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Review

Recent Development of Abrasive Machining Processes Enhanced with Non-Newtonian Fluids

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Abstract: Abrasive machining processes have long been integral to various manufacturing industries, enabling precise material removal and surface finishing. In recent years, the integration of non-Newtonian fluids has emerged as a promising strategy to enhance the performance and efficiency of these processes. This review paper provides a comprehensive overview of the current state of research on abrasive machining processes, including abrasive lapping, abrasive polishing, and chemical mechanical polishing, and then analyzes in detail the abrasive machining processes enhanced with non-Newtonian fluids. It explores the fundamental principles underlying the rheological behavior of non-Newtonian fluids and their application in abrasive machining, with a focus on shear-thickening fluids. The paper will begin by introducing the abrasive machining processes, including abrasive lapping, abrasive polishing, and chemical mechanical polishing. Then, the current research status of non-Newtonian fluids will be comprehensively analyzed, and we will explore the enhancement of abrasive machining processes with non-Newtonian fluids. Finally, the paper will conclude with a discussion of the future directions and challenges in the field of abrasive machining enhanced with non-Newtonian fluids. Overall, this review aims to provide valuable insights into the potential benefits, limitations, and opportunities associated with the use of non-Newtonian fluids in abrasive machining, paving the way for further research and innovation in this promising area of manufacturing technology.

Keywords: abrasive machining processes; abrasive lapping and polishing; non-Newtonian fluids; shear-thickening principle

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1. Introduction

With the continuous development of aerospace and other fields, the processing of high-performance components has become a focus of scholarly research, with both traditional and non-traditional machining methods playing increasingly important roles [1–8]. Abrasive machining processes, as one of the non-traditional methods, have long been integral to precision manufacturing techniques, including lapping and polishing, playing a crucial role in achieving high-quality surfaces [9–13]. Typically, these methods utilize abrasive particles suspended in a carrier medium to meticulously remove material from a workpiece [14,15]. Despite their effectiveness, traditional abrasive machining approaches encounter challenges when striving for specific surface characteristics, particularly in intricate contours, narrow spaces, and inaccessible regions [16–18]. These limitations arise due to the inherent nature of abrasive machining, where achieving uniform material removal across diverse workpiece geometries proves challenging [19,20]. As manufacturing demands evolve towards greater intricacy and miniaturization, there is an increasing need for innovative solutions that can address these challenges and enhance the capabilities of abrasive machining processes.

The integration of non-Newtonian fluids into abrasive machining processes represents a significant advancement in addressing the challenges inherent in traditional methods [21–23]. Unlike Newtonian fluids, which follow linear viscosity patterns, non-Newtonian fluids exhibit diverse rheological behaviors such as viscoelasticity and thixotropy [24,25]. These unique characteristics enable them to respond dynamically to shear forces, adapting their viscosity accordingly. As a result, non-Newtonian fluids can efficiently carry and distribute abrasive particles during machining operations. This dynamic behavior enhances the fluid's ability to penetrate intricate geometries, reach challenging areas, and optimize material removal rates [26]. By effectively controlling the flow and distribution of abrasive particles, non-Newtonian fluids facilitate more uniform and precise machining processes, ultimately leading to improved surface finishes and dimensional accuracy [27–29]. Moreover, the versatility of non-Newtonian fluids allows for tailored formulations to suit specific machining requirements, further enhancing their applicability across a wide range of manufacturing scenarios [30,31]. Therefore, the integration of non-Newtonian fluids presents a promising avenue for advancing abrasive machining processes and offering greater flexibility, efficiency, and precision in achieving desired machining outcomes.

In recent years, there has been a notable surge in interest surrounding the utilization of non-Newtonian fluids in abrasive machining processes, driven by their capacity to augment material removal rates, refine surface finish, and prolong tool lifespan. These fluids offer a customizable approach to address specific machining challenges by allowing adjustments to their rheological attributes, including viscosity and shear-thinning characteristics. Through meticulous manipulation of parameters such as the type and concentration of abrasive particles, alongside the rheological profile of the non-Newtonian fluid, engineers and manufacturers can fine-tune the machining process to achieve precise outcomes tailored to their requirements [32]. This adaptability not only enhances the efficiency and effectiveness of abrasive machining but also enables optimization across diverse applications and materials. Moreover, the ability to tailor non-Newtonian fluids to specific machining tasks facilitates greater control over process variables, leading to enhanced repeatability and consistency in production. As a result, the integration of non-Newtonian fluids into abrasive machining processes represents a promising avenue for advancing manufacturing capabilities, offering a versatile and customizable solution to meet the evolving demands of precision manufacturing across various industries [33].

Thus, this review paper will first introduce the abrasive machining processes, including abrasive lapping, abrasive polishing, and chemical mechanical polishing. Then, the current research status of non-Newtonian fluid will be comprehensively analyzed, and we will explore the enhancement of abrasive machining processes with non-Newtonian fluids. Finally, the paper will conclude with a discussion of the future directions and challenges in the field of abrasive machining enhanced with non-Newtonian fluids.

2. Abrasive Machining Processes

Abrasive lapping and polishing stand as indispensable processes in the realm of precision machining and surface finishing, serving as linchpins in the quest for superior surface quality across a multitude of industrial sectors [34,35]. Their significance lies in their ability to meticulously refine surfaces to meet stringent specifications demanded by industries such as aerospace, automotive, optics, and electronics. Chemical mechanical polishing further advances the precision abrasive machining domain by operating at the atomic level, enabling the attainment of ultra-smooth surfaces with unparalleled accuracy [36]. In aerospace applications, these processes are pivotal for ensuring the aerodynamic efficiency of components, while in automotive manufacturing, they contribute to enhancing the performance and longevity of critical engine and transmission parts. Optics industries rely on abrasive lapping and polishing to fabricate precision lenses and mirrors for optical instruments, telescopes, and cameras, whose surface smoothness directly impacts performance. Similarly, the electronics sector benefits from these processes in producing

semiconductor wafers with immaculate surface finishes, crucial for the reliable operation of integrated circuits and microelectronics.

