International Journal of Scientific Engineering and Science
Volume 9, Issue 5, pp. 20-28, 2025.
ISSN (Online): 2456-7361

A Comprehensive Review of Polishing Methods for Curved Optical Surfaces

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Abstract— *Attaining ultra-smooth surface finishes and high-precision geometries is a fundamental requirement in the manufacturing of high-performance optical lenses. While conventional polishing techniques such as mechanical polishing (MP) and chemical mechanical polishing (CMP) have been extensively adopted, they present notable limitations, especially when applied to soft polymeric materials like Polymethyl Methacrylate (PMMA) or lenses with complex freeform surfaces. This review explores recent technological advancements in optical lens finishing, focusing on cutting-edge, non-contact polishing methods including Ion Beam Figuring (IBF), Laser Polishing (LP), Fluid Jet Polishing (FJP), and particularly Magnetorheological Finishing (MRF). These emerging technologies offer superior control over material removal rates, enabling the high-precision processing of delicate materials and non-conventional geometries, with surface roughness well below the nanometer scale and accuracy in the nanometric range. Special emphasis is placed on the unique advantages of MRF in polishing PMMA lenses, where the use of magnetically responsive fluids allows for finely tunable shear forces. This minimizes mechanical stress on the substrate while achieving high-fidelity surface finishes. Additionally, the expanding scope of MRF applications in the fabrication of PMMA-based optics for augmented/virtual reality (AR/VR) systems, medical instrumentation, and miniaturized photonic sensors is discussed. Finally, the paper outlines promising future directions in the field, including the refinement of magnetorheological flow modeling, the adoption of advanced nanoscale abrasive materials (e.g., silica-coated or diamond-magnetic composites), integration of real-time in-situ metrology for closed-loop process control, and the development of compact, adaptive MRF platforms suitable for micro-optical and freeform lens fabrication. These innovations collectively pave the way for the next generation of optical components, distinguished by exceptional surface quality and enhanced functional capabilities.*

Keywords— *Lens Manufacturing, Magnetorheological Finishing, Fluid Jet Polishing, Laser polishing, Ion Beam Figuring, Chemical Mechanical Polishing.*

I. Introduction

Optical lenses, essential for manipulating light through convergence and divergence, are fundamental components across a vast range of systems—from everyday eyeglasses to sophisticated scientific instruments such as microscopes and telescopes [1-4]. The optical performance of these systems is highly dependent on the surface quality of the lenses, defined by ultra-smooth surface roughness and high form accuracy. Any surface irregularities can introduce unwanted light scattering, reduce contrast, and significantly impair overall system performance. Consequently, the final surface finishing step, particularly polishing, is critical for ensuring the quality and functionality of precision optical elements.

For decades, conventional polishing methods such as Mechanical Polishing (MP) and Chemical Mechanical Polishing (CMP) have been the cornerstone of optical manufacturing. MP employs a compliant pad combined with abrasive particles and is noted for its simplicity and versatility across various materials. CMP, by integrating mechanical abrasion with chemical reactions, achieves superior surface smoothness and is especially effective for planar surfaces in semiconductor and flat optical substrate fabrication. However, these traditional approaches encounter significant challenges when applied to soft, deformable polymers such as Polymethyl methacrylate (PMMA), or when nanometric surface accuracy is required on complex geometries. The substantial mechanical forces involved in MP can induce surface deformation or damage in soft substrates, while CMP often lacks uniformity when dealing with intricate curved surfaces [5-9].

To address these limitations, a suite of advanced polishing technologies has been developed, offering innovative solutions for the surface finishing of optical lenses. Notable among these are Ion Beam Figuring (IBF) [10], a non-contact method utilizing high-energy ion beams for material removal with sub-micrometer precision; Laser Polishing (LP), which leverages localized laser-induced melting to smooth surfaces [11, 12]; and Fluid Jet Polishing (FJP), where abrasive-laden fluid jets are used to process complex surface profiles with minimal mechanical stress [13, 14]. Each technique presents unique advantages tailored to specific applications, all aiming to achieve ever-greater surface quality and form precision.

Of particular interest is Magnetorheological Finishing (MRF), an emerging technology demonstrating significant promise, especially for the polishing of soft polymers like PMMA [15-17]. MRF operates by modulating the viscosity of a magnetorheological fluid—composed of magnetic particles suspended in a carrier liquid—through an external magnetic field. This mechanism allows for highly controlled, gentle material removal, minimizing the risk of surface damage or distortion. PMMA, known for its light weight, high optical transparency, and ease of processing, is increasingly utilized in medical devices, augmented/virtual reality (AR/VR) optics, and photonic sensors. However, its low hardness and susceptibility to thermal and mechanical stresses render traditional polishing techniques inadequate.

