Chapter 6
Shear Thickening Fluid in Surface Finishing Operations

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6.1 Introduction

Shear thickening is a non-Newtonian flow behavior mostly observed in highly dense suspensions [1–3], exhibiting sudden phase transitions between liquid and solid states due to the reversible changes in viscosity (Fig. 6.1) [5]. The term "shear thickening" describes a sudden increase in viscosity by increasing shear rate. Numerous efforts have been made to explain the rheological properties of this smart fluid: one is hydro-cluster theory, where the Brownian interactions between suspended particles make the fluid flow easily at low shear rates, while hydrodynamic effects on the particles increase with the increasing shear rate [6]. Over the years, more theories have been proposed to explain the shear thickening mechanism, such as disorder-order transition [7], jamming [8], and dilatancy [9]. Recent studies have led to a new model, namely contact rheology model, suggesting that contact forces increase for the thickening onset where the particles contact each other at high shear rates [10, 11]. Although being studied for a long time, STF has not been utilized for engineering applications until the last two decades, including smart dampers [12] and liquid/soft armors [13–15].

The introduction of STF into the field of manufacturing and surface finishing is a more recent and a very novel idea. The first description of shear thickening polishing (STP) was reported in a 2013 patent disclosure by a research team from the University of Sydney [16]. The suspension was an ethylene glycol–based STF filled with 60 wt% polymeric particles (BASF AG, Ludwigshafen, Germany), which were in its liquid state under static conditions so that the specimen could be fully immersed. Silicon carbide (SiC) particles with sizes in the range of 45–1000 μm

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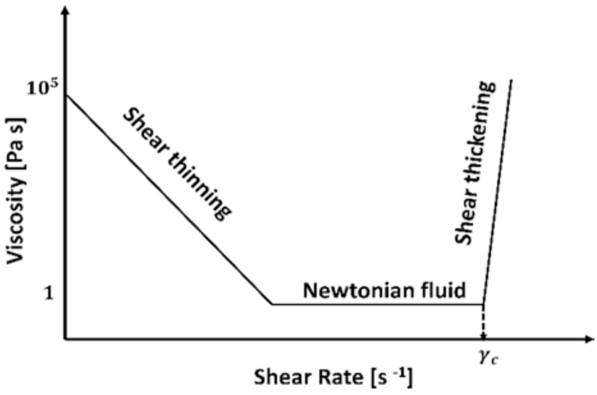

Fig. 6.1 Rheological behavior of dense suspensions [4]

were added to the STF as the abrasive medium. STP used the liquid- to solid-like characteristics of the STF when the rotational speed of the specimen reached the critical value, the surrounding STF substantially solidified, which firmly held the abrasive particles in place. Meanwhile, a normal force was also generated due to the shear thickening behavior of the STF. This leads to the formation of a "flexible fixed abrasive tool" [17] and, subsequently, the abrasive particles can polish all the surfaces of the specimen in contact with the STF simultaneously. It can be seen that STP enables the polishing of complex structures, for instance, curved surfaces, and surfaces at different heights or orientations, and even the potential of enabling inner surfaces to be polished simultaneously with the exterior surfaces.

In recent years, the STP method has been concept-proofed by different research groups [18, 19] and received increasing attention [20–22]. The process is currently used to polish the products with complex surfaces [23–25]. STP has great potential to address the limitations of the abovementioned non-conventional finishing methods. Compared to the traditional operations, common problems such as deep scratches on the surfaces, excessive plunge of abrasives, and drastic force increase are avoided due to the tough backing effect of the slurry in the process [26]. Nevertheless, up to now, there are still some limitations, for example, (1) difficulty in controlling shear thickening behavior in the optimal range with a nonlinear increase in the viscosity; (2) influenced machining efficiency and surface integrity due to the increasing contacting temperature within fluid [27]; and (3) larger agglomerates and poor surface integrity caused by shear induced clustering of particles [19].

STF has undergone a rapid development in the past decade, attributable to its great potential in surface finishing applications. Moreover, a large number of recent works has largely expanded this field and produced a new knowledge along with new methods such as chemistry-enhanced STP and magnetorheological STP. This chapter aims to provide the state-of-the-art literature studies on STF polishing from experimental, analytical, and numerical methods. It is anticipated to provide a better understanding of polishing mechanisms, improve the current processing systems, and broaden the applications of STP.

