Rheological properties of magnetic field-assisted thickening fluid and high-efficiency spherical polishing of ZrO₂ ceramics

Yang Ming · Xiang Ming Huang · Dong Dong Zhou · Qing Zeng · Hong Yu Li

Received: 23 December 2021 / Accepted: 9 May 2022 / Published online: 25 May 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Shear thickening polishing technology using non-Newtonian polishing fluids is a low-cost, low-damage polishing method for the ultra-precision machining of complex curved surfaces. However, the low polishing efficiency and poorly controlled viscosity of traditional shear thickening polishing fluids significantly limit their practical applications. In this study, a novel weak magnetic field-assisted shear thickening polishing fluid (WMFA-STPF) containing carbonyl iron particles, which utilized a weak magnetorheological effect to promote the shear thickening process, was developed, and its rheological characteristics were investigated. The obtained results revealed that WMFA-STPF exhibited good fluidity at low shear rates and enhanced thickening characteristics in the working shear rate range. To verify the high efficiency, high quality, and uniform polishing ability of WMFA-STP technology applied to the spherical surface of a zirconia ceramic workpiece, contrast polishing experiments were performed. After 75 min of polishing, the surface damage was effectively mitigated; the surface quality and uniformity were significantly improved; and the material removal rate increased by 156% up to 7.82 μm/h. Hence, the WMFA-STP method can be successfully utilized for the high-efficiency high-quality polishing of hard and brittle ceramics.

Keywords Non-Newtonian polishing fluid · Ultra-precision machining · Shear thickening · Rheological characteristic · Weak magnetic field-assisted thickening effect

1 Introduction
Zirconia ceramics possess good mechanical properties (including high toughness, bending strength, and wear resistance), high chemical stability, excellent heat insulation performance, and low thermal expansion coefficients. Therefore, they are widely used in medical/biological materials, grinding media, molds, cutting tools, 3C product shells, and other applications [1–5]. However, many fields in the manufacturing industry specify that the surface roughness of zirconia ceramic parts should be in the nanometer range and have strict requirements regarding the surface and subsurface damage [6–10]. As commonly used hard and brittle ceramic materials, zirconia ceramics fabricated by traditional processing methods (turning, milling, and grinding) exhibit low processing efficiency and processing quality, ultimately leading to mechanical and/or thermal processing damage [11].

Flexible machining plays an increasingly important role in ultra-precision manufacturing due to its nondestructive effect on complex surfaces and hard and brittle materials. In particular, studying the shear thickening of non-Newtonian fluids in the machining field helped significantly increase the material removal rate (MRR) and improve the surface quality of hard and brittle materials. Using abrasive flow machining (AFM), highly viscous non-Newtonian fluids were employed to increase the AFM efficiency under shear disturbance [12]. For example, Wei et al. [13] utilized a gel-based shear thickening fluid with high viscosity during AFM to increase the MRR by a factor of four, resulting in a machined surface roughness of 6.48 nm. Similarly, by applying hydraulic pressure polishing technology, low-viscosity polishing fluids were replaced by non-Newtonian polishing fluids with shear thickening properties to perform the high-efficiency adaptive polishing of curved workpieces. Gürgen and Sert [14] compounded a highly viscous shear thickening fluid with abrasive particles for the precision machining of a steel bar workpiece and achieved a surface roughness (Ra) of
0.24 μm. Duc-nam [15] used a shear thickening fluid polishing method to process the spherical surface of ball-milled steel. By performing fluid simulations, various process parameters such as the workpiece inclination angle, fluid viscosity, and polishing speed were optimized to obtain the final surface roughness of 12 nm. Shao et al. [16] adopted a shear thickening polishing (STP) method based on the use of non-Newtonian power-law fluids for the high-efficiency high-quality polishing of the high-temperature nickel-based alloy surface of a turbine blade. The obtained results revealed that the surface roughness decreased from 72.3 to 4.2 nm after 9 min of polishing. Li et al. [17] performed the high-efficiency ultrahigh-precision polishing of the die steel Cr12MoV using an STP slurry with high shear thickening performance; the resulting MRR and surface roughness were equal to 13.69 μm/h and 5.1 nm, respectively. Li et al. [18–20] polished the surfaces of bearing steel and optical crystal (KDP and LN) workpieces by the traditional shear thickening polishing method utilizing the auxiliary effects of energy fields (such as chemical energy and temperature fields). The obtained ultra-precision processed surfaces exhibited roughness values of approximately 10 and 1 nm, respectively. By combining the shear thickening effect and chemical induction mechanism, Li and Xie [21] used a green chemical jump thickening polishing method to polish silicon carbide ceramics and achieved high surface integrity with surface roughness values below 32 nm and low sub-surface damage. In addition, a combination of a shear thickening polishing fluid with a polishing tool produced damage-free/low damage machined surfaces with improved quality. For example, the researchers in [22] combined a shear thickening polishing fluid with bonnet polishing using a flexible polishing pad to perform the nondestructive ultra-precision machining of the free surfaces of a nickel-based alloy die with a roughness up to 3.9 nm.