2.1. Abrasive Lapping

Abrasive lapping is a precision machining technique used to remove surface imperfections such as scratches, nicks, and roughness from the surface of a workpiece. It involves the use of abrasive particles bonded on a lapping plate; the workpiece is moved against the rotating lapping plate in a controlled manner, allowing the abrasive particles to abrade the surface and achieve the desired finish. The goal of abrasive lapping is to create a flat and smooth surface with high efficiency and minimal surface defects. Figure 1 shows a schematic representation of the bonded abrasive lapping process [37]. Its movement setup mainly consists of two motors which control the rotation of the lapping plate and the workpiece clamped by a fixture, respectively. The material can be removed by the cutting action of the diamond abrasives that are embedded on the lapping plate. Dong et al. [38] conducted a study on the removal mechanisms and characteristics of SiC and molten silica using fixed abrasive particles, analyzing the material removal mechanisms of fixed abrasives from a fracture mechanics perspective. The results indicate that at smaller cutting depths, the cutting depths for silicon carbide and molten silica are approximately 22 nm and 27 nm, respectively, facilitating plastic removal. The critical particle sizes for the transition from brittle fracture to ductile fracture for silicon carbide and fused quartz are 9.56 μm and 0.53 μm, respectively, which can reduce surface roughness and minimize subsurface damage.

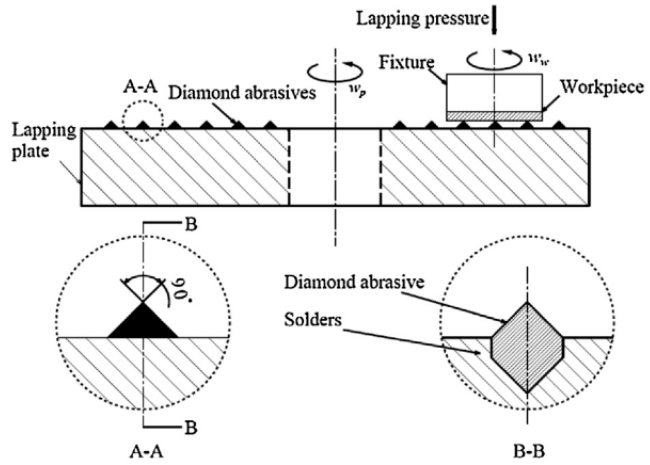


Figure 1. Schematic representation of the abrasive lapping process [37].

2.2. Abrasive Polishing

Abrasive polishing is a surface finishing process that follows abrasive lapping to further refine the surface quality of the workpiece. Abrasive polishing typically involves the use of polishing pads or abrasive films along with a polishing compound or slurry to remove any remaining surface imperfections and enhance the surface finish. Unlike abrasive lapping, which focuses on material removal, abrasive polishing aims to achieve a mirror-like finish by smoothing out surface irregularities and reducing surface roughness to nanometer-scale levels. As shown in Figure 2, the workpiece, fused silica, adhered to the polishing head is placed on the polishing pad under a certain pressure, and the polishing head rotates at a constant speed, while the polishing slurry drops on the polishing pad at a certain speed. In this process, the abrasive will leave certain scratches on the fused silica, which should be avoided as much as possible during the polishing process [39]. Su et al. [40] conducted a study on the C and Si faces of SiC substrates, primarily focusing on the influence of process parameters such as chuck speed, rotational speed of the turntable, polishing pressure, and abrasive particle size on material removal rate (*MRR*) and surface

roughness in diamond abrasive-based polishing processes. The research findings revealed that the chuck speed and polishing pressure had a significant impact on *MRR*, while the rotational speed of the turntable had a minor effect. *MRR* increased with the increase in abrasive particle size, disc speed, and polishing pressure. The influence of abrasive particle size, disc speed, and polishing pressure on surface roughness was found to be insignificant.

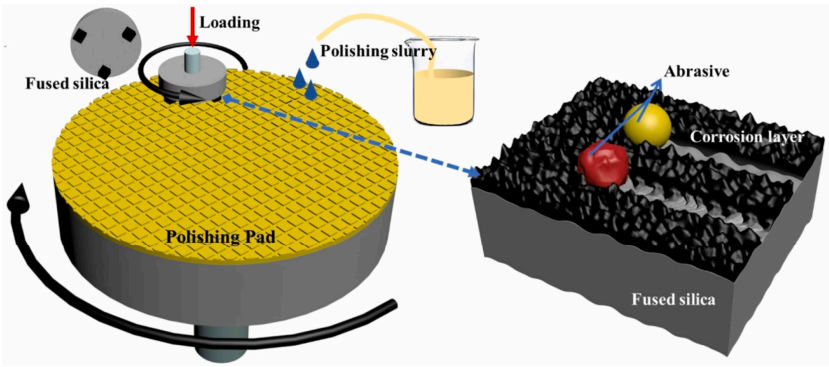


Figure 2. Schematic representation of the abrasive polishing process [39].