6.2 Fundamental Principles in Polishing with STF

Over the past decades, the surface qualities of components not only influenced their performance and life but also had a close relationship with the usability and reliability of the entire machine. The surface processing technology, as an effective method to promote surface qualities, has become one of the important ways to improve the serviceable performance and prolong lifespan of products [28]. Conventional finishing processes include grinding, polishing, shot peening, turning, milling, lapping, superfinishing, and honing. However, as it is quite challenging to control what happens in the processing and in that they entail the application of high pressures, deterministic machining could not always be ensured, and deep cracks on the finished surface are often generated [29]. To improve surface finishing quality, a large number of research studies have been carried out via the development of novel abrasive tools, for example, diamond whisker wheels, biomimetic grinding wheels, and fiber wheels [30]. Moreover, in the recent times, there has been a continuous development of non-conventional surface finishing to obtain ultra-precision surfaces with high surface quality and integrity (e.g., magnetorheological finishing, chemical mechanical polishing, electric emission machining, and abrasive flow machining) [31]. However, these methods may have certain limitations: (1) magnetorheological finishing is achieved by controlling viscosity with a magnetic field requiring a costly installation and large equipment, thus restricting its application in a much wider range; (2) chemical mechanical polishing requires chemical slurries that would impact on the environment; (3) surface finishing efficiency of the electric emission machining is limited by its nano or sub-nano level of material removal mechanism; and (4) rheological behavior of the polishing medium in the abrasive flow machining cannot be controlled externally, resulting in reduced accuracy and efficiency [26, 27, 32]. This, therefore, leads to searching for new surface processing techniques with higher quality and efficiency, environmental friendliness, and lower cost.

Very recently, STF has been introduced into the field, enabling a novel surface finishing technique for various engineering materials [16–25]. As schematically demonstrated in Fig. 6.2, the principle of STP process is based on the micro-level material removal actions [19]. Shear thickening effect of non-Newtonian fluids is triggered by flow velocity change (shear rate). The workpiece material is hard to be removed without shear thickening because of the insufficient dynamic force on the abrasive particles. Once the shear thickening occurs, the suspended particles in the slurry form particle clusters (i.e., hydroclusters), in which the abrasives are packed. The applied force on the abrasive particles is significantly increased to make the abrasive particles cut rather than rolling across the micro peak on the surface. After the removal of a small chip, hydrodynamic pressure increases, contributing to the increased dynamic force. Subsequently, more parts of the peak can be removed. As a result of the decreased peaks on the surfaces, the magnitude of shear thickening decreases as the abrasive particles pass over. Finally, as it approaches a smooth surface, the hydroclusters disintegrate.

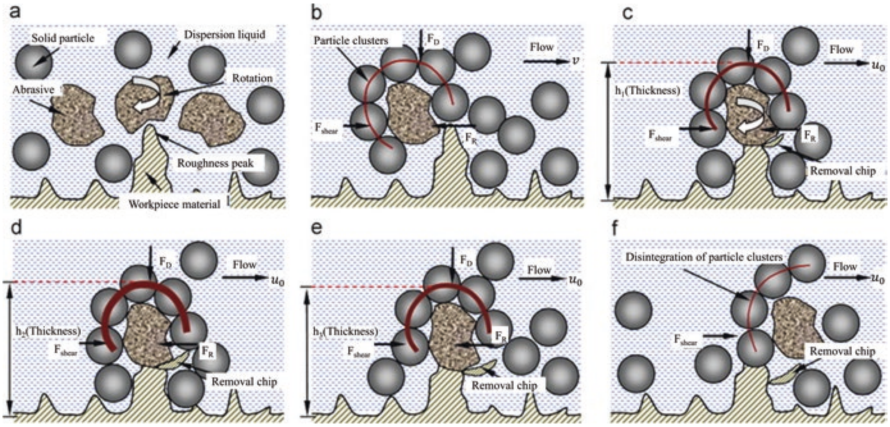

Fig. 6.2 Material removal mechanism in STP: (**a**) without shear thickening, (**b**) with shear thickening, (**c**) with a small removal chip sheared off by abrasive particle, (**d**) with a bigger removal chip under enhanced shear thickening, (**e**) material removal completed, and (**f**) disintegration of particle clusters [19]

According to recent studies, shear thickening behavior is governed by the contact forces between the particles rather than the hydrodynamic interactions at high shear rates [10]. The abovementioned mechanisms have been supplemented by Gürgen et al. [26]; at shear thckening regime, the inter-particle contact forces are added to the hydrodynamic forces, and thus, the abrasives are sufficiently supported by the shear thickened medium to realize the material removal from the workpiece. Besides, the fluid medium could provide a damping property in case of sudden force increases. Accordingly, excessive force generation and surface scratches are suppressed during the surface polishing process. It is also worth noting the work carried out by Span et al. [33], who firstly reported the shear-induced dynamic jamming mechanism in abrasive finishing applications. Within the context of their study, jamming refers to the formation of a localized, solid-like granular extensions of force chains at particle densities well below the critical value required for global jamming, with a characteristic feature of a significant increase in force when the jammed domain reaches and interacts with a rigid boundary [8].