This review aims to provide a comprehensive analysis of modern optical lens polishing technologies, with a particular emphasis on the application of MRF for finishing PMMA optical components. We explore the fundamental working principles of MRF, evaluate its effectiveness in achieving sub-

Volume 1, Issue 1, pp. xx-xx, 2017.
ISSN (Online): 2456-7361

nanometer surface roughness and high form accuracy on PMMA based on recent research, and discuss the expanding application scope of MRF in precision optics manufacturing. Finally, future directions are outlined, including optimization of MRF process modeling, development of novel nano-abrasives, integration of in-situ metrology for automated feedback control, and the design of miniaturized, flexible MRF systems for micro-optical lens fabrication—paving the way for next-generation high-performance optical components.

II. Lens Manufacturing Process

In the production of precision optical lenses, the polishing sequence is central to achieving the surface quality and optical performance required. Fig.1 illustrates a typical end-to-end workflow, spanning from raw blank preparation through final inspection and packaging. This multi-stage process must rigorously satisfy tight optical tolerances at each step.

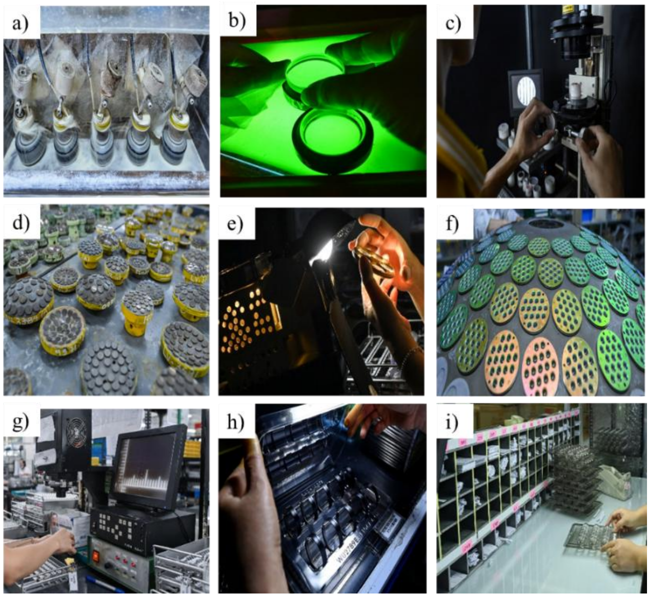

Fig. 1. Stages in Optical Lens Production (a) Rough grinding; (b) Fluorescent defect inspection; (c) Fine-grind alignment; (d) Fine grinding; (e) Polishing; (f) Cleaning & sorting; (g) Automated metrology; (h) Ultrasonic wash; (i) Classification & packaging.

The initial stage (Fig. 1a) involves primary mechanical processing, encompassing coarse grinding, fine grinding, and preliminary polishing. Lens blanks are mounted on rotating holders and processed using abrasive materials to remove excess material, shape the basic lens geometry, and prepare the surface for subsequent precision processing stages. This cycle typically lasts between 2.5 and over 4 minutes, depending on the material properties and lens dimensions. Following grinding, the lenses undergo preliminary surface inspection (Fig. 1b) using fluorescent illumination to detect surface defects such as microcracks, air bubbles, or foreign inclusions. This step ensures that only quality-compliant blanks proceed to the next stages of fabrication. Subsequently, the absolute surface accuracy is evaluated (Fig. 1c) using specialized metrology instruments, typically employing interferometers or high-resolution optical sensors to assess surface curvature, decentration, and flatness post-pre-polishing. The fine grinding stage (Fig. 1d) utilizes advanced machinery and finer abrasive particles to improve geometric precision and minimize surface irregularities. This step is critical for preparing the lens for the ultra-precision polishing phase. After passing intermediate inspections, the lenses are mounted in a precision jig for functional thin-film deposition (Fig. 1e). This coating process enhances optical performance by adjusting the transmission coefficient and reducing surface reflectivity. As shown in Fig. 1f, the lenses are completed with dual-side multilayer coatings, typically consisting of 7 to 12 alternating layers. These coatings optimize light transmission, suppress unwanted reflections, and provide protection against environmental factors. Common deposition technologies include thermal evaporation, sputter deposition, and chemical vapor deposition (CVD). Once coated, lenses undergo post-coating centration measurement (Fig. 1g) to ensure alignment between the optical and mechanical axes—an essential requirement for high-precision optical systems. The final inspection (Fig. 1h) is conducted before packaging. Quality control is performed at least three times throughout the production line to ensure reliability and consistency of the optical components. Lastly, packaging and labeling are carried out (Fig. 1i), during which the finished lenses are classified, coded according to specifications, and prepared for shipment. Packaging solutions typically offer dustproofing, anti-static protection, and scratch resistance to maintain product integrity during transportation.