At present, the ultra-precision grinding of zirconia ceramics remains a challenging task due to surface burns, cracks, and sub-surface damage [23, 24]. Furthermore, the energy-field-assisted non-Newtonian fluid flexible machining is commonly used in the ultra-precision machining of zirconia ceramics. Hong’s team [25, 26] increased the efficiency of a chemical mechanical removal process involving non-Newtonian fluid polishing by constructing a surface consisting of thick nanosilica particles. The MRR of this method was 242% higher than that of the traditional spherical abrasive technique, and the obtained ultra-precise non-destructive machined surfaces had roughness values below 2 nm. Heng et al. [27] conducted the ultra-efficient processing of a zirconia bar by a magnetorheological grinding method and maintained the high surface quality and original surface shape with an Ra of 20 nm and roundness of 0.2 μm. Li et al. [28] polished a zirconia cylindrical workpiece using high-efficiency STP technology with optimized process parameters. The obtained MRR was 3.05 μm/h, while the ultra-precision machined surface was characterized by Ra = 25.7 nm and PV = 1.5 μm. Among various polishing techniques, the fluid polishing technology based on a chemical mechanical mechanism can produce a superior (lossless) surface quality; however, its processing efficiency is very low. The magnetic lapping and polishing method utilizing a high magnetic field exhibits high processing quality and efficiency; however, its practical applications are limited by the high processing costs and workpiece shape. Meanwhile, a polishing method based on the shear thickening effect of non-Newtonian fluids is an ultra-precision machining method that takes into account machining quality, machining efficiency, machining cost, and machining adaptability. However, due to the constitutive characteristics of shear thickening polishing fluids, their viscosity and shear rate are strongly related to each other, which does not allow precise MRR control. Second, pure shear thickening fluids possess low peak viscosity and thus cannot increase the machining efficiency. Third, the efficiency of the shear thickening effect decreases with an improvement of the workpiece surface quality, which reduces both the polishing force and MRR. Fourth, the upper viscosity limits of these fluids are low, which makes the high-efficiency polishing of hard materials (such as hard and brittle ceramics) a difficult process.

To further optimize the viscosity peak and rheological controllability of non-Newtonian polishing fluids, increase the polishing efficiency, and realize the non-destructive ultra-precision machining of hard and brittle ceramics, a low magnetic field-assisted machining method was proposed [27, 29, 30]. By considering the chain-forming effect of magnetic particle polarization on the rheological properties of shear thickening polishing fluids, rheological properties were investigated at different mass fractions of carbonyl iron particles (CIPs) and magnetic field intensities in this study. As a result, weak magnetic field-assisted shear thickening polishing (WMFA–STP), an efficient and high quality polishing method for hard and brittle ceramic spheres based on the non-Newtonian fluid-assisted thickening by a weak magnetic field, has been developed. By performing field emission scanning electron microscopy (SEM) observations and utilizing the Cross constitutive model, the formation mechanism of free magnetic chains and WMFA thickening effect were systematically examined. In addition, contrast processing experiments were performed to verify the influence of a weak magnetorheological effect on the polishing of zirconia ceramics. The findings of this study can stimulate further research in the non-Newtonian fluid polishing field.

2 Materials and methods

2.1 Materials

The WMFA shear thickening polishing fluid (STPF) used in this study contained CIPs with diameters of 3–5 μm...
(Yuhuan CNC Machine Tool Co., Ltd.), SiO₂ particles with sizes of 7–40 nm (surface area: 300 m²/g, Nanjing Cook Biotechnology Co., Ltd., China), and SiC abrasive particles with diameters of 3 μm (Chuangying Metal Material Co., Ltd., China), which served as dispersed phases. SiC abrasive particles were selected to polish ceramic workpieces. Polyethylene glycol organic dispersant (PEG200 HOCH₂(CH₂OCH₂)_nCH₂OH, molecular weight: 200) (China National Pharmaceutical Group Chemical Testing Co., Ltd., China) was used as a continuous phase carrier.

First, nano-SiO₂ and SiC particles were added in an appropriate proportion to the continuous phase carrier, and the resulting mixture was mechanically stirred for 1 h. The obtained sample was poured into a vacuum device for 1 h to remove bubbles from the polishing fluid. To prepare the STPF, the mass fractions of nano-SiO₂, SiC, and PEG200 in the resulting fluid were maintained at constant levels of 20, 10, and 70%, respectively [31, 32] followed by CIP addition. The described process was repeated to obtain WMFA-STPF samples with CIP mass fractions of 5, 10, and 15%, which were named CIP-5 wt.%, CIP-10 wt.%, and CIP-15 wt.%, respectively [17, 31]. To explore the micro-morphology and distribution of CIP chains in WMFA-STPF more effectively, the obtained samples were observed with a MAIA3 TESCAN scanning electron microscope. For this purpose, each analyzed sample was evenly smeared on the surface of a slide, and two cubes of the strong Nd–Fe–B magnetic material were fixed at both ends of this slide. Subsequently, the sample was dried at 80 °C under the field produced by a magnet (100 mT) and coated with a gold spray. Finally, SEM images of free CIP short chains were obtained for the sample under a weak magnetic field.

2.2 Rheological tests

According to the continuum hypothesis, shear stress is the fluid friction value per the unit area of the surface. For non-Newtonian fluids, the change in the shear stress with shear rate is nonlinear. To obtain a constitutive equation and construct a WMFA-STP removal model, the rheological characteristics of the polishing fluid were examined by an advanced rotary magnetometer (Anton Paar/MCR301, Antonpa, Austria), as shown in Fig. 1. The test temperature was maintained at 25 °C; a parallel plate with a diameter of 20 mm was used; and the working gap was set to 1 mm. The appropriate amount of the polishing fluid was then slowly added to the circular groove. At a constant shear rate of 100 s⁻¹ and target magnetic induction intensity, the fluid samples were pre-sheared for 30 s to ensure the uniform distribution of the dispersed phase particles and stability of the magnetic chain structure. After that, the steady shear and dynamic vibration shear modes were utilized to measure the rheological characteristics of the fluid at various parameters [17, 31]. The change in the shear stress with shear rate was measured at magnetic field intensities of 0, 100, 200, and 300 mT. We also used the magnetic field strength as a label in parentheses after the sample name to indicate the magnetic field conditions of the rheological test (for example, CIP-5 wt.% (100 mT)). The described procedure was repeated three times for each group, and the mean values of the obtained parameters were calculated.