6.3 Recent Advances in Polishing with STF

In recent years, numerous works have been performed on STP with a focus on the surface finishing of parts, aiming to achieve flexible polishing with higher efficiency and wider applications. In this section, the recent advances in STF finishing are reviewed about experimental characterization, numerical modelling and theoretical analysis.

6.3.1 Experimental Investigations

6.3.1.1 Materials and STF Preparation

In order to achieve high-efficiency polishing, emphasis should be firstly put on the preparation process of STP slurries, whose base liquid is a kind of non-Newtonian fluid added with abrasives, e.g., aluminum oxide (Al_2O_3), cerium dioxide (CeO_2), and diamond. From the relative literature, it is known that different compositions of STP slurries can result in various rheological properties, hence contributing to different surface finishing results. The most commonly used slurry is composed of the micro-sized multi-hydroxyl polymer as the first dispersion phase particle and deionized water as the dispersant. In Li et al.'s work [19], Al_2O_3 abrasives were added into the suspension, and the viscosity in terms of shear rate under different concentrations of abrasives was examined as shown in Fig. 6.3a. It is possible to mention that

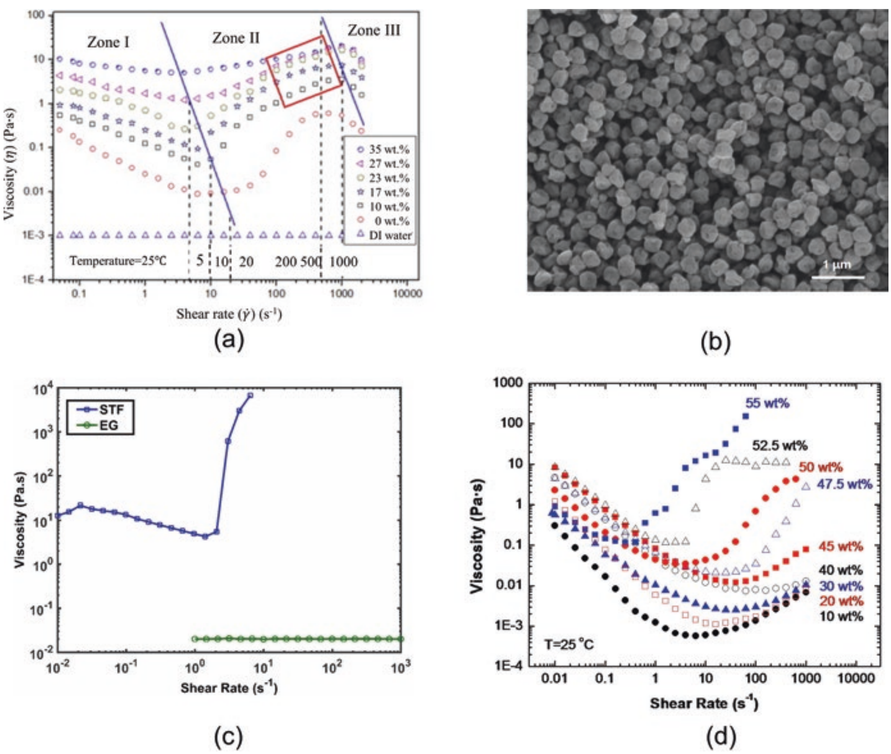

Fig. 6.3 (**a**) Variation of viscosity with respect to different shear rates for STP slurry with different concentration of Al_2O_3 abrasives [19]; (**b**) SEM image of styrene/acrylate particles [34]; (**c**) steady-state viscosity as a function of shear rate for EG and STF; (**d**) steady state shear rate ramp of cornstarch and water suspensions ranging in concentration from 10 to 55 wt.% [35]

the viscosity of deionized water was independent of the shear rate, while the slurries presented a shear thinning phase followed by a shear thickening regime. The inclusion of the particle abrasives interfered with the STF flow, which led to increased original viscosity of STF and decreased peak viscosity [36]. With increasing abrasive concentration, the shear rate at which shear thickening starts became lower and viscosity became larger.