The traditional lens-polishing process remains prevalent in industrial optics manufacturing due to its straightforward implementation, low capital investment, and operational simplicity. This method employs abrasive slurries in conjunction with mechanical motion to generate smooth lens surfaces, and it suffices for optics whose surface-accuracy requirements are not extremely stringent. However, significant limitations arise when striving for nanometer-scale surface precision—an essential demand in high-end optical applications. Moreover, the inherent contact pressures and abrasive action render this approach unsuitable for soft polymers, as the mechanical forces can induce deformation or alter the substrate's material properties. Particularly for lenses with intricate curved profiles, achieving uniform material removal and consistent surface finish across the entire optic remains a formidable challenge. To address these shortcomings, advanced polishing techniques have been developed to meet the ever-increasing demands for surface accuracy and to accommodate complex materials and geometries.

III. Overview of Modern Lens Polishing Techniques

3.1. Conventional Mechanical Polishing

Conventional mechanical polishing remains one of the most widely utilized surface finishing methods in the optical manufacturing industry, particularly in the production of lenses and high-precision optical components. Originating in the 19th century, this technique continues to play a vital role in achieving the smooth, mirror-like surfaces required for optical applications. The process involves using a compliant polishing pad in conjunction with abrasive particles—typically cerium oxide (CeO_2) or aluminum oxide (Al_2O_3)—to facilitate controlled material removal through mechanical abrasion. This method is effective in eliminating surface defects and achieving the optical-grade surface finish demanded by high-performance systems. The roots of conventional mechanical polishing trace back to the early 1800s, coinciding with initial studies on abrasive techniques for optical materials. One of the pioneering figures in the advancement of this method was Carl Zeiss, who made significant contributions to lens manufacturing during the late 19th century. Along with his collaborators, Zeiss developed advanced polishing techniques for producing high-precision lenses used in microscopes and other optical instruments. Although abrasive technologies have evolved considerably since then, the core principles of traditional mechanical polishing have remained largely unchanged [16].

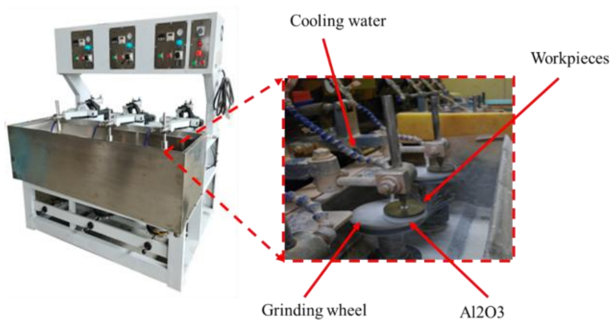

Fig. 2. Contemporary Polishing Machines

The fundamental principle of conventional mechanical polishing is based on the use of a compliant polishing pad in combination with abrasive particles such as cerium oxide (CeO_2) or aluminum oxide (Al_2O_3). During the polishing process, the workpiece is placed on a rotating or oscillating platform, while the abrasive particles are suspended in a slurry medium. The combined action of applied pressure and relative motion between the workpiece and the polishing pad generates frictional forces, allowing the abrasives to progressively remove material from the surface. This controlled abrasion process produces smooth, highly finished surfaces [18, 19]. Conventional mechanical polishing has played a crucial role in the fabrication of high-precision optical components such as camera lenses, microscope objectives, and other sophisticated optical assemblies. The technique is particularly effective for polishing hard materials including glass, metals, and various alloys. The evolution of modern machinery—such as rotary polishers and automated polishing systems—has significantly enhanced process efficiency and precision, while resducing operational errors. Traditional mechanical polishing systems commonly employ high-speed rotating polishing disks, which induce a consistent surface motion. These systems are typically used in conjunction with polishing slurries, in which abrasive particles are dispersed in a fluid medium to minimize friction and optimize the material removal process.

