \mu_0 \mu_1 a^2 H^2 R (1 - \cos^2 \varphi) \]

The moment \( M_{m_0} \) 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:

\[ F_m = \frac{3}{4} \pi \mu_0 \mu_1 a^2 H^2 R (1 + \cos \varphi) \]
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 $F_{mi}(H)$ 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 [25], 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 magneto-compressive force with magnetic field strength under different compressive strains can be obtained. As shown in Fig. 10a, the corresponding magneto-induced compression force $F_m$ can be determined by determining the compression strain and the applied magnetic field strength. Meanwhile, according to Hooke’s law, the magneto-elastic modulus of the magnetorheological elastic polishing body can be calculated in combination with the experiment, as shown in Fig. 10b.

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 [26, 27]. Fig. 11 shows the three-dimensional and two-dimensional Hertz contact theoretical model. The relevant calculation formula for the pressure $\rho(x, y)$ can be obtained as follows:

$$
\rho(x, y) = \frac{F_m}{\pi R^2} \left(1 - \frac{y^2}{R^2}ight)
$$
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; $v_1$ and $v_2$ are the Poisson’s ratio of the MREPCs and the workpiece, respectively; $p(x, y)$ is the stress at the $Q$ point.

From Formulas (8), (18), (19), and (20) and $F_m(H)$, the calculation formula of the pressure distribution of the polishing contact area is:

$$
\begin{align*}
\frac{1}{R} & = \frac{1}{r} + \frac{1}{R^*} \\
\frac{1}{E^*} & = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}
\end{align*}
$$

\begin{align*}
(19) \\
(20)
\end{align*}

$$
\begin{align*}
\begin{cases}
p(x,y) = & \begin{cases}
\left( \frac{3F}{2\pi a^2} \right)^\frac{1}{2} \sqrt{1 - \frac{x^2 + y^2}{a^2}}, & \sqrt{x^2 + y^2} \leq a \\
0, & \sqrt{x^2 + y^2} > a
\end{cases} \\
\end{cases}
\end{align*}
$$

\begin{align*}
(18)
\end{align*}

$$
\begin{align*}
\begin{cases}
p(x,y) = & \begin{cases}
\left[ \frac{3(F_N + F_m^i(H))}{2\pi} \left( \frac{3(F_N + F_m^i(H))}{4} \right) \frac{E_1 + E_2 - E_1 v_1^2 - E_2 v_2^2}{E_1 E_2} \right]^\frac{1}{2} \\
1 - \frac{x^2 + y^2}{\left[ \frac{3(F_N + F_m^i(H))}{4} \right] \frac{E_1 + E_2 - E_1 v_1^2 - E_2 v_2^2}{E_1 E_2}}^\frac{1}{2}
\end{cases}
\end{cases}
\end{align*}
$$

\begin{align*}
(21)
\end{align*}
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:

\[
R(x, y) = k\nu(x, y)p(x, y)
\]  

(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 \( \mu m \); 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.

4.2 Simulation and experimental results of fixed-point polishing

When the MREPCs on the polishing tool presses 0.1mm under zero magnetic field (i.e., its compressive strain is 2%), the positive pressure \( F^p_m \) measured by the dynamometer is 1.65N; when a 500mT magnetic field is applied, from the data in Fig. 10, the corresponding \( F^m_m \) 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 magnetorheological elastic polishing body polishing tool to a certain extent distribution of actual material removal.