2.3 Processing experiments

To explore the feasibility of the WMFA-STP method, an experimental setup for fluid polishing machining was
constructed (Fig. 2). It consisted of an upper rotating shaft, which controlled the high-speed rotation of the workpiece (the upper limit of the rotating speed was 10,000 rpm); a lower rotating mechanism, which controlled the rotation of the polishing groove (0 – 200 rpm); a workpiece clamping device; and a permanent magnet with a remanence of approximately 1.2 T. As shown in previous studies [17, 32], the viscosity of a non-Newtonian polishing fluid determines the gripping force of abrasive particles, which is positively correlated with the polishing force. Therefore, based on the rheological parameters of the polishing fluid, the CIP-5 wt.% group was selected for further experiments, and the workpiece surface magnetic field was set to 100 mT.

After that, a contrast processing experiment was designed (Table 1) [14, 15, 17]. The processing parameters, such as processing clearance (h₀, d₀), rotation speed (n, N), and turning direction, are marked in Fig. 3. Using a shear rate calculation method [17], it was found that the fluid in the polishing region was in a high-viscosity state (weak magnetic field-assisted shear thickening). The workpieces were fabricated from a hard and brittle zirconia ceramic with a Vickers hardness of 12 (see the upper left corner of Fig. 2). An electronic analytical balance was used to monitor quality changes of the studied workpieces. A Wyko NT9100 optical surface profilometer was utilized to investigate the surface topography of the machined workpiece and numerical distribution of the hemispherical surface roughness. The locations of selected test points are shown in the upper left corner of Fig. 3. The test point on the horizontal axis is point 0 (α = 0°), and the other test points were obtained by rotating this axis in the counterclockwise direction at increments of 15°. Three contour lines with the same clearance were selected in the horizontal direction, and surface roughness was measured to evaluate the surface quality.

### 3 Results and discussion

The rheological characteristics of WMFA-STPF are affected by the material properties, external field (such as force, temperature, or magnetic field), particle mass fraction, and particle size [33–37]. In this study, the effect of the mass fraction of CIPs on the rheological characteristics of WMFA-STPF was investigated under different magnetic fields, and the WMFA thickening effect was confirmed.

#### 3.1 Rheological characteristics of WMFA-STPF

The effect of magnetic field intensity on the rheological properties of the fabricated WMFA-STPF samples with three different CIP mass fractions was studied first. For this purpose, the key rheological parameters, such as the initial viscosity (η₀), peak viscosity (ηₓₐₓ), and thickening amplitude value (ηₓₐₓ − ηₘᵟₐₓ), were determined (the obtained results are presented in Fig. 4). The rheological properties of the WMFA-STPF samples with different CIP mass fractions were strongly influenced by the magnetic field intensity. The corresponding curves depicted in Fig. 4a–c indicate that the rheological properties of WMFA-STPF are described

---

**Table 1** Processing parameters used in this study

| Parameter                        | Values                  |
|----------------------------------|-------------------------|
| Polishing fluid                  | CIP-5 wt.%              |
| Magnetic flux intensity (B/mT)   | 0, 100                  |
| Processing time (t/min)          | 75                      |
| Bottom clearance (h₀/mm)         | 10                      |
| Side clearance (d₀/mm)           | 10                      |
| Rotation speed of the workpiece (n/rpm) | 2000                   |
| Rotation speed of the polishing pool (N/rpm) | 50                |
by the “shear thinning–shear thickening–shear thinning” sequence. At magnetic fields of 0 and 100 mT, the “shear thinning” effect is relatively weak during the initial stage, which is close to the state of a Newtonian fluid. However, this effect becomes more pronounced at 200 and 300 mT. Furthermore, when the CIP mass fraction increased to 15%, the characteristics of a Bingham body were clearly observed (Fig. 4c). According to the rheological characteristic curves, increasing the CIP mass fraction and magnetic field intensity changed the studied sample from the STPF to a magnetorheological fluid (Fig. 4d) [38, 39].

A non-Newtonian polishing fluid with low viscosity in the low shear rate range and high viscosity in the high shear rate range is combined with the processing method in this study. Therefore, the rheological parameters of WMFA-STPF obtained at different CIP mass fractions and magnetic field intensities are statistically analyzed in Fig. 5. Figure 5a displays the initial viscosity ($\eta_0$) values of each test group. It shows that the initial viscosities of WMFA-STPF obtained at different CIP mass fractions increase with an increase in the magnetic field intensity. In particular, at a CIP mass fraction of 15%, the initial viscosity suddenly increases to 8070 and 13,800 Pa at magnetic field intensities of 200 and 300 mT, respectively. It is noteworthy that the measured viscosity values are close to the magnitudes obtained for solid-like systems [33, 39]. According to Preston’s equation, effective material removal cannot be achieved at low shear rates. In addition, the low viscosity of the polishing fluid during the pool start prolongs the equipment life and saves energy. At the same time, the low viscosity facilitates the circulation of the polishing fluid through a peristaltic pump. Therefore, the lower initial viscosity increases the process efficiency. Figure 5b displays the peak viscosity ($\eta_{\text{max}}$) values determined for each test group. It shows that the peak viscosity with a magnetic field is generally higher than that without a magnetic field. The test group CIP-5 wt.% exhibited the highest peak viscosity (180 Pa s) at a weak magnetic field of 100 mT, indicating that the polishing fluid possessed the maximum material removal capacity under these conditions. In particular, the magnetorheological effect observed for the test group CIP-15 wt.% at magnetic fields 200 and 300 mT suppressed shear thickening in the studied shear rate range, reducing the peak viscosity. In general, the peak viscosity of a non-Newtonian polishing fluid determines the gripping effect of particle clusters on abrasive particles. Therefore, the higher is the peak viscosity, the more favorable is the material removal process to fluid polishing. Figure 5c depicts the average viscosities determined in the shear rate range from 100 to 700 s$^{-1}$. It shows that the numerical distribution characteristics of the average viscosity obtained for each test group are similar to those of the peak viscosity. The test group CIP-5 wt.% demonstrated the highest average viscosity (138 Pa s) at a weak magnetic field of 100 mT, which was 1.67 times higher than the value obtained without a magnetic field. This result indicates that the polishing flow can achieve higher material removal rates under suitable conditions. Figure 5d shows the thickening amplitude ($\eta_{\text{max}}-\eta_{\text{min}}$) values of each test group. At a magnetic field intensity of 100 mT.
mT, the CIP-5 wt.% test group exhibited a high thickening amplitude of 152 Pa s. According to the results of previous fluid polishing studies [13, 15, 17], a high viscosity polishing fluid can reach high material removal efficiency and machining ability for high-hardness materials while maintaining high machining accuracy.