One of the key advantages of conventional mechanical polishing lies in its simplicity and ease of deployment within industrial environments. The method does not require highly complex equipment and can be applied to a broad range of materials. It is particularly cost-effective for achieving high surface gloss on hard substrates such as glass and metal, requiring relatively low capital investment and minimal process supervision. Nevertheless, this method is not without limitations. A primary concern is the substantial mechanical force exerted on the surface, which may cause deformation or damage, especially in the case of soft or mechanically sensitive materials. As a result, this technique is less suitable for polishing polymers or ductile alloys. Additionally, achieving uniform polishing across intricate or highly curved geometries is challenging, as abrasive force distribution becomes uneven, hindering the attainment of consistent surface quality and high dimensional accuracy [8]. Another limitation is the difficulty in achieving nanometric-level surface control. While high levels of gloss can be attained, managing ultra-smooth surface finishes at the sub-nanometer scale remains problematic. This shortcoming becomes especially critical in high-end optical applications that demand exceptional surface precision.

Despite being a widely used and effective technique for polishing optical components, conventional mechanical polishing faces increasing challenges in meeting the stringent demands of modern optical manufacturing. Consequently, advanced technologies—such as ultrasonic polishing and magnetorheological finishing (MRF)—are being developed and adopted to overcome the inherent limitations of traditional methods and to meet the evolving standards of optical fabrication.

3.2. Chemical Mechanical Polishing (CMP)

Chemical Mechanical Polishing (CMP) is an advanced surface finishing technique that synergistically combines mechanical abrasion with chemical reactions. Originally developed for planarizing semiconductor wafers in the microelectronics industry, CMP has since been adapted for broader applications, including precision optics manufacturing. Its ability to achieve ultra-smooth surfaces with high dimensional accuracy has made it increasingly valuable in the production of optical lenses and high-precision optical components. CMP works through the interplay between mechanical forces and surface-specific chemical reactions. Abrasive particles suspended in a chemically active slurry interact with the workpiece under controlled pressure and motion, facilitating the removal of surface irregularities and achieving sub-nanometer surface finishes. This makes CMP an essential process for fabricating high-performance optical devices. The technique was first introduced in the 1980s within the semiconductor industry, driven by the need to planarize the surfaces of materials like silicon and gallium arsenide to enhance the performance of microelectronic components. The process was commercialized by Applied Materials in 1988 and quickly became a critical step in integrated circuit manufacturing. Following its success in microelectronics, CMP was extended to other high-precision fields, including optical engineering and advanced materials fabrication [20-24].

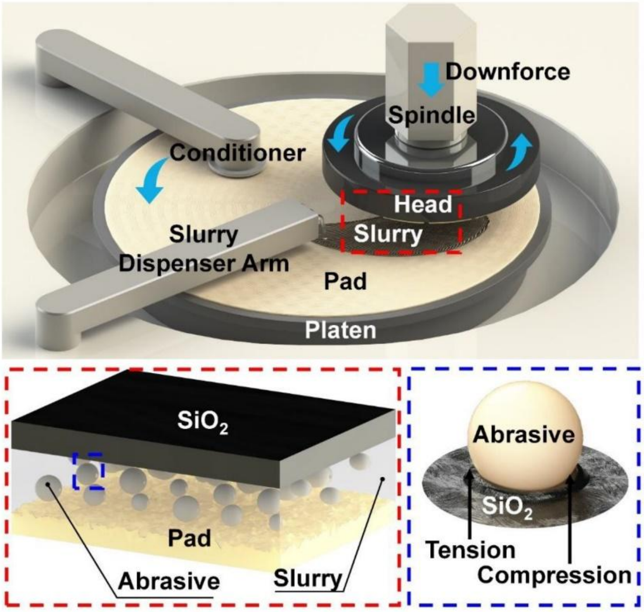

Fig. 3. Schematic of oxide CMP and the interactions [25].

Operating Principle and Applications of Chemical Mechanical Polishing (CMP). The underlying principle of Chemical Mechanical Polishing (CMP) lies in the combined effect of mechanical abrasion and chemical surface reactions. In this process, the surface of a material is brought into contact with a rotating polishing pad saturated with slurry containing both abrasives and reactive chemical agents. The chemicals in the slurry interact with the surface, weakening the chemical bonds and softening the outermost layer. Simultaneously, the mechanical force from the rotating pad removes this modified layer, effectively smoothing the surface while eliminating impurities and defects. CMP slurries typically contain abrasive particles such as silica (SiO_2) or alumina (Al_2O_3), and chemical agents—often acids or alkaline compounds—that facilitate selective material removal by promoting surface reactions. This dual-action mechanism enables the process to achieve both exceptional smoothness and defect reduction, making CMP a cornerstone technique in industries requiring atomic-level precision. Initially developed for the semiconductor industry, CMP has proven indispensable in achieving the ultra-flat and clean surfaces required for integrated circuit fabrication. Over time, its applications have expanded to the optics sector, where it is employed in the fabrication of high-performance components such as lenses, mirrors, and precision optical assemblies. CMP enables surface finish at the nanometer scale, which is essential for devices like cameras, microscopes, and other sophisticated optical systems. Beyond semiconductors and optics, CMP is also widely used in the planarization of flat substrates like glass, silicon, and optical-grade materials, particularly in the manufacture of lenses with strict surface quality requirements. The process is further applied in polishing metals and alloys in industries such as automotive and electronics, where high surface integrity is critical [26-30].