2.3. Chemical Mechanical Polishing

Chemical mechanical polishing (CMP) is a hybrid machining technique that combines chemical corrosion with mechanical abrasion using nano-abrasives to remove material at the nanometer and atomic scales [41,42]. As one of the core technologies in integrated circuit manufacturing, CMP is the only commercially available polishing method capable of simultaneously addressing both local and global planarization of semiconductor wafers. A typical CMP system, as illustrated in Figure 3, comprises a wafer carrier, polishing pad, polishing platen, and slurry system. During the polishing process, the polishing solution chemically reacts with surface contaminants on SiC wafers to transform them into an oxidized layer that is more easily removed by hard abrasive particles. Subsequently, under the relative motion between the polishing pad and the wafer carrier, the hard abrasive particles remove the oxidized layer. Then, the polishing pad strips away the oxidized layer from the surface of the workpiece, exposing the unreacted surface of the wafer, ensuring the smooth progress of the CMP process.

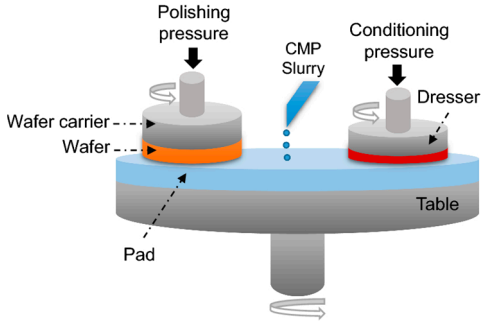


Figure 3. Schematic representation of the CMP process.

Xie et al. [43] developed a novel polishing slurry and discovered that potassium ions effectively enhance the *MRR* during the CMP process. This slurry consists of monodisperse colloidal silica, organic/inorganic acids, and inorganic salts. Experimental results demonstrated excellent stability and dispersion of colloidal silica in the developed slurry. When the potassium ion concentration reached 125 mmol/L, the *MRR* of CMP silicon wafers increased by 53.42%, reaching 1778.71 Å/min. Additionally, the surface roughness Sa also showed slight improvement, reaching 0.887 nm. The CMP mechanism was investigated using X-ray photoelectron spectroscopy, friction coefficient measurements, and electrochemical analysis. The results revealed that potassium ions can alter the electrical

properties of the soft layer formed on the silicon wafer surface, dissolve the soft layer, and oxidize the silicon surface. Cui et al. [44] developed an environmentally friendly CMP polishing slurry composed of cerium dioxide, hydrogen peroxide, sodium pyrophosphate, sodium carboxymethyl cellulose, sodium carbonate, and deionized water. After CMP, measurements were conducted on a 50 × 50 μm^2 area, revealing a surface roughness Sa of 0.067 nm, achieving sub-angstrom surface quality. Transmission electron microscopy showed a damage layer thickness of 2.8 nm after CMP.

In summary, based on above discussions it can be found that the characteristics of slurry fluids play a crucial role in affecting abrasive machining processes, and most of the slurry fluids are Newtonian fluids, which exhibit a linear relationship between shear stress and shear rate. However, non-Newtonian fluids demonstrate more complex behavior. They can exhibit shear-thinning or shear-thickening behavior, where the viscosity decreases or increases with increasing shear rate, respectively. Shear-thinning, or pseudoplastic behavior, occurs when the microstructural elements like polymer chains or particles align with the direction of flow, reducing internal friction and thus decreasing viscosity as shear rate increases. In contrast, shear-thickening, or dilatant behavior, arises when the applied shear causes suspended particles to form temporary clusters or aggregates, which increases resistance to flow and consequently raises viscosity with increasing shear rate. These mechanisms are influenced by the composition and interactions within the fluid, leading to complex flow behaviors. Additionally, non-Newtonian fluids may display viscoelastic properties, meaning they exhibit both viscous and elastic characteristics under stress. These unique rheological properties of non-Newtonian fluids influence various aspects of abrasive machining processes, such as lubrication, material removal rates, surface quality, and tool wear. Understanding and controlling the behavior of non-Newtonian fluids are therefore essential for optimizing abrasive machining operations and achieving desired machining outcomes.

3. Characteristics of Non-Newtonian Fluids

Most substances of low molecular weight, such as organic and inorganic liquids, low-molecular-weight inorganic salt solutions, molten metals, and gases, exhibit Newtonian flow characteristics. This means that under constant temperature and pressure, the shear stress is proportional to the shear rate under simple shear or shear stress, with the proportionality constant denoted as viscosity (η). Although the concepts of flow and viscosity predate Newton, these fluids are generally referred to as Newtonian fluids. For most liquids, viscosity decreases with increasing temperature and increases with increasing pressure. For gases, viscosity increases with increasing temperature and pressure. Generally, the higher the viscosity of a substance, the greater its resistance to flow (making it more difficult to pump out) [45]. Table 1 provides typical viscosity values for commonly used fluid fractions. Looking from top to bottom in Table 1, viscosity increases by several orders of magnitude. Therefore, it can be considered that a solid can be viewed as a fluid with infinite viscosity. Thus, the distinction between fluid and solid is not always clear-cut.

Table 1. Values of viscosity for common fluids at room temperature [46].

Fluids	η (Pa·s)
Air	10^{-5}
Water	10^{-3}
Alcohol	1.2×10^{-3}
Mercury	1.5×10^{-3}
Glycol	20×10^{-3}
Olive oil	0.1
Glycerol	1.5
Honey	10
Corn syrup	100
Asphalt	10^{8}
Fused glass	10^{12}

The following section outlines the current research status of non-Newtonian fluids and compares the rheological characteristics of several commonly encountered polymer suspensions, namely non-Newtonian power-law fluids. Parameters such as critical shear rate and maximum attainable viscosity are compared, providing valuable insights for selecting shear-thickening phases in shear-thickening polishing slurries.