Based on the obtained results and requirements established for fluidity and viscosity characteristics at low shear rates and viscosity and thickening amplitude at high shear rates, the testing set CIP-5 wt.% (100 mT) was selected for the subsequent polishing experiments.

3.2 Weak magnetic field-assisted thickening effect

3.2.1 Microscopic formation mechanism and properties of magnetic chains in a weak magnetic field

Figure 6a displays the composite structure formed by the free CIP short chains and nano-SiO$_2$ thickening phase. It shows that the spherical particle chain is in a discrete state and oriented along the magnetic field direction. The remaining voids filled with gray matter represent nano-SiO$_2$ thickening phase particles with shear thickening characteristics. Meanwhile, the thixotropic behavior of the dispersed system with shear thickening properties is strongly influenced by the external shear disturbance. In other words, when shear disturbance is applied to a turbid system containing suspended matter, dispersed particles rapidly accumulate in this area [40]. Based on the microscopic behavior of particles observed at different energy fields, it can be inferred that under a composite energy field, CIP short chains are spatially folded due to the aggregation of other dispersed particles. In addition, because multiple dispersed particles (CIP, SiO$_2$, and SiC) have different sizes, dense composite clusters can be formed (Fig. 6b).

The magnetic chain theory, hybrid molecular dynamics model, and organic polymer polymerization mechanism [41, 42] can be used to explain the WMFA-STPF rheological properties observed under the applied magnetic field. The CIP chain shear stress can be expressed by the following formula:

![Rheological characteristics of the WMFA-STPF samples determined at different magnetic field strengths. Viscosity–shear rate characteristic curves obtained for the a CIP-5 wt.%, b CIP-10 wt.%, and c CIP-15 wt.% samples](image)
\[ \tau = 2.446 \phi \mu_0 M_s^2 H^{3/2} \]  

(1)

where \( \phi \) is the volume fraction of CIPs, \( \mu_0 \) is the vacuum permeability, \( M_s \) is the saturated magnetization of CIPs, and \( H \) is the magnetic field intensity.

According to Eq. (1), the strength of the external magnetic field and fraction of magnetic particles are directly related to the binding force (shear stress) of the magnetic chain. When the shear stress is small, the magnetic chain exists as a free short chain (this phenomenon is called a weak magnetorheological effect). With an increase in the magnetic flux intensity and CIP fraction, the shear stress of the magnetic chain increases sharply. At the same time, the length of the magnetic chain also increases, and the linear structure is transformed into a dendritic or even reticulate structure. Macroscopically, the fluid assumes a solid state represented by a Bingham body \([43–46]\). This phenomenon is called a strong magnetorheological effect.

Under the action of the weak magnetic field, magnetic chains are uniformly distributed in the laminar flow of WMFA-STPF. At this point, WMFA-STPF exhibits Newtonian fluid characteristics. As the shear rate increases, the turbulent state and phase particles dispersed due to shear thickening assemble, making the magnetic chains fold and agglomerate in space. Subsequently, under the dual action of the magnetic field force and shear force, composite clusters are formed. In this case, WMFA-STPF behaves as a non-Newtonian fluid.

### 3.2.2 Weak magnetorheological strengthening thickening mechanism

Figure 7 describes various states of the dispersed phase particles in the WMFA-STPF sample with increasing shear rate under a weak magnetic field. The curve equation used to characterize its rheological properties is based on the Cross–Williamson model \([47]\):

- **Fig. 5** Key rheological parameters of WMFA-STPF: a initial viscosity, b peak viscosity, c average viscosity, and d thickening amplitude
where $\eta$ is the viscosity, $\eta_c$ is the critical viscosity, $\dot{\gamma}$ is the shear rate, $\dot{\gamma}_c$ is the critical shear rate, $\lambda$ is the time dimension, and $n$ is the dimensionless constant.

Equation (2) and the particle cluster theory [48, 49] can elucidate the shear thickening mechanism of the WMFA-STPF samples involving a WMFA thickening effect. The obtained curve is divided into three sections: Newtonian interval (Interval I), weak magnetorheological strengthening thickening interval (Interval II), and shear thinning interval (Interval III). In Interval I, the thickening phase particles, abrasive particles, and magnetic chain clusters are uniformly distributed in the base liquid. At low shear rates, the particles and clusters in the polishing fluid gradually form an orderly spatial arrangement, which allows the macroscopic characterization of the fluid as a Newtonian fluid. In Interval II, the shear disturbance (high shear rates) provided sufficient energy to the dispersed phase particles to overcome the potential energy barrier. Simultaneously, short CIP chains replaced the polymer clusters, thereby increasing the average particle size of the dispersed phase in the suspension and binding force between the polymer clusters and abrasive particles [50]. Consequently, the density of the polishing fluid increases, causing a drastic macroscopic shear thickening, which explains the mechanism of WMFA thickening fluid during the shear thickening process. In Interval III, because of the high shear rate, the energy provided by shear disturbance is higher than the yield stress of the mixed polymer clusters. This phenomenon eliminated the synergistic thickening effect, decreased the apparent viscosity, and resulted in shear thinning [51].