Another well-studied slurry was prepared by dispersing micro- or nano-sized particles in polyethylene glycol (PEG) medium. For instance, in our previous study [34], we prepared styrene/acrylate particles (Fig. 6.3b) suspended in PEG. As shown in Fig. 6.3c, the viscosity of PEG almost remains constant with increasing shear strain rate, which indicates that the PEG is a Newtonian fluid. In comparison, STF exhibits a transition from shear thinning to shear thickening above a critical shear rate. In recent studies, nano-sized fumed silica was introduced, which showed a more beneficial effect on shear thickening behavior than the micron-sized colloidal particles [32]. This can be explained by the branchy particle structure of fumed silica and the increased surface area that contributes to a strong hydro-clustering mechanism of the suspension [26]. When comparing the multi-hydroxyl-based STF with fumed silica-based fluid, the maximum viscosities of neat slurry without abrasives were 0.6 Pa.s and 85.02 Pa.s, respectively. A similar observation has been made by Tian et al. [30], where the rheological properties of different dispersion systems were studied. The viscosity at the same shear rate differed by up to 11-fold when comparing 15 w.t.% and 20 w.t.% silica loadings. This was because the viscosity became large with increased particles and hydrogen bonds.

It is also worth noting a more accessible and environmentally friendly non-Newtonian fluid, i.e., cornstarch suspension, that has been utilized in multiple surface polishing applications [33, 37]. Its rheological behavior with different amounts are shown in Fig. 6.3d. Although being widely adopted, the size of starch agglomerates may vary in a very broad range for the suspension consisting of only starch and abrasives at high shear rates [38]. These larger starch agglomerates would greatly result in surface scratching during polishing. To address the issue, Zhu et al. [39] added polyacrylamide (PAM) into the mixture of starch and water to shift the thickening onset to a higher shear rate, which was attributed to the overall thinning effect in the suspension. Additionally, PAM polymer could form bridges between the destabilized particles, thereby developing hydroclusters [40] and promoting a stable suspension that enables both thickening mechanism by the starch and entangling of abrasive particles within the hydroclusters.

6.3.1.2 Polishing Systems with STF

Substantial experimental works have been conducted to assess STF surface finishing performance over the years; therefore, a range of experimental devices for STP process have been developed. As illustrated in Fig. 6.4, the polishing specimen is mounted and submerged to a cup filled with STP slurries, while the polishing tank is driven by a step motor. During the polishing process, the rotational speed and the

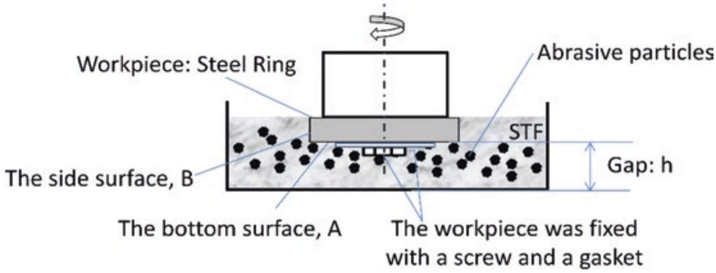

Fig. 6.4 Illustration of STP experimental configuration [41]

distance between the specimen and cup base are adjusted to guarantee the shear thickening conditions [19]. By using a similar setup, the impact of inclination angle on surface quality during the machining process has also been investigated by several researchers [20, 21]. In their studies, the workpiece was fixed with a certain tilt angle, i.e., the angle between the substrate surface and the horizontal plane. In some works, tribometers with pin-on-disk configurations have also shown the capability of STF polishing [26, 41]. All the above mentioned works mainly concentrate on full-aperture finishing by immersing the workpiece into a polishing slurry, which could simplify the industrial production equipment. However, deterministic polishing cannot be realized by such an apparatus. In order to achieve freeform surface polishing, a 7-axis CNC machine was utilized in Zhu et al.'s works, which offer great potential to have a controllable material removal process. In their studies, the A-axis and B-axis enabled different process angles and tool directions, while the workpiece was fixed to an XYZ translational stage on the other side [39, 42].

6.3.1.3 Effect of Processing Parameters

The shear thickening finishing is closely related to a number of processing variables such as polishing speed, abrasive grit size and particle loading, and impact angle. Li et al. [19] were among the pioneers who studied the effect of polishing speed in STP process. The experimental results showed that the material removal rate (MRR) presented a power-function rise with increasing polishing velocity, while surface roughness gradually decreased with time and reached a steady value at the final stage. Better surface finishing was achieved with higher speed during the same period of polishing. This could be explained by the enhanced shear thickening and cutting ability of abrasive particles surrounded firmly by colloidal particles. According to Span et al.'s study [33], the polishing speed not only gives the material removal rate but also directly influences the shear rate in STF [23], which determines the resultant force applied on the abrasive particles. The positive effect of polishing speed on STP has also been reported by the following researchers [22, 24]. Gürgen et al. [26] compared the polishing effect within different viscosity zones (i.e., shear thinning and shear thickening) by controlling the linear speed of