One of the key advantages of CMP is its ability to deliver ultra-smooth surfaces that finish with nanometer-level accuracy, especially on hard and brittle materials such as glass and semiconductors. The process offers precise control over material removal depth, making it highly suitable for planar surfaces and integral to modern microfabrication workflows. In optics manufacturing, CMP is vital for achieving the high surface quality needed in complex optical instruments. Moreover, it effectively removes surface contaminants and defects, enhancing product performance and minimizing manufacturing errors. However, CMP is not without limitations. One significant drawback is its reduced efficiency when applied to complex curved surfaces. Since the process is optimized for flat planarization, it struggles to uniformly polish non-flat geometries, such as aspheric or freeform optical surfaces. This presents a particular challenge in lens fabrication, where maintaining uniform surface quality over curved regions is critical. Another notable limitation is the relatively high initial capital cost of CMP equipment, which can be a barrier for small-scale or budget-sensitive production environments [20, 31].

Despite these challenges, CMP continues to play a pivotal role in the production of high-precision optical components, especially where ultra-smooth surfaces and nanometric accuracy are required. While further advancements are needed to overcome its limitations, particularly for complex surface geometries, CMP remains a leading choice in both the semiconductor and optics industries. The ongoing research is expected to broaden its applicability and enhance its performance across an even wider range of advanced manufacturing sectors.

3.3. Ion Beam Figuring (IBF)

Ion Beam Figuring (IBF) is an advanced technique used for finely finishing surfaces. It works by using a concentrated stream of high-energy ions to precisely eliminate material from the surface of optical substrates [32-36]. The ion beam, typically generated using inert gas ions such as argon (Ar^+) or xenon (Xe^+), interacts with the surface at an atomic level, enabling ultra-fine material removal. This process modifies the microstructure of the surface, effectively eliminating defects and achieving an exceptionally smooth finish. IBF is particularly well-suited for processing high-precision materials such as optical glass, metals, and other substrates where nanometric accuracy is essential. The development of IBF began in the late 1970s, with foundational research conducted by scientists such as H. H. Sawin and D. L. Huffman. Over the decades, the technique has evolved significantly and proven to be highly effective in generating ultra-smooth, defect-free optical surfaces. IBF has found widespread adoption in the fabrication of advanced optical components and other precision-engineered devices. Today, IBF is a standard method in the finishing of high-accuracy components, particularly in the production of astronomical telescope optics and other high-end optical systems. Its non-contact, deterministic nature allows for precise control over material removal without introducing mechanical stress or surface damage, making it an invaluable tool in the optical manufacturing industry.

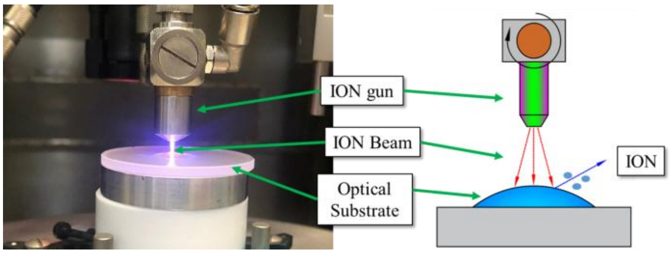

Fig. 4. Ion Beam Figuring process

Ion Beam Figuring (IBF) offers exceptionally high precision in surface processing through a non-contact technique, thereby significantly reducing the risk of mechanical damage to the substrate. Its capability to process complex surface geometries with nanometric control over the depth of material removal makes IBF a powerful tool for ultra-precise surface finishing. Moreover, IBF achieves superior surface smoothness, positioning it as an ideal method for applications demanding ultra-fine surface quality. Despite its advantages, IBF comes with notable limitations, primarily its high capital and operational costs. The technique requires highly specialized equipment, controlled vacuum environments, and complex maintenance protocols, making it less suitable for large-scale or cost-sensitive manufacturing operations. Additionally, the IBF process must be meticulously controlled to prevent deviations that could compromise the precision of the final surface [37-40].