Yu [47] investigated a series of suspensions by combining different-sized silica (SiO_2) particles with polyethylene glycol (PEG) using rheological methods to systematically study the effect of particle size, particle concentration, temperature, and shear mode on the shear-thickening behavior of SiO_2 fluids. The study found that with the increase in SiO_2 particle concentration, the viscosity and critical shear rate of the fluid increased, resulting in a more pronounced shear-thickening phenomenon. The rheological properties of the SiO_2 fluid were highly sensitive to shear rate, with the system viscosity rapidly changing with shear. Networks formed by small nanoparticles were more easily restored after shear disruption. The relationship between viscosity and shear rate for SiO_2/PEG fluids of different particle sizes and concentrations is depicted in Figure 4. It is evident from the figures that SiO_2/PEG with larger particle sizes (micron level) exhibited less noticeable shear-thickening effects and lower viscosity, whereas SiO_2/PEG with smaller particle sizes (nanometer level) showed significant shear-thickening effects with varying concentrations.

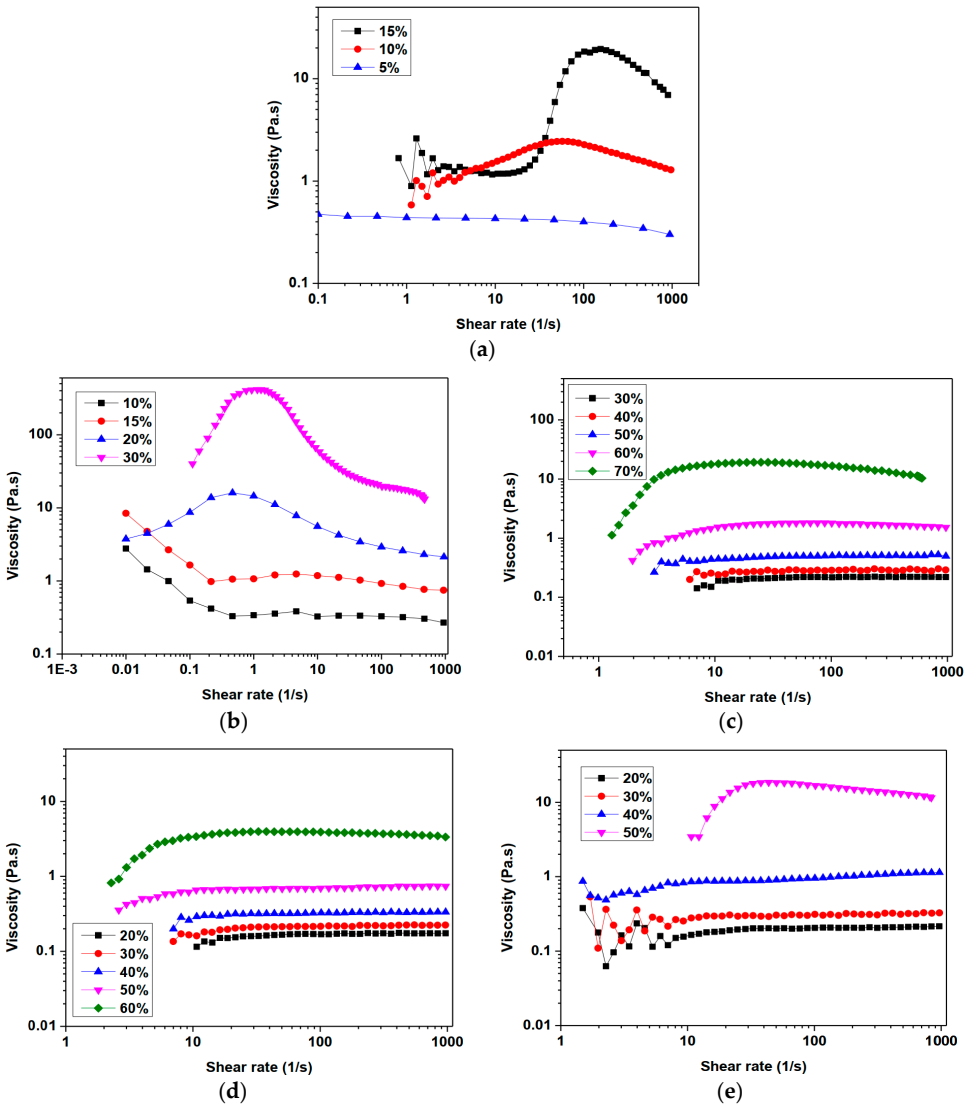


Figure 4. Plots of viscosity versus shear rate for the silica fluids with different particle size andconcentration: (**a**) 15 nm, (**b**) 30 nm, (**c**) 2 μm, (**d**) 5 μm, (**e**) 10 μm [47].

Madraki et al. [48] introduced large non-Brownian spheres into corn starch suspensions and found that this addition significantly enhanced the shear-thickening effect, leading to a shift towards lower critical shear rates for shear-thickening transition. The corn starch used in the experiment consisted of irregularly shaped particles ranging from 5 to 20 μm, with an average diameter of 13 μm. The viscosity–shear rate curves for corn starch-water suspensions with different volume fractions are depicted in Figure 5.

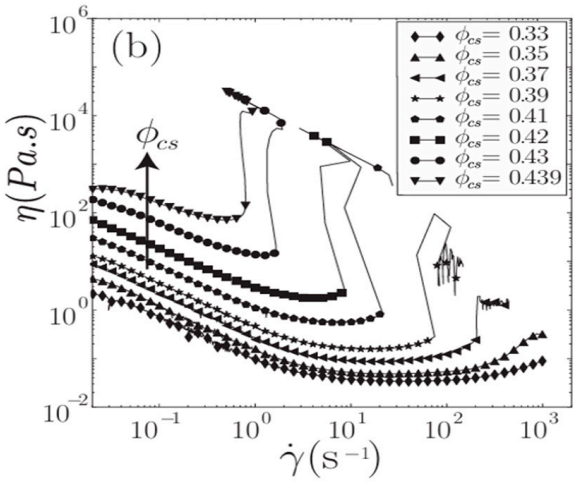


Figure 5. Curves of corn starch water suspension, viscosity and shear rate with different volume fractions [48].