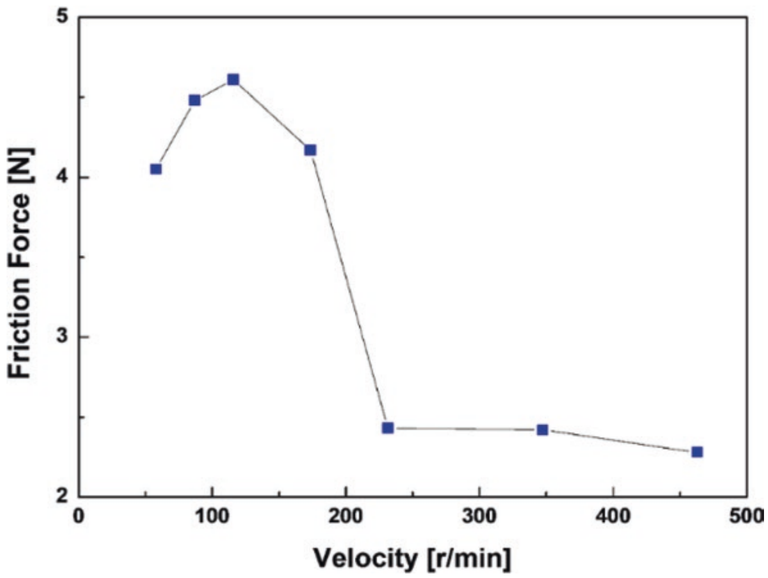

Fig. 6.5 Friction force under various rotation speeds [41]

specimen. It is found that an efficient surface finishing result can only be achieved when the velocity reflects the shear thickened regime. In a recent work [41], the friction force as a function of rotation speed was examined in a wider range as shown in Fig. 6.5, depicting the average friction values in the steady polishing phase. It is important to state that the friction force was initially increased with the rotation speed, which was attributed to the thickening effect owing to the increasing shear rate, with the growing friction force associating with shear jamming in STF. However, the friction force significantly dropped with the further increase in the rotation speed. Afterward, increasing velocity resulted in a much lower friction force, which may be due to the wall-slip behavior in the STF. Though the thickened STF exhibited a stable, smooth surface against the workpiece, no strong polishing ability was observed at higher rotational speeds.

Extensive studies have also been conducted to examine the influence of abrasive particles [19, 20]. Figure 6.6a shows that MRR has a linear rise with the increase of abrasive concentration, as the active number of abrasive particles is increasing. However, excessive amount of abrasives will suppress the polishing effect, which can be explained by the uneven agglomeration of particles that may result in damages on the surface. Interestingly, different conclusions based on the effect of abrasive size upon polishing performance were drawn by various research teams. For example, Li et al. [19] found that, although increasing grain size resulted in decreased MRR, it had a slight effect on the average surface roughness after polishing [19]. It is believed that large abrasive particles are similar to small abrasives in the sense that neither will cause visible scratches on the surface and can produce a smooth surface [43]. According to our previous study, the resultant surface

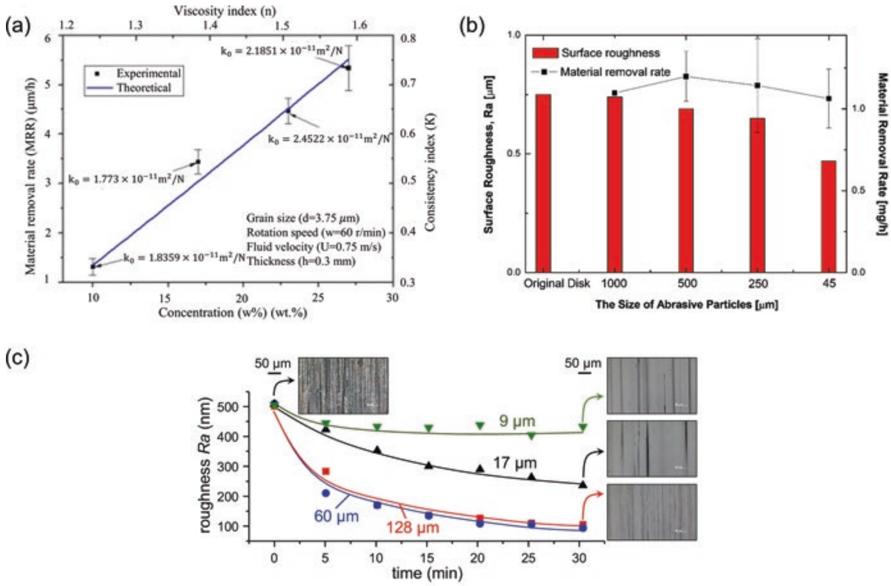

Fig. 6.6 Influence of abrasive particles on STP performance: (**a**) MRR as a function of abrasive concentration [19]; (**b**) surface roughness and MRR as a function of grain size [41]; (**c**) dependence of finishing performance on abrasive size [33]