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. 14b, 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. Thus, the external magnetic field will increase the material removal rate.

| Table 1 Experimental parameters of fixed-point polishing. |
|---------------------------------------------------------|
| Describe objects | Size (mm) | \( E \) (MPa) | \( \nu \) | \( \delta \) (mm) | \( \omega \) (rpm) | \( \theta \) (°) | \( H \) (mT) | \( t \) (s) |
| MREPCs          | \( r \): 7.25 | \( E_1 \): 1.05 | \( \nu_1 \): 0.47 | -- | -- | -- | -- |
| Workpiece      | 15×15×1 | \( E_2 \): 1.3×10³ | \( \nu_2 \): 0.28 | -- | -- | -- | -- |
| Work condition | -- | -- | -- | 0.1 | 1500 | 20 | 0, 500 | 120 |
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 min, 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 the SEM image of the surface morphology of a single-crystal silicon wafer before and after polishing. There are a large number of obvious scratches and pits on the silicon wafer before polishing. After zero magnetic field polishing, the scratch marks are effectively reduced, and only shallower traces and pits, and after 500mT magnetic field polishing, the scratch marks on the surface of the silicon wafer completely disappeared, only a small amount of pits 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 Ra 0.192μm. However, the workpiece surface profile curve after polishing under zero magnetic field shows that the peaks and troughs are uneven, but the overall amplitude is reduced, and the roughness value is reduced to 0.041μm. 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 0.024μm. 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.

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 which reduces the normal stress applied by the polishing tool to the surface [28], 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 [29]; 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 0.041μm, while the polishing under the 500mT magnetic field can reduce the surface roughness to 0.024μm. The
### Magnetic field

| Simulation result | 0mT | 500mT |
|-------------------|-----|-------|
| ![Simulation result 0mT](image1) | ![Simulation result 500mT](image2) |

| Measurement result | 0mT | 500mT |
|--------------------|-----|-------|
| ![Measurement result 0mT](image3) | ![Measurement result 500mT](image4) |

### Curves of 2D

| X-Z profile | Material removal depth(μm) |
|-------------|---------------------------|
| ![X-Z profile 0mT](image5) | ![X-Z profile 500mT](image6) |

| Y-Z profile | Material removal depth(μm) |
|-------------|---------------------------|
| ![Y-Z profile 0mT](image7) | ![Y-Z profile 500mT](image8) |

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

**Availability of data and material** All relevant data are available on reasonable request.
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. Guangfeng Zhang and Shengqiang Jiang contributed to the injection molding process, including the concept of curing process and experimental test results.

Funding This research was funded by the National Natural Science Foundation of China (grant nos. 51605410, 91860133) and Hunan Provincial Natural Science Foundation (grant no. 2020JJ5545, 2020JJ5541, 2021JJ20009). The authors are grateful for the support.

Declarations

Ethics approval The manuscript will not be submitted elsewhere until the editorial process is completed.

Consent for publication The author transfers to Springer the non-exclusive publication rights.

Conflict of interest The authors declare no competing interests.