Jiang et al. [49] employed steady-state and dynamic rheological methods to investigate the rheological behavior of poly(methyl methacrylate) (PMMA) particle suspensions in glycerol-water mixtures. The viscosity–shear rate curves for suspensions with different PMMA volume fractions are depicted in Figure 6, with PMMA particle sizes at 14 μm. It was observed that some suspensions exhibited pronounced shear-thickening effects. The variation of viscosity with glycerol volume fraction and glycerol–water ratio was discussed. The influence of volume fraction can be qualitatively explained by a clustering mechanism, attributed to the transient hydrodynamic clustering effect. Furthermore, the impact of interactions between glycerol–water mixtures and PMMA particles on shear thickening was investigated by varying the ratio of glycerol to water.

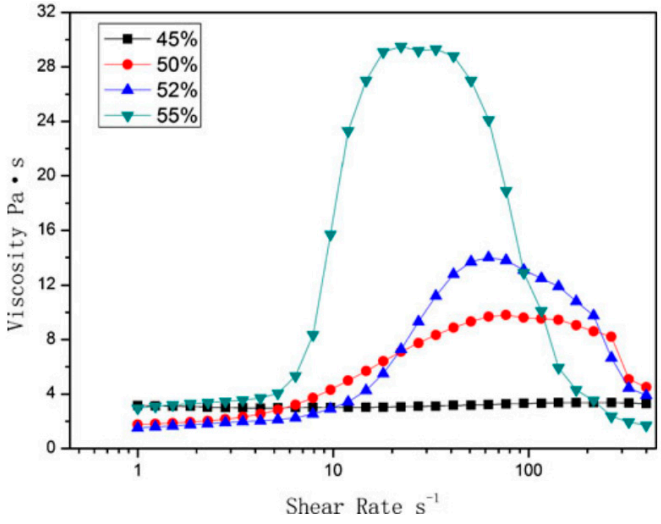


Figure 6. Viscosity and shear rate of suspensions with different PMMA volume fractions [49].

Dong [50] investigated a polishing base liquid composed of polyhydroxy high polymer (PHHP) as the shear-thickening phase and water as the solvent. The basic preparation

method of the polishing liquid was determined, and the influence of PHHP particle size and concentration on the rheological properties of the polishing base liquid was tested using a rotational rheometer. The analysis results indicated that the polishing base liquid exhibited good shear-thickening characteristics when the mass fraction of dispersed phase particles was 50% and the particle size ranged from 5 to 15 μm. The viscosity–shear rate relationship curves for PHHP polishing base liquids of different concentrations are shown in Figure 7.

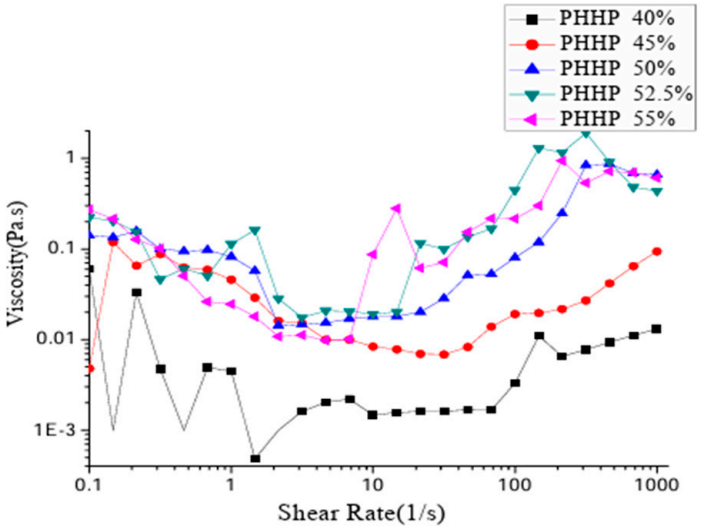


Figure 7. Curves of viscosity and shear rate of different concentrations of PHHP polishing solution [50].

The rheological data of shear thickening base liquids with similar particle sizes and concentrations from the aforementioned articles were selected for comparison, and the rheological characteristics of non-Newtonian power-law fluids with similar shear-thickening phase concentrations were compared (Table 2). From the comparison in the table below, it can be observed that, under conditions where the particle sizes and concentrations of the four shear-thickening phase particles are similar, the corn starch suspension is the least sensitive to changes in shear rate, while achieving a maximum viscosity 30 times that of the PMMA suspension.

Table 2. Comparison of rheological properties of non-Newtonian fluids with similar shear thickening phase concentrations.

Non-Newtonian Fluids	Particle Size (μm)	Concentration	Critical Shear Rate (s^{-1})	Maximum Viscosity (Pa·s)
Corn starch suspension	13	41%	20	1000
PMMA suspension	14	45%	5	29
SiO_2/PEG suspension	14	40%	2	1
PHHP suspension	14	40%	1.5	0.01

Comparison was conducted among the rheological data of shear-thickening base fluids with the best performance from the aforementioned articles, and the results are summarized in Table 3. It was observed that under the selected optimal rheological data of the shear-thickening base fluids, while corn starch suspension exhibited the least sensitivity to changes in shear rate, it achieved a maximum viscosity 2.5 times higher than that of the SiO_2/PEG suspension.