3.4. Laser Polishing

Laser polishing is a surface finishing technology that has been studied and refined since the 1990s, with foundational contributions from researchers such as P. M. W. C. W. McKenzie and R. R. L. A. Lambourne. Subsequent studies have demonstrated the method's capability to significantly enhance the smoothness of metallic materials. This technique has shown promise in the context of additive manufacturing (3D printing) and precision metal component fabrication [41-43]. In recent years, laser polishing has gained increasing traction in industrial applications, particularly within sectors such as medical device manufacturing, aerospace engineering, and the automotive industry. Its non-contact nature and ability to selectively melt and re-solidify the surface layer of a material allow for the reduction of surface roughness without introducing mechanical stress [44-46].

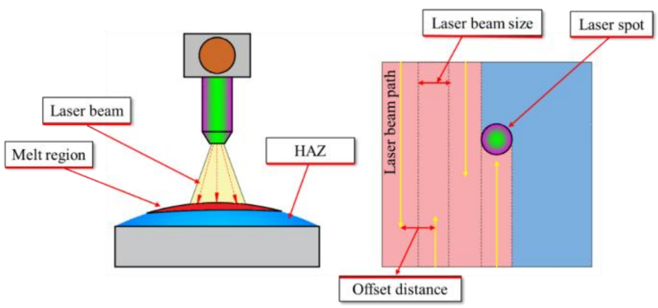

Fig. 5. Laser polishing process

Laser Polishing is a surface finishing technique that utilizes high-energy laser beams to locally melt the outermost layer of material. This controlled melting process smooths surface irregularities and enhances surface gloss by allowing the molten material to re-solidify into a more uniform layer. The method is applicable to a wide range of materials, including metals, polymers, and alloys, and is commonly used in the production of precision components.

One of the major advantages of laser polishing is its non-contact nature, which eliminates mechanical abrasion and minimizes surface damage. It is well-suited for automation and can be effectively applied to complex geometries. The technique is particularly beneficial for reducing surface roughness and enhancing the surface finish of parts produced by additive manufacturing technologies such as 3D printing. However, a key limitation of laser polishing is its high initial capital cost and the complexity of its operational requirements. These factors may restrict their feasibility for low-cost or high-volume production environments [12, 47].

3.5 Fluid Jet Polishing - FJP

Fluid Jet Polishing (FJP) is an advanced surface finishing technique that has been investigated since the 1990s, particularly for machining complexes and non-uniform surfaces. Research conducted by Z. Zhang and colleagues (2014) demonstrated that FJP can produce ultra-smooth surfaces on materials such as polycarbonate and aluminum alloys [48-50]. This method is currently employed in various industries, including precision optical prototyping and the fabrication of intricately shaped components.

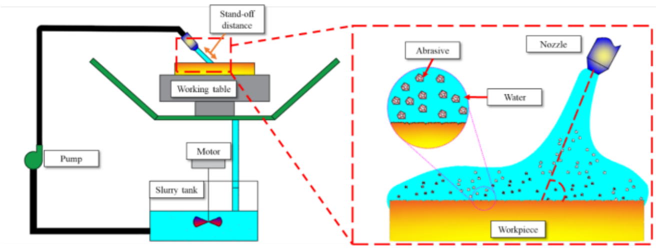

Fig. 6. Schematic diagram of the maskless fluid jet polishing (MFJP) of structured surface

Fluid Jet Polishing (FJP) is a non-contact surface finishing technique that employs a high-pressure jet of slurry containing abrasive particles to remove surface irregularities and enhance smoothness. The abrasive-laden fluid is directed onto the workpiece surface, eroding imperfections without direct mechanical contact. This method is particularly suitable for processing complex geometries and softer materials such as polymers [51-53]. FJP is ideal for finishing intricate surfaces without imposing significant mechanical stress on the material. It minimizes surface defects while preserving the integrity of delicate or easily deformable components. Furthermore, key process parameters—such as jet pressure and abrasive type—can be finely tuned to optimize the polishing performance for various materials and surface quality requirements [54-57]. However, one of the primary limitations of FJP is the challenge in precise controlling the material removal zone. The fluid jet may disperse beyond the targeted area, making it difficult to maintain high precision, especially when working on small-scale features or surfaces requiring ultra-smooth finishes [58-61].