**3.3 Flow field states**

To verify the thickening effect of the weak magnetic field and its predicted improvement of the polishing performance of the non-Newtonian fluid, comparative experiments were conducted on workpieces 1 and 2 with CIP-5 wt.%. They included 75-min polishing without a magnetic field and under the weak magnetic field, respectively. A photograph of the flow field in the polishing region on the workpiece surface obtained during the machining process is presented in Fig. 8. It shows that the viscosity of the flow field in the polishing area significantly increases when a weak magnetic field of 100 mT is applied to the workpiece surface because it promotes the formation of short and free CIP magnetic

![SEM images of the WMFA-STPF sample under a weak magnetic field. a Free CIP short chain and thickened cluster. b Microstructure of the WMFA-STPF clusters](image-url)
chains, which agglomerate with other dispersed phase and abrasive particles due to shear disturbance. Owing to the space entanglement of the magnetic short chains, the produced composite clusters exhibit larger binding forces and diameters than those of the clusters generated without an applied magnetic field. Therefore, the WMFA-STPF viscosity increases under the action of the weak magnetic field.

3.4 Material removal capacity

The masses of workpieces 1 (no magnetic field) and 2 (weak magnetic field) were obtained before and after processing. The mass of workpiece 1 decreased by 0.6 mg from 142.4595 g to 142.4589 g, and its MRR could not be determined precisely. However, the mass of workpiece 2 decreased by 81.2 mg from 142.7146 to 142.6334 g. In this case, the MRR was equal to 7.82 μm/h assuming that the polishing area included the entire hemispherical surface and that the workpiece density was 5.89 g/cm³. The MRR calculation formula is shown in Eq. (3). Here, \( m_0 \) is the workpiece mass before polishing, \( m_a \) is the workpiece mass after polishing, \( \rho \) is the density of the zirconia ceramic workpiece, \( S_{\text{hemisphere}} \) is the surface area of the hemisphere, and \( t \) is the polishing time.

![Fig. 7 Rheological characteristics of WMFA-STPF based on the Cross constitutive model](image1)

The International Journal of Advanced Manufacturing Technology (2022) 121:1049–1061
The obtained results indicate that the micro-clusters formed in high-viscosity fluids exert large wrapping and clamping forces on abrasive particles and high polishing force on the workpiece surface. Therefore, high-viscosity fluids can achieve high polishing efficiency for hard and brittle ceramic materials. The MRR obtained in this study is 1.56 times larger than that of STP zirconia ceramics [28].

### 3.5 Surface quality

Test points 3 ($\alpha=45^\circ$) and 6 ($\alpha=90^\circ$) in the main polishing area were selected to characterize the microscopic surface morphology before and after polishing (Figs. 9 and 10, respectively). First, the microscopic morphologies of the polished surface at test point 3 obtained without a magnetic field and under the weak magnetic field were compared. Figure 9a shows that surface polishing without a magnetic field cannot effectively remove the deep scratches caused by the previous grinding process. In contrast, under the action of the weak magnetic field, the polishing flow can effectively restore the damaged hemispherical zirconia surface (Fig. 9b). Similarly, the microscopic morphologies of the polished surface obtained at test point 6 without a magnetic field and under the weak magnetic field were compared. Figure 10a shows that the polished surface without a magnetic field contains unremoved grinding scratches and pits. In contrast, the microscopic surface topography depicted in Fig. 10b exhibits only shallow scratches.

Without the assistance of a weak magnetic field, the material removal mechanism of the polishing flow is consistent with that of shear thickening polishing [14, 15, 32, 38]. According to the rheological properties discussed above, the thickening of the polishing flow under this condition is weak and cannot provide a sufficient gripping force for abrasive particles. Therefore, the surface damage of a zirconia ceramic workpiece cannot be mitigated effectively. By applying a weak magnetic field, the thickening property of the polishing flow is enhanced. As a result, the abrasive particles are clamped more effectively to alleviate surface damage. In particular, Figs. 9b and 10b show that the removal traces formed by WMFA-STP are dense and uniform.
reflecting flexible processing characteristics. Therefore, it can be inferred that this polishing method causes very low subsurface damage.

These results indicate that WMFA-STP is a flexible machining method that can effectively mitigate surface damage.