Table 3. Comparison of optimal rheological properties of non-Newtonian fluids.

Non-Newtonian Fluids	Particle Size (μm)	Concentration	Critical Shear Rate (s^{-1})	Maximum Viscosity (Pa·s)
Corn starch suspension	13	41%	20	1000
PMMA suspension	14	55%	5	29
SiO_2/PEG suspension	0.03	30%	1	400
PHHP suspension	14	52.5%	8	2

4. Abrasive Machining Processes with Non-Newtonian Fluids

4.1. Shear-Thickening Principle

Simple shear can be decomposed into pure rotational strain and pure shear strain. Apart from rotational motion, the atoms in the system also compress or extend along the ±45° direction. Therefore, after shear-thickening fluids are subjected to external shear, thickening particles form force chain clusters with increasing shear rate, intensifying thickening effects. At low shear rates, the viscosity of the polishing fluid is low, and frictional contacts are infrequent. However, at high shear rates, frictional contacts between liquid layers occur frequently, forming a highly congested network of frictional contacts. At this point, there are not too many thickening particles in the polishing base fluid to encapsulate abrasive particles, resulting in a stronger thickening effect (see Figure 8).

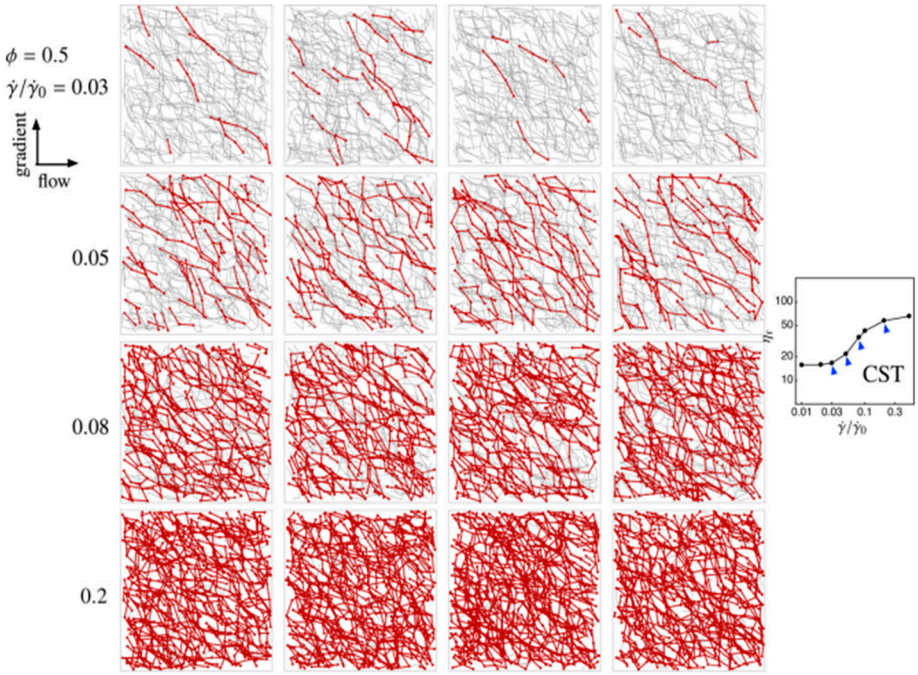


Figure 8. Schematic diagram of the contact force chain for the shear-thickening effect [51].

Shear-thickening fluids are unique energy-absorbing materials that consist of a large number of dispersed micro-particles within a non-Newtonian medium [52,53]. Unlike Newtonian fluids with fixed rheological properties, non-Newtonian fluids exhibit characteristics that are contrary to conventional understanding. Specifically, non-Newtonian fluids with shear-thickening (ST) rheological properties demonstrate a significant increase in viscosity with higher shear rates. These fluids have garnered attention in manufacturing engineering and protective equipment fields, such as shock absorbers, bulletproof vests and helmets, and polishing slurries [54]. Numerous research efforts have explored several typical mechanisms of shear thickening, such as the ordered–disordered transition, clustering, and jamming, as shown in Figure 9, indicating that shear-driven particle frictional

contact is a key mechanism leading to viscosity increase. Wagner et al. [55] extensively explained that the ST phenomenon arises from increased random interactions between particles with increasing shear stress, leading to aggregation in colloidal dispersions. Macroscopic properties indicate that the viscosity of dispersed systems first decreases and then suddenly increases, with the shear-thickening polishing fluid exhibiting a critical shear rate. Below the critical shear rate, viscosity decreases from an initially high value to a minimum viscosity. Above the critical shear rate, polymers form "particle clusters" with abrasives, resulting in an increase in viscosity from the minimum viscosity to the maximum viscosity throughout the entire shear-thickening process.

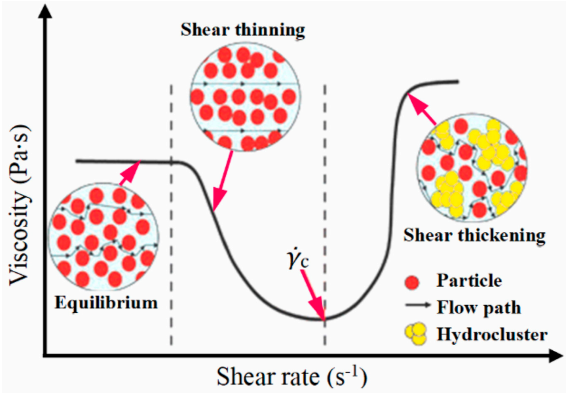


Figure 9. Flow states and cluster effects in non-Newtonian fluid [56].