roughness decreased by using finer particles, which was in agreement with the observation by Lyu et al. [23]. It is believed that a smaller size means more abrasive particles are included in the STP suspension under the same abrasive loading, leading to improved surface polishing efficiency. Yet the removal rate in the process was slightly affected by the size of particles (Fig. 6.6b). This may be because the friction force and normal pressure mainly depend on the mechanical properties of suspension beyond the thickening point. Those are the key factors in determining the MRR from the workpiece [41]. In comparison, different observations were obtained in the work by Span et al. [33] as shown in Fig. 6.6c; the coarser abrasives attributed to a better surface processing performance. It was obvious that relatively poor performance of the finer abrasive particles was due to their ineffectiveness in removing a few deep scratches on the workpiece surface. It is also claimed that the abrasive effect on surface processing may be related to the size and morphology of solid colloidal particles [19], which has been further proved by Li et al. [18] by performing STP under different ratios of abrasive particle size to polymer size. When the ratio was smaller than 0.5, material removal was predominated by plastic ploughing; thus, the workpiece ahead of the abrasive cutting edge was heavily squeezed and polished, causing the deterioration of surface quality. If the ratio was greater than 0.5, an increased ratio would lead to a better surface finish.

In addition, the effect of the inclination angle of specimen is often discussed, particularly in polishing complex-shaped parts [23, 39, 44]. It is known that the rapidly growing demand for complex surfaces requires high surface finishing and high-efficiency processing technologies, which have contributed to the research of

STP of cylindrical and complex workpieces over the past few years. According to the literature, the selection of angle range varied significantly, which is strongly dependent on workpiece geometries. In the work of STP for spherical steels by Nguyen et al. [22], the experimental results showed that surface roughness increased in the tilt angle ranging from 0° to 3° due to the smallest cutting pressure. Better surface finishing can be achieved with the increased inclination angle in the range of 5° and 15°. For inner raceway surface polishing, the overall roughness lowers significantly at tilt angles between 12.5° and 25°; however, further increase in angle brings uneven surface characteristics, indicating poor polishing quality [44]. It is also worth noting that the surface roughness has different levels on the workpiece surface. The smoothest surface was found near the top position of the component. This could be explained by the fact that the bottom surface of the polishing slurry tends to change into solid than the upper fluid layer and, therefore, the cutting pressure on the surface is larger. Similar phenomenon has been observed in other work, where the polishing effect varied upon different locations of gear surfaces [21]. Because of the less contact of the back surface with polishing fluid, the distributed pressure is smaller than the front gear surfaces, and the surface finishing is thus worse. It is also reported by Guo et al. [44] that the over-processing phenomenon at the entrance leads to uneven polishing, namely the edge effect in STP. To realize the uniformity and high quality of surface polishing, a guide block with the same angle as that of the ring cross-section is introduced in the fixture. Considering a series of processing parameters, some researchers extensively utilized the Taguchi experimental design method or the analysis of variance (ANOVA) to explore the optimization of multiple factors involved in the STP [20, 21, 45]. Results showed that by selecting the optimal combination of the polishing parameters, STP is an effective and feasible technique for surface finishing, even with complicated shapes.

6.3.2 Analytical Modeling

It can be seen that experimental investigations require specific workpieces and equipment, which can result in a heavy burden of resources and time. Therefore, numerous works have been performed to develop analytical models with high efficiency and low cost solutions for STP performance, and providing key estimation for the optimal selection of polishing parameters. To identify the polishing mechanism, it is of great significance to study the material removal. The Preston equation is a widely adopted empirical formula relating the MRR to work done by the friction force and guiding the precision finishing [46]. The Preston equation is expressed in Eq. (6.1).

$$\mathrm{MRR} = kPv = k_0 P U_0 \tag{6.1}$$

where k is a proportional constant ($k_0 = k_1 \times k_2 \times k_3$), P is the pressure on the specimen surface, and v is the abrasive velocity. Under specific process parameters, k_1, k_2, and

k_3 are the coefficients corresponding to the specimen material hardness, the coefficient related to abrasive particle size, and the coefficient influenced by other factors, respectively; U_0 is the relative velocity of the polishing fluid to the workpiece surface [19]. The theoretical prediction is normally verified by the experimentally obtained MRR, i.e.,

$$\mathrm{MRR} = \Delta m / \rho S \tag{6.2}$$

where Δm is the weight loss after polishing, ρ is the density, and S is the processing area [31].