In addition, surface roughness was measured for each test point on the hemispheric surface, and its numerical distribution is presented in Fig. 11. As shown in Fig. 11a, at \( \alpha = 0^\circ \), the \( R_a \) value of test point 0 is approximately 189 nm because it is located in a region that cannot be effectively polished. As angle \( \alpha \) increases, the test points reach the edge area of the main polishing region. Owing to the WMFA–STPF swelling plasticity, the polishing flow expands, and its edge demonstrates a limited polishing ability. The \( R_a \) values obtained at test points 1 and 2 were 98 and 74 nm, respectively. When \( \alpha \) becomes greater than or equal to 45°, the test points reach the main polishing region, and their \( R_a \) values are equal to approximately 30 nm. The surface quality in the main polishing area (test points 3–6) was also evaluated before and after polishing, and the obtained results are presented in Fig. 11b. It shows that the original surface roughness varies between 82 and 152 nm before polishing. However, the polished surface roughness values of test points 3–6 in the main polishing zone are equal to 29.7, 30.4, 34.7, and 31.4 nm, respectively. To further characterize the degree of surface quality improvement by this processing method, the surface roughness improvement rate (SRIR) and surface uniformity improvement rate (SUIR) were calculated via Eqs. (4) and (5), respectively.

\[
SRIR = \frac{R_{a before} - R_{a after}}{R_{a before}} \times 100\%
\]

\[
SUIR = \frac{\Delta R_{a before} - \Delta R_{a after}}{\Delta R_{a before}} \times 100\%
\]

where \( R_{a before} \) is the surface roughness of the test point before machining, \( R_{a after} \) is the surface roughness after machining, \( \Delta R_{a before} \) is the surface roughness distribution threshold of each point in the main polishing area before machining, and \( \Delta R_{a after} \) is the surface roughness distribution threshold of each point in the main polishing area after machining.

The \( R_a \) value of test point 6 significantly decreased from 152 to 31.4 nm after machining, while the SRIR reached 79.3%. The SUIR calculated by substituting the \( R_a \) values of the main polishing area before and after processing into Eq. (5) was equal to 92.8%. Therefore, using the WMFA-STP method, the surface quality and uniformity in the main polishing area were significantly improved.

4 Conclusions

In this study, we explored the weak magnetorheological thickening effect in WMFA-STPF by analyzing its rheological properties and compared the results obtained for the hard brittle zirconia ceramic workpieces. The main conclusions from the findings of the present work can be summarized as follows.

1. Owing to the thickening effect of the weak magnetic field, the thickening performance of the polishing fluid at the machining shear rate represented by the average viscosity increased by approximately 67% with respect to that of the traditional STPF (without a magnetic field),
providing a theoretical support for the subsequent comparative processing experiments.

2. Because of its higher thickening performance, WMFA-STPF can more effectively polish hard and brittle zirconia ceramics, which are otherwise difficult to process. Its MRR value reached 7.82 μm/h, which was 56% higher than that of the traditional STP method. Therefore, the proposed technique is highly efficient in polishing hard and brittle ceramic materials.

3. Although WMFA-STPF demonstrated good thickening properties, it did not cause any damage to the processed surface, but effectively removed the damage traces of the previous grinding process. Therefore, this method has the nondestructive characteristics of flexible machining.

4. Most importantly, the WMFA-STP method can effectively improve the surface quality of zirconia ceramics during machining (SRIR = 79.3%), obtain ultra-precision surfaces (Ra < 30 nm), and significantly enhance the surface uniformity (SUIR = 92.8%). Therefore, this method achieves the high surface quality of ultra-precision machining.