References

1. Martin H, Burge J, Davis J, Kim DW, Kingsley J, Law K, Loeff A, Lutz R, Merrill C, Strittmatter P, Tuell M, Weinberger S, West S (2016) Status of mirror segment production for the Giant Magellan Telescope. SPIE 9912:9912–9930
2. Guo J, Beaucamp A, Ibaraki S (2017) Virtual pivot alignment method and its influence to profile error in bonnet polishing. Int J Mach Tools Manuf 122:18–31
3. Chen M, Liu H, Su Y, Yu B, Fang Z (2016) Design and fabrication of a novel magnetorheological finishing process for small concave surfaces using small ball-end permanent-magnet polishing head. Int J Adv Manuf Technol 83:823–834
4. Zhang L, Kuriyagawa T, Kaku T, Zhao J (2005) Investigation into electrorheological fluid-assisted polishing. Int J Mach Tools Manuf 45:1461–1467
5. Li M, Lyu B, Yuan J, Dong C, Dai W (2015) Shear-thickening polishing method. Int J Mach Tools Manuf 94:88–99
6. Xin J, Cai W, Tichy JA (2010) A fundamental model proposed for material removal in chemical–mechanical polishing. Wear 268: 837–844
7. Sun C, Xiux S, Hong Y, Kong X, Lu Y (2020) Prediction on residual stress with mechanical-thermal and transformation coupled in DGH. Int J Mech Sci 179:105629
8. Gong X, Wang Z, Hu T, Xuan S (2017) Mechanical property and conductivity of a flax fibre weave strengthened magnetorheological elastomer. Smart Mater Struct 26:075013
9. Xu Z, Wang Q, Zhu K, Jiang S, Wu H, Yi L (2019) Preparation and characterization of magnetorheological elastic polishing composites. J Intell Mater Syst Struct 30:104538X983596
10. Xu Z, Wang J, Wu H, Bo X, Tang Z, Zhang G (2021) Effect of abrasive particles on mechanical properties of magnetorheological elastomer. Polym Adv Technol 32(2):630–640
11. Wang C, Wang Z, Yang X, Zj S, Yi P, Yb G, Xu Q (2014) Modeling of the static tool influence function of bonnet polishing based on FEA. Int J Adv Manuf Technol 70:341–349
12. Ke X, Wang C, Guo Y, Xu Q (2015) Modeling of tool influence function for high-efficiency polishing. Int J Adv Manuf Technol 84: 2479–2489
13. Lu A, Jin T, Guo Z, Qm M, Chang Y, Liu Q, Zhang C (2018) Characterization of the tool influence function in a dual-axis wheel polishing process to achieve high material removal rates. Precis Eng 52:276–290
14. Ren L, Zhang G, Zhang L, Zhang Z, Huang Y (2018) Modelling and investigation of material removal profile for computer-controlled ultra-precision polishing. Precis Eng 55:144–153
15. Rao Z, Guo B, Zhao Q (2015) Investigation of contact pressure and influence function model for soft wheel polishing. Appl Opt 54: 8091–8099
16. Pan R, Zhong B, Chen D, Wang Z, Fan J, Zhang C, Wei S (2017) Modification of tool influence function of bonnet polishing based on interfacial friction coefficient. Int J Mach Tools Manuf 124:43–52
17. Cao Z-C, Cheung C (2015) Multi-scale modelling and simulation of material removal characteristics in computer-controlled Bonnet polishing. Int J Mech Sci 106:147–156
18. Cao Z-C, Cheung C, Zhao X (2016) A theoretical and experimental investigation of material removal characteristics and surface generation in bonnet polishing. Wear 360-361:137–146
19. Misra A, Pandey P, Dixit US (2017) Modeling of material removal in ultrasonic assisted magnetic abrasive finishing process. Int J Mech Sci 131-132:853–867
20. Hagiwara S, Kawashima N, Umehara N, Shibata I (2003) Proposal for die polishing using a new bonding abrasive type grinding stone: development of MAGIC grinding stone. Machin Sci Technol - MACH SCI TECHNOL 7:267–279
21. Chen L, Gong X, Li W (2007) Microstructures and viscoelastic properties of anisotropic magnetorheological elastomers. Smart Mater Struct - SMART MATER STRUCT 16:2645–2650
22. Preston F (1927) The theory and design of plate glass polishing machines. J Glass Technol 11:214–256
23. Krause F (1987) Rosensweig, R. E., Ferrohydrodynamics. Cambridge etc. Z Angew Math Mech 67:279–279
24. Jolly M, Carlson JD, Muoz BC (1996) A model of the behaviour of magnetorheological materials. Smart Mater Struct 5:607–614
25. Oguro T, Endo H, Kikuchi T, Kawai M, Mitsumata T (2017) Characterization of the tool influence function in a dual-axis wheel polishing process to achieve high material removal rates. Precis Eng 52:273–279
26. Greenwood J (1985) Formulas for moderately elliptical Hertzian contacts. J Tribol 107:501–504
27. Greenwood J (1997) Analysis of elliptical Hertzian contacts. Tribol Int - TRIBOL INT 30:235–237
28. Kansal H, Singh A, Grover V (2017) Magnetorheological nano-finishing of diamagnetic material using permanent magnets tool. Precis Eng 51:30–39
29. Jha S, Jain V (2004) Design and development of the magnetorheological abrasive flow finishing (MRAFF) process. Int J Mach Tools Manuf 44:1019–1029

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.