Regarding STP, it is also essential to study the fluid field and calculate the pressure acting on the workpiece [45]. According to the rheological flow mechanics, STP suspension can be characterized as non-Newtonian power-law fluid with the assumption of being homogeneous, isotropic, and incompressible in nature [19]. Li et al. [18] firstly developed a mathematical model with dynamic pressure to analytically govern the Reynolds equation for predicting MRR. As an extension to the MRR model, a surface roughness model was then developed, which can predict the surface evolution process. The model was proposed based on the workpiece Brinell hardness, shear thickening mechanism, and plastic indentation on abrasive wear theory. Additionally, Li et al. [27] recently established a subsurface damage predictive model for adaptive shearing-gradient thickening polishing. According to the results, the theoretical calculation is verified by the experiments, being close to that from experimental data, and the maximum difference between experimental and analytical results is no greater than 12.02% [18]. In Zhu et al. [42]'s study, the STP slurry was considered as incompressible viscous laminar flow governed by Navier-Stokes equations, and then the equivalent principal stress, as well as the material removal, was estimated. Nevertheless, it is pointed out that the varying viscosity of non-Newtonian slurry couples with fluid velocity and dynamic pressure, which affects the stress field distribution [39]. Hence, Reynolds approximation in the lubrication-based model cannot make an accurate prediction of MRR due to the overestimation of fluid stress. In a recent study by Zhu et al. [39], a comprehensive model describing the dynamic couplings of pressure and velocity and microscopic abrasive removal mechanism correlating to the suspension rheology is proposed, offering a generic and flexible model for STP process.

6.3.3 Numerical Simulation

With the rapid growth of computational methods and computer science, numerical simulations have been widely used to predict the stress distribution, rheological flow, and material removal behavior, which are quite complicated to measure by direct experimental effort. Considering the multiple influential factors that are discussed in the last section, the numerical study also enables the optimization of polishing parameters more efficiently. Most finite element simulation is carried out by

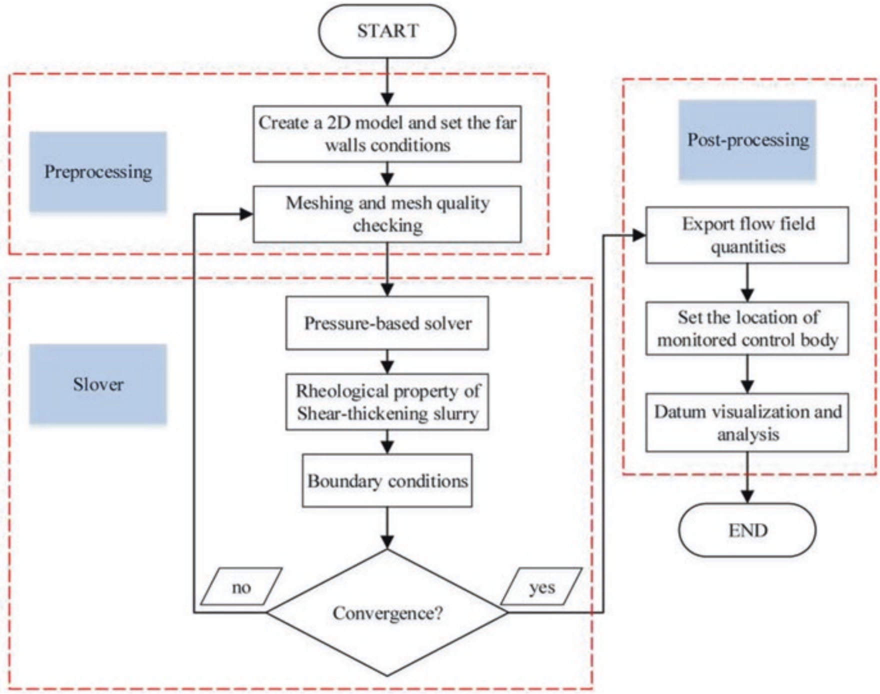

Fig. 6.7 Flowchart of numerical calculation process [44]

computational fluid dynamics (CFD) software such as ANSYS CFX [21, 24], and a representative flowchart of the simulation analysis is demonstrated in Fig. 6.7. In Guo et al. [44]'s work, a 2D model was established to simplify the numerical work with the assumption of a rectilinear flow through the channel. In the literature, as STP is commonly utilized for complex-shaped surfaces, such an assumption is not always valid. Hence, 3D models are more frequently created based on the geometry of the workpiece [24, 47]. Before the simulation work, the STF flow curve is input to the software, which can also be described as the specific consistency coefficient and flow index of the shear thickening slurry [21]. In addition, boundary conditions, including the parameters of the liquid inlet, the liquid outlet, the polishing cup and the workpiece, are required to be specified. Mostly, the constant velocity of low corresponding to the non-Newtonian power-law is set at the inlet, and the outlets are set to constant pressure.