IV. Magnetorheological Finishing (MRF)

4.1 Principles of the MRF Technique

Magnetorheological Finishing (MRF) is an advanced, non-contact surface finishing technique that offers high precision in material removal processes. Initially introduced in the mid-1990s by the Center for Optics Manufacturing at the University of Rochester, led by Dr. Stephen D. Jacobs and his team, MRF has showcased outstanding potential in the ultra-accurate polishing of optical components. The core mechanism of MRF involves the use of a magnetorheological (MR) fluid—typically a suspension containing abrasive particles—whose rheological properties can be dynamically altered by an applied magnetic field. Under regular circumstances, the MR fluid acts like a standard low-viscosity liquid. However, when subjected to a high-intensity magnetic field, the dispersed ferromagnetic particles (e.g., Fe_3O_4) or composite core–shell structures (e.g., $Fe_3O_4@SiO_2$) align into structured chains along the field lines. This alignment significantly increases the fluid's apparent viscosity and elasticity, transforming it into a semi-solid polishing ribbon. As this magnetically stiffened ribbon interfaces with the workpiece surface under controlled relative motion, it generates a localized and precisely regulated shear force. This interaction enables fine-scale material removal without inducing mechanical stress or damage to the surface, making MRF particularly suitable for finishing high-value optical and precision engineering components [62-64].

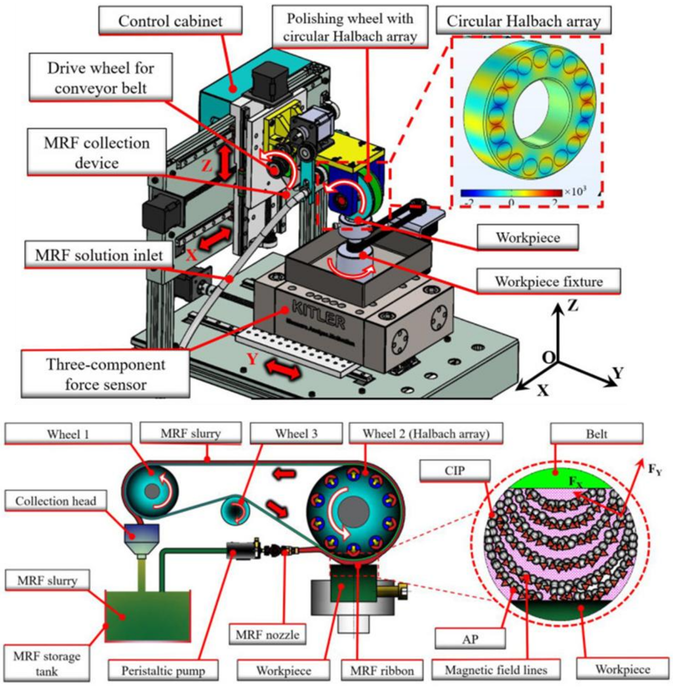

Fig. 7. Magnetorheological Finishing process [65].

Modern Magnetorheological Finishing (MRF) systems typically comprise three primary components: (1) Magnetic field generation system – employing either permanent magnets or electromagnets to precisely control the shape and intensity of the polishing zone; (2) MR fluid delivery and agitation mechanism – often designed to induce a small-angle oscillatory or vibratory motion to refresh the working interface and ensure consistent abrasive action; (3) Counter-rotational drive – involving opposing rotational motions between the workpiece and the polishing ribbon to enhance cutting efficiency and maintain surface form accuracy. A key advantage of MRF lies in its tunable process parameters. The material removal force can be finely controlled by adjusting the magnetic field strength, flow velocity of the polishing medium, or rheological properties of the MR fluid. This makes the technique particularly well-suited for processing delicate materials such as PMMA, which are susceptible to mechanical deformation under high contact pressure. Moreover, MRF can finish complex surface geometries, achieving final surface roughness levels in the nanometer range.

Since its inception, technology has undergone significant advancements in terms of equipment architecture, fluid formulation, and processing strategies—broadening its applicability across various precision engineering domains. Over the past two decades, researchers have continuously refined the MRF process. Pioneers such as Jacobs and colleagues at the University of Rochester successfully demonstrated, in 1999, sub-30 nm form accuracy and surface roughness in the 1–2 nm range on optical lenses and mirrors using MRF. This milestone laid the groundwork for the commercial adoption of the technology and accelerated its integration into the optical manufacturing industry. Subsequent contributions, such as those by Kordonski et al. (2004) [66-68], introduced advanced models of MR fluid dynamics and developed numerical simulation tools capable of predicting the material removal footprint with high accuracy. These instruments have become essential for planning and refining processes related to finishing freeform surfaces. More recently, Cheng et al. (2016) [69] applied MRF to polish silicon carbide (SiC)—a material known for its extreme hardness and resistance to conventional polishing methods—achieving a surface roughness of just 0.8 nm after a 60-minute polishing cycle. In the context of soft materials like PMMA, Shi et al. (2020) investigated an MRF setup using a $Fe_3O_4@SiO_2$-based MR fluid and a highly uniform hemispherical magnetic field. Their system achieved a surface roughness of 9–12 nm without introducing mechanical deformation, marking a significant advancement in adapting MRF for soft, non-spherical optical components. Additional studies, including those by Chen et al. [70] (2007), have integrated MRF with real-time monitoring tools such as force sensors, 3D surface imaging, and machine learning algorithms. These innovations enable adaptive control over the polishing process, thereby improving surface quality and facilitating full system automation. These achievements underscore MRF's evolution into a core enabling technology for finishing freeform surfaces, ultrahard materials, and ultrasoft polymers in high-precision manufacturing environments.