4.2. Comparison between Shear Thickening and Traditional Abrasive Machining Processes

As shown in Figure 10, in the abrasive lapping process, material removal primarily occurs through actions such as cutting, scratching, and plowing by the abrasive particles. When manufacturing fixed abrasive lapping discs, the depth and quantity of particle embedding are random, resulting in minimal contribution from the abrasive particles to material removal during the lapping process. Non-uniform and inconsistent distribution of particles and embedding depth can lead to localized pressure concentration [57]. Moreover, the process of feeding the workpiece can easily cause abrasive loss from the lapping disc. Consequently, the fixed abrasive lapping process is highly variable due to these factors [58].

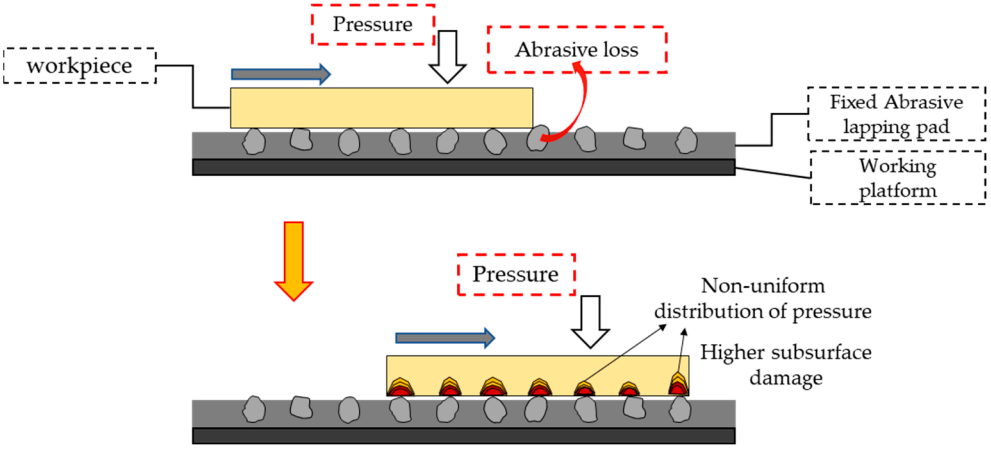


Figure 10. Working principle of the abrasive lapping process.

In free abrasive polishing processes, as shown in Figure 11, material removal primarily occurs through rolling and pressing actions exerted by the abrasive particles. Only abrasive particles with larger diameters can effectively contribute to material removal, compared to smaller ones. In this regard, compared to fixed abrasive lapping, the surface pressure distribution in free abrasive polishing is relatively uniform [59]. The rolling action predom-

inantly induces material removal through micro-scale brittle fracture. While the surface pressure distribution is relatively uniform, it can still result in certain subsurface damage.

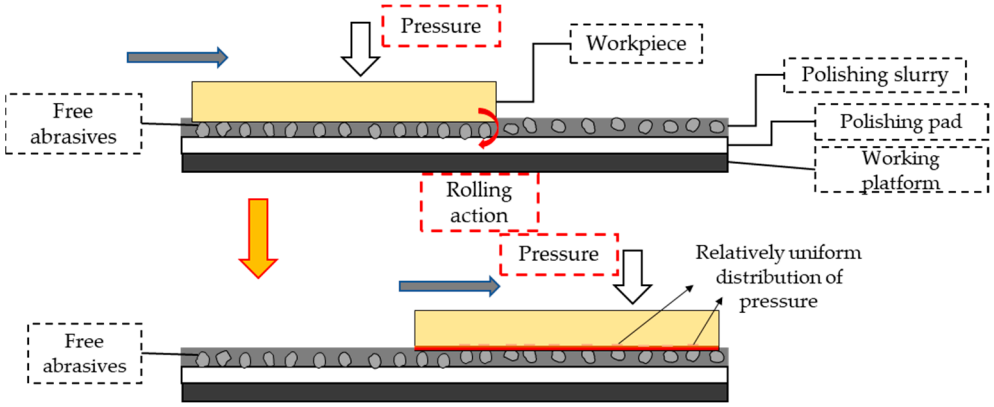


Figure 11. Working principle of the abrasive polishing process.

During shear-thickening polishing processes, as shown in Figure 12, shear-thickening polishing fluid is injected into the shear-thickening polishing baseplate. A certain amount of the polishing fluid overflows, immersing the workpiece. At this point, the clamping tool applies pressure to the workpiece, causing relative motion between the workpiece and the rotating worktable. Under high shear rates, the shear-thickening fluid between the workpiece and the polishing pad undergoes shear-thickening phenomena [60]. A shear-thickening elastic thin layer forms beneath the workpiece, where abrasive particles are held by shear-thickening nanoparticles. The closer these nanoparticles are to the workpiece, the more pronounced the shear-thickening phenomenon, resulting in greater particle retention force. Consequently, a semi-adherent flexible abrasive forms in the shear-thickening thin layer closest to the workpiece. During this process, the workpiece undergoes grinding, with the spindle rotating and the workpiece feeding. As the workpiece advances, the position of the shear-thickening elastic thin layer changes accordingly. Meanwhile, the polishing fluid returns to a free state at the location where shear thickening occurred previously. Due to the even surface pressure distribution in this semi-bound flexible polishing, the resulting subsurface damage is relatively low. When the relative shear rate between the workpiece and the polishing pad is low, the shear-thickening elastic thin layer disappears, and the abrasive particles return to a free state throughout the flow field [61]. However, the polishing base fluid still retains some viscosity. This process resembles free abrasive polishing, but with comparatively lower subsurface damage than in conventional free abrasive polishing.