As known from the experimental results, polishing angle heavily influences the flow field distribution of polishing slurry, which affects the velocity and pressure distribution on the workpiece surface. Accordingly, the MRR and surface quality are directly influenced by the pressure and velocity distribution. Therefore, numerical works investigate the distribution of velocity (v) and pressure (P) in terms of different processing parameters [22, 24, 44]. For example, by investigating the normalization of P.v value at different impact angles through numerical methods, it is found that using an inclination angle of 45° would contribute to the highest P.v value and the lowest variance on the surface, as well as the best removal efficiency and polishing quality. The numerical results have shown consistency with the experimental data [44]. Apart from velocity and pressure, the maximum principal stress and maximum tool deformation are also used as output for simulation analysis [39]. Zhu et al. [42] studied the shear stress and equivalent principal stress in a tool contact region with regard to the varying working gap and tool rotation speed. The results also proved the simulation analysis to be a powerful methodology to predict the STF polishing results.

6.3.4 Engineering Applications

STP method, utilizing the shear thickening behavior, has developed recently to process complicated surfaces with high quality, high efficiency, and low cost. However, it should be noted that the quality and efficiency of surface processing are restricted since the material removal is driven by the mechanical action of the abrasives [48]. This is particularly significant for hard and brittle crystals with a lack of chemical mechanisms. Therefore, Li et al. [32] proposed an approach with the combination of shear thickening based micro-cutting and chemo-physical friction for ultra-precision finishing optical materials, lithium niobite ($LiNbO_3$). The formation of chemical soft reaction layers can effectively lower the surface hardness of $LiNbO_3$, realizing the polishing action of the "polymer-Al_2O_3-network." Their results show that an ultra-precision high-accuracy surface with roughness Ra 1.46 nm and low subsurface damage (<5 nm of damage depth) can be attained, proving to be a novel STF processing concept for optical crystal materials.

Regarding the machining of optical materials, another factor that should be taken into account is reducing subsurface damage, which would heavily influence the mechanical strength and optical quality [49]. In Li et al. [32]'s study, a novel adaptive shearing-gradient surface finishing method is first developed for enhanced surface quality and suppressed subsurface damage on $LiNbO_3$. The STP system includes thermo-sensitive particles and a temperature-controlling device, in order to achieve the concept of fluid-workpiece contacting temperature-induced gradient thickening mechanism. The results showed different levels of jamming with changing temperatures, while the subsurface damage depth and surface roughness were lowered to a minimum critical threshold of 1 nm under certain conditions.

In order to improve the efficiency of STP, some researchers observed that the magnetic field could raise the shear rate in STF, thus resulting in a liquid with a higher yield stress, which affects the polishing effect. Ren et al. [50] and Ming et al. [51] introduced carbonyl iron particles into STF, and it was found that the shear thickening behavior of magnetorheological STF contributes to the particle clustering due to magnetic chains and hydrogen bonds. Under the magnetic field, the shear stress becomes higher, and the maximum MRR is approximately 5.96 μm/h, which is 95.4% higher than that of neat STP. In addition, the magnetic-assisted STF did not cause any damage to the processed zirconia surface, providing characteristics of non-destructive, adaptive and ultra-precision processing of ceramic-based brittle and hard materials [52].

Apart from the abovementioned applications of STP, STF was also applied to improve other surface finishing methods. For instance, abrasive flow machining is a technique for polishing complex components by extruding abrasive media. However, conventional abrasive media with shear-thinning properties present poor capacities of anti-deformation and carrying abrasives under high shear rate conditions [53]. By changing media to STF, the MRR increases from 69 to 351 mg/h, and the value of Ra reduces from 19.49 nm to 6.48 nm, appearing with fewer machining strokes. Another concept of using cornstarch mixture in a cutting-based vibration attenuation system was proposed by Wang et al. [37]. In the milling operation of thin-walled structures, vibrations induced by the cutting forces could lead to low surface quality and static deflections. By comparing milled workpieces immersed with and without cornstarch mixture, the average maximum amplitudes of the acceleration signals are decreased by 90% by using the cornstarch loading rate of 48% or more in the slurry.

6.4 Conclusions

This chapter reviews recent advances in developing new surface finishing technology by utilizing STF. It can be stated that a lot of experimental work has demonstrated that the new technology is promising to polish complex structures having curved surfaces. Compared with the conventional mechanical polishing process, it is less dependent on the geometric features of the treated surface. Further, a polishing pad is not required, as the abrasive particles are held by solidified STF. In this case, the polishing process relies on the shear thickening behavior of the STF, depending on operation parameters such as speed and working gap. Besides the experiment work on surface finishing with STF, the chapter also reviews the theoretical modeling for understanding the underlying mechanisms. Finally, some practical applications of this new polishing technology are discussed.

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