In summary, WMFA-STPF allows high-efficiency nondestructive polishing of hard and brittle materials due to its WMFA thickening effect. Based on the field-induced rheological and flexible polishing properties of this fluid, it can be potentially used for the ultra-precision machining of complex surfaces.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by D. D. Zhou, Q. Zeng, and H. Y. Li. The first draft of the manuscript was written by Y. Ming and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the National Natural Science Foundation of China and the Natural Science Foundation of Hunan Province (grant numbers 51975203 and 2021JJ30113). Author Y. Ming, X. M. Huang, D. D. Zhou, Q. Zeng, and H. Y. Li have received research support from Company Hunan University, College of Mechanical and Vehicle Engineering.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Vila-Nova TEL, Gurgel de Carvalho IH, Moura DMD et al (2020) Effect of finishing/polishing techniques and low temperature degradation on the surface topography, phase transformation and flexural strength of ultra-translucent ZrO2 ceramic. Dent Mater 36(4):e126–e139. https://doi.org/10.1016/j.dental.2020.01.004
2. Ghosh G, Sidpara A, Bandyopadhyay PP (2019) An investigation into the wear mechanism of zirconia-alumina polishing pad under different environments in shape adaptive grinding of WC-Co coating. Wear 428–429:223–236. https://doi.org/10.1016/j.wear.2019.03.020
3. Manicone PF, Rossi Iommetti P, Raffaelli L (2007) An overview of zirconia ceramics: Basic properties and clinical applications. J Dent 35(11):819–826. https://doi.org/10.1016/j.jdent.2007.07.008
4. Roualdes O, Duclos M-E, Gutknecht D, Frappart L, Chevalier J, Hartmann DJ (2010) In vitro and in vivo evaluation of an alumina–zirconia composite for arthroplasty applications. Biomaterials 31(8):2043–2054. https://doi.org/10.1016/biomaterials.2009.11.1007
5. Oetzel C, Caslen R (2006) Preparation of zirconia dental crowns via electrophoretic deposition. J Mater Sci 41(24):8130–8137. https://doi.org/10.1007/s10535-006-0621-7
6. Suzuki H, Okada M, Namba Y, Goto T (2019) Superfinishing of polycrystalline YAG ceramic by nanodiamond slurry. CIRP Ann 68(1):361–364. https://doi.org/10.1016/j.cirp.2019.04.062
7. Wan L, Li L, Deng Z, Deng Z, Liu W (2019) Thermal-mechanical coupling simulation and experimental research on the grinding of zirconia ceramics. J Manuf Process 47:41–51. https://doi.org/10.1016/j.jmapro.2019.09.024
8. Zhang X, Kang Z, Li S, Shi Z, Wen D, Jiang J, Zhang Z (2019) Grinding force modelling for ductile-brittle transition in laser macro-micro-structured grinding of zirconia ceramics. Ceram Int 45(15):18487. https://doi.org/10.1016/j.ceramint.2019.06.067
9. Zucuni CP, Pereira GKR, Valandro LF (2020) Grinding, polishing and glazing of the occlusal surface do not affect the load-bearing capacity under fatigue and survival rates of bonded monolithic fully-stabilized zirconia simplified restorations. J Mech Behav Biomed Mater 103:103528. https://doi.org/10.1016/j.jmbbm.2019.103528
10. Zucuni CP, Dapieve KS, Rippe MP, Pereira GKR, Bottino MC, Valandro LF (2019) Influence of finishing/polishing on the fatigue strength, surface topography, and roughness of an yttrium-stabilized tetragonal zirconia polycrystals subjected to grinding. J Mech Behav Biomed Mater 93:222–229. https://doi.org/10.1016/j.jmbbm.2019.02.013
11. Fiocchi AA, de Angelo Sanchez LE, Lisboa-Filho PN, Fortulan CA (2016) The ultra-precision Uld-lap grinding of flat advanced ceramics. J Mater Process Tech 231:336–356. https://doi.org/10.1016/j.jmatprotec.2015.10.003
12. Kumar S, Jain VK, Sidpara A (2015) Nano-finishing of freeform surfaces (knee joint implant) by rotational-magneto-thermoelectric abrasive finishing (R-MARF) process. Precis Eng 42:165–178. https://doi.org/10.1016/j.precisioneng.2015.04.014
13. Wei H, Gao H, Wang X (2019) Development of novel guar gum hydrogel-based media for abrasive finishing of mold: shear-thickening behavior and finishing performance. Int J Mech Sci 157–158:758–772. https://doi.org/10.1016/j.ijmecsci.2019.05.022
14. Gürgen S, Sert A (2019) Polishing operation of a steel bar in a shear thickening fluid medium. Compos Part B-Eng 175:107127. https://doi.org/10.1016/j.compositesb.2019.107127
15. Nguyen D (2020) Simulation and experimental study on polishing of spherical steel by non-Newtonian fluids. Int J Adv Manuf Tech 107(6):763–773. https://doi.org/10.1007/s00170-020-05055-w
16. Shao Q, Lyu B, Yuan J, Wang X, Ke M, Zhao P (2021) Shear thickening polishing of the concave surface of high-temperature nickel-based alloy turbine blade. J Mater Res Technol 11:72–84. https://doi.org/10.1016/j.jmrt.2020.12.112
17. Li M, Lyu B, Yuan J, Dong C, Dai W (2015) Shear-thickening polishing method. Int J Mach Tool Manuf 94:88–99. https://doi.org/10.1016/j.ijmachtools.2015.04.010
18. Li M, Huang Z, Dong T, Mao M, Lyu B, Yuan J (2018) Surface integrity of bearing steel element with a new high-efficiency shear thickening polishing technique. Procedia CIRP 71:313–316. https://doi.org/10.1016/j.procir.2018.05.030
19. Li M, Karpuschewski B, Ohmori H et al (2021) Adaptive shearing-gradient thickening polishing (AS-GTP) and subsurface damage inhibition. International J Mach Tool Manuf 160:103651. https://doi.org/10.1016/j.ijmachtools.2020.103651

20. Li M, Liu M, Riemer O, Song F, Lyu B (2021) Anhydrous based shear-thickening polishing of KDP crystal. Chinese J Aeronaut 34(6):90–99. https://doi.org/10.1016/j.cja.2020.09.019

21. Li M, Xie J (2022) Green-chemical-jump-thickening polishing for silicon carbide. Ceram Int 48(1):1107–1124. https://doi.org/10.1016/j.ceramint.2021.09.196

22. Zhu WL, Beaucamp A (2020) Non-Newtonian fluid based contactless sub-aperture polishing. CIRP Ann 69(1):293–296. https://doi.org/10.1016/j.cirp.2020.04.093

23. Yang M, Li C, Zhang Y, Jia D, Li R, Hou Y, Cao H (2019) Effect of friction coefficient on chip thickness models in ductile-regime grinding of zirconia ceramics. Int J Adv Manuf Tech 102(5–6):2617–2632. https://doi.org/10.1007/s00170-019-03367-0

24. Yang M, Li C, Zhang Y et al (2017) Maximum undeformed chip thickness for ductile-brittle transition of zirconia ceramics under different lubrication conditions. Int J Mach Tool Manuf 122:55–65. https://doi.org/10.1016/j.ijmachtools.2017.06.000

25. Xu L, Lei H (2020) Nano-scale surface of ZrO2 ceramics achieved efficiently by peanut-shaped and heart-shaped SiO2 abrasives through chemical mechanical polishing. Ceram Int 6(9):13297–13306. https://doi.org/10.1016/j.ceramint.2020.02.108

26. Dong Y, Lei H, Liu W (2020) Effect of mixed-shaped silica sol abrasives on surface roughness and material removal rate of zirconia ceramic cover. Ceram Int 46(15):23828–23833. https://doi.org/10.1016/j.ceramint.2020.06.159

27. Heng L, Kim JS, Tu JF, Mun S (2020) Fabrication of precision meso-scale diameter ZrO2 ceramic bars using new magnetic pole designs in ultra-precision magnetic abrasive finishing. Ceram Int 46(11):17335–17346. https://doi.org/10.1016/j.ceramint.2020.04.022

28. Li M, Huang Z, Dong T, Tang C, Lyu B, Yuan J (2018) Surface quality of Zirconia (ZrO2) Parts in shear-thickening high-efficiency polishing. Procedia CIRP 77:143–146. https://doi.org/10.1016/j.procir.2018.08.256