4.2 Application of Magnetorheological Finishing in Polishing PMMA Lenses

For polishing PMMA (Polymethyl Methacrylate), Magnetorheological Finishing (MRF) has emerged as a highly effective technique, primarily due to its precise control over the polishing zone and its ability to minimize mechanical stress on delicate surfaces. PMMA is a lightweight, optically transparent polymer that is easy to shape and widely used in the fabrication of medical lenses, AR/VR optics, endoscopic devices, and optical sensors. However, its low hardness and high susceptibility to thermal and mechanical deformation renders it unsuitable for traditional polishing methods such as Chemical Mechanical Polishing (CMP) or conventional mechanical polishing. In MRF, a suspension containing magnetically responsive abrasive particles (e.g., Fe_3O_4@SiO_2 or CeO_2) is subjected to a controlled magnetic field. Upon field activation, the fluid undergoes a rheological transformation, behaving like a high-viscosity elastic medium. This enables uniform, finely regulated shear forces to be applied across the PMMA surface, allowing material removal to occur without inducing surface scratches or distortions—critical for maintaining the optical integrity of soft polymer substrates [15, 71].

Numerous studies have highlighted the superior performance of MRF in the precision finishing of polymer lenses. For instance, N. Ngoc Quan et al. [72] (2020) developed an MRF system incorporating magnetic nanoparticles to polish PMMA, achieving a surface roughness reduction from 78 nm to approximately 9.3 nm within just 15 minutes, with no compromise in form accuracy [3]. Zhang et al. (2021) [73] further demonstrated the feasibility of a hemispherical MRF setup for polishing aspheric PMMA lenses, attaining geometric form accuracy better than $\lambda/10$ (with λ = 632.8 nm), underscoring MRF's potential for manufacturing high-quality optical components. Beyond laboratory research, MRF is increasingly being adapted for industrial-scale applications in high-tech sectors. Optical elements made from PMMA, such as lenses for augmented reality (AR) systems, medical diagnostics equipment, and miniature optical sensors, demand exceptional smoothness and tight geometric tolerance performance benchmarks that MRF consistently meets. The non-contact nature of the process also ensures greater reliability during mass production of fragile, thin-walled components, making MRF particularly advantageous for modern precision optics manufacturing [74].

V. CONCLUSION

In the finishing of optical lenses, polishing techniques play a pivotal role in achieving ultra-smooth surface finishes and precise surface geometries—both are critical to the overall performance of optical systems. A review of current technologies reveals a clear transition from traditional polishing approaches, such as Mechanical Polishing (MP) and Chemical Mechanical Polishing (CMP), toward more advanced, adaptive, and precision-driven methods. These include Ion Beam Figuring (IBF), Laser Polishing (LP), Fluid Jet Polishing (FJP), and, notably, Magnetorheological Finishing (MRF). Each technique offers unique advantages and is suited to specific application domains. However, for soft polymeric materials like PMMA, which are highly sensitive to heat and mechanical stress, MRF stands out due to its non-contact nature, micrometer-level precision in material removal, and high adaptability in system configuration. MRF enables sub-10 nm surface roughness while maintaining optical form integrity—without introducing thermal or mechanical damage to the substrate.

The adoption of MRF for the fabrication of PMMA-based polymer lenses not only enhances surface quality but also expands its applicability to a wide range of high-tech sectors, including augmented/virtual reality (AR/VR) optics, medical imaging devices, bio-optical systems, micro-opto-electro-mechanical systems (MOEMS), and miniature sensor components. From a production standpoint, MRF is proving to be a viable solution for low-to-medium volume manufacturing where high surface quality and complex geometries are required.

Looking ahead, several promising directions are anticipated to further advance MRF technology:

- Optimization of magnetorheological flow field simulations to improve the accuracy of the localized material removal region.
- Integration of advanced nanoscale abrasives (e.g., silica-coated magnetic particles or diamond@Fe_3O_4 composites) to enhance process efficiency and broaden material compatibility.
- Implementation of in-situ metrology systems for real-time surface monitoring and feedback control, enabling fully automated closed-loop processing.
- Development of compact and reconfigurable MRF systems, tailored for fabricating ultra-small optical components and freeform microstructures.

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