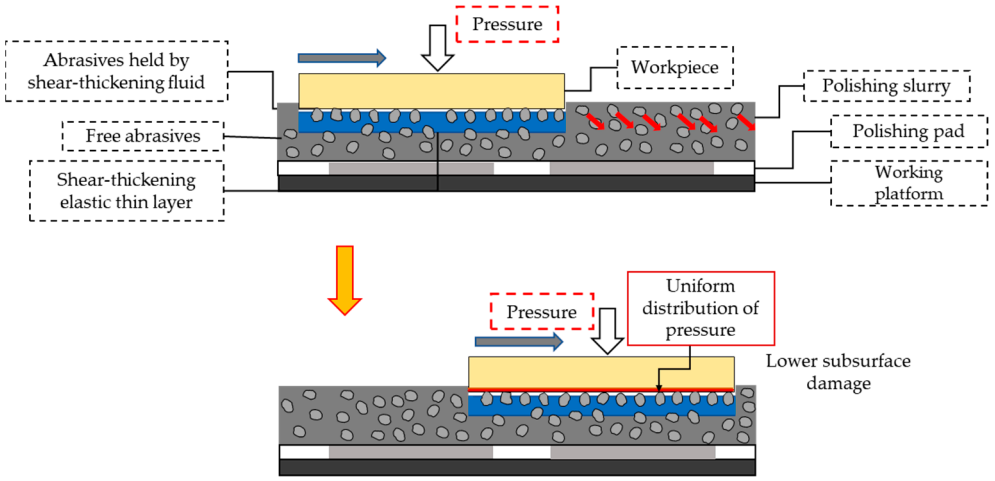


Figure 12. Working principle of the shear-thickening polishing process.

In summary, fixed abrasive lapping primarily targets the peaks on the workpiece surface, whereas free abrasive polishing removes material from the entire global surface of the workpiece. Both the fixed abrasive lapping and free abrasive polishing processes result in a certain degree of subsurface damage, mainly due to the dominance of mechanical action by the abrasives during the polishing process. In contrast, in CMP, the mechanical action of the abrasives and the chemical action of the polishing slurry alternate. The polishing slurry catalytically oxidizes the surface of the workpiece, making it easier for the abrasives to remove material from the workpiece surface, thereby weakening the mechanical action of the abrasives. Therefore, in CMP, a good polishing process typically involves an equal contribution from physical and chemical removal. As for shear-thickening polishing, it lies between pure mechanical polishing and chemical mechanical polishing. This method utilizes the characteristics of non-Newtonian fluid shear thickening. Consequently, in a polishing process where shear thickening is more pronounced, the subsurface damage resulting from abrasive mechanical action is reduced. Thus, in an integrated lapping and polishing process, minimizing subsurface damage from lapping and polishing processes can provide a low-subsurface-damage substrate for subsequent CMP processes. Compared to pure abrasive lapping and polishing, this approach offers significant advantages.

4.3. Potential of Abrasive Machining with Non-Newtonian Fluids

The prospects of abrasive machining enhanced with non-Newtonian fluids, particularly through methods like shear thickening, present a promising avenue for advancing manufacturing processes. These innovative approaches offer the potential to improve material removal rates, surface finish quality, and overall machining efficiency. By leveraging the unique rheological properties of non-Newtonian fluids, such as shear thickening, researchers and engineers can tailor the fluid's behavior to optimize machining performance for specific applications and materials. However, along with these promising prospects come notable challenges. One significant challenge lies in understanding and controlling the complex rheological behaviors of non-Newtonian fluids, especially under varying conditions encountered during abrasive machining operations. Effectively addressing the challenges associated with understanding and controlling the complex rheological behaviors of non-Newtonian fluids in abrasive machining operations requires a multifaceted approach. Advanced rheological characterization techniques are essential to capture the fluid's response under different shear conditions, providing detailed insights into its behavior. Computational modeling and simulation can predict how the fluid will behave in various machining scenarios, allowing for the optimization of fluid formulations and process parameters. Additionally, real-time monitoring and adaptive control systems can adjust operating conditions dynamically to maintain optimal performance. Collaboration between material scientists, engineers, and process operators ensures that theoretical insights are translated into practical solutions, ultimately enhancing the efficiency and quality of manufacturing processes. Additionally, achieving consistent and predictable results across different machining scenarios remains a challenge, requiring further research into fluid formulation and process optimization. Moreover, the integration of non-Newtonian fluids into existing machining systems may require modifications and adaptations, adding complexity to implementation. Despite these challenges, the potential benefits of abrasive machining enhanced with non-Newtonian fluids are considerable, offering opportunities for improved precision, productivity, and cost-effectiveness in manufacturing processes. Continued research and innovation are essential to overcome these challenges and fully realize the transformative potential of non-Newtonian fluid-based abrasive machining techniques.

5. Summary

In conclusion, the integration of non-Newtonian fluids into abrasive machining processes offers significant potential for enhancing material removal rates, surface quality, and process stability. Through a comprehensive investigation of various abrasive machining

techniques enhanced with non-Newtonian fluids, including shear-thickening methods, this review has highlighted the promising advancements and key findings in this field. The rheological behavior of non-Newtonian fluids, particularly shear-thickening fluids, has been elucidated, providing a fundamental understanding of their role in abrasive machining. Experimental studies have demonstrated the effectiveness of non-Newtonian fluid-enhanced abrasive machining in improving machining performance and achieving superior surface finishes. However, challenges such as fluid formulation, stability, and compatibility with existing machining equipment remain to be addressed. Future research efforts should focus on optimizing fluid properties, exploring novel fluid formulations, and developing advanced machining strategies to fully harness the potential of non-Newtonian fluids in abrasive machining. Overall, this review underscores the importance of continued research and innovation in this area to advance the state of the art in abrasive machining technology and meet the evolving demands of modern manufacturing processes.

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