29. Zhang J, Wang H, Kumar AS, Jin M (2020) Experimental and theoretical study of internal finishing by a novel magnetically driven polishing tool. Int J Mach Tool Manuf 153:103552. https://doi.org/10.1016/j.ijmachtools.2020.103552

30. Fan Z, Tian Y, Zhou Q, Shi C (2020) Enhanced magnetic abrasive finishing of Ti–6Al–4V using shear thickening fluids additives. Precis Eng 64:300–306. https://doi.org/10.1016/j.precisioneng.2020.05.001

31. Wei M, Sun L, Zhang C, Qi P, Zhu J (2018) Shear-thickening performance of suspensions of mixed ceria and silica nanoparticles. J Mater Sci 54:346–355. https://doi.org/10.1007/s10853-018-2873-4

32. Li M, Lyu B, Yuan J, Yao W, Zhou F, Zhong M (2016) Evolution and equivalent control law of surface roughness in shear-thickening polishing. Int J Mach Tool Manuf 108:113–126. https://doi.org/10.1016/j.ijmachtools.2016.06.007

33. Zhang X, Li W, Gong X (2010) Thixotropy of MR shear-thickening fluids. Smart Mater Struct 19(12):125012. https://doi.org/10.1088/0964-1726/19/12/125012

34. Singh AK, Jha S, Pandey PM (2012) Nanofinishing of fused silica glass using ball-end magnetorheological finishing tool. Mater Manuf Process 27(10):1139–1144. https://doi.org/10.1080/104246914.2011.654159

35. Peng GR, Li W, Tian TF, Ding J, Nakano M (2014) Experimental and modeling study of viscoelastic behaviors of magneto-rheological shear thickening fluids. Korea-Aust Rheol J 26(2):149–158. https://doi.org/10.1007/s13367-014-0005-3

36. Deng XJ, Klein B, Hallbom DJ, de Wit B, Zhang JX (2018) Influence of particle size on the basic and time-dependent rheological behaviors of cemented paste backfill. J Mater Eng Perform 27(7):3478–3487. https://doi.org/10.1007/s11665-018-3467-7

37. Wang X, Wang Y, Yang W, Xie BH, Yang MB, Dan W (2012) A rheological study on temperature dependent microstructural changes of fumed silica gels in dodecan. Soft Matter 8(40):10457. https://doi.org/10.1039/c2sm25668a

38. Tian Y, Jiang J, Meng Y, Wen S (2010) A shear thickening phenomenon in magnetic field controlled-dipolar suspensions. Appl Phys Lett 97(15):151904. https://doi.org/10.1063/1.3501128

39. Zhang X, Li W, Gong XL (2008) Study on magnetorheological shear thickening fluid. Smart Mater Struct 17(1):015051. https://doi.org/10.1088/0964-1726/17/1/015051

40. Labanda J, Llorens J (2005) A structural model for thixotropy of colloidal dispersions. Rheol Acta 45(3):305–314. https://doi.org/10.1007/s00397-005-0035-5

41. Chen K, Wang Y, Xuan S, Gong X (2017) A hybrid molecular dynamics study on the non-Newtonian rheological behaviors of shear thickening fluid. J Colloid Interf Sci 497:378–384. https://doi.org/10.1016/j.jcis.2017.03.038

42. Moctezuma RE, Donado F, Arauz-Lara JL (2013) Lateral aggregation induced by magnetic perturbations in a magnetorheological fluid based on non-Brownian particles. Phys Rev E 88(3):032305. https://doi.org/10.1103/physrev.e.88.032305

43. Boczkowska A, Awiśtian SF, Wejrzanoski T, Kurzydłowski KJ (2009) Image analysis of the microstructure of magnetorheological elastomers. J Mater Sci 44(12):3135–3140. https://doi.org/10.1007/s10853-009-3417-8

44. Briscoe B, Luckham P, Zhu S (1999) Pressure influences upon shear thickening of poly(acrylamide) solutions. Rheol Acta 38(3):224–234. https://doi.org/10.1007/s00397-000-0072-0

45. Jiang W, Ye F, He Q, Gong X, Feng J, Lu L, Xuan S (2014) Study of the particles’ structure dependent rheological behavior for polymer nanospheres based shear thickening fluid. J Colloid Interf Sci 413:8–16. https://doi.org/10.1016/j.jcis.2013.09.020

46. Saraswatamma K, Jha S, Venkateswarra Rao P (2017) Rheological behaviour of magnetorheological polishing fluid for Si polishing. Mater Today Proc 4(2):1478–1491. https://doi.org/10.1016/j.matpr.2017.01.170

47. Giurgen S, Sotoğlu MA, Kuşhan MC (2019) Rheological compatibility of multi-phase shear thickening fluid with a phenomenological model. Smart Mater Struct 28(3):035027. https://doi.org/10.1088/1361-665x/ab018c

48. Ball RC, Melrose JR (1999) Shear thickening in colloidal dispersions. AIP Conf Proc 62(10):27–32. https://doi.org/10.1063/1.58445

49. Zhao P, Fu Y, Li H, Zhang C, Liu Y (2019) Three-dimensional simulation study on the aggregation behavior and shear properties of magnetorheological fluid. Chem Phys Lett 722:74–79. https://doi.org/10.1016/j.cplett.2019.02.042

50. Fernandez N, Mani R, Rinaldi D et al (2013) Microscopic mechanism for shear thickening of non-Brownian suspensions. Phys Rev Lett 111(10):108301. https://doi.org/10.1103/physrevlett.111.108301

51. Karthikeyan S, Mohan B, Kathiresan S (2021) Influence of rotational magnetorheological abrasive flow finishing process on biocompatibility of stainless steel 316L. J Materi Eng Perform 30(2):1545–1553. https://doi.org/10.1007/s11665-020-05442-0

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