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Magnetorheological method applied to optics polishing: A review

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Abstract. Magnetorheological finishing method is carried out in order to correct errors of figures which are produced by conventional polishing methods on planes, spheres, aspheres and freeform optics having surface roughness value as low as 1 nm RMS. Low surface roughness and mid-spatial frequencies in advanced optical systems are essential for minimizing flare and energy loss. Magnetorheological polishing fluid is a clever fluid that can alternate from its liquid phase to almost solid under magnetic field influence. The main key process parameters in magnetorheological finishing process such as fluid composition, rheological properties along with the surface quality of polished optical components (including metal, glass, and ceramic) are reviewed in the present manuscript.

1. Introduction

High resolution, image quality and capture speed are required for advanced optical systems. Better evaluation photos with better efficiency and lower distortion can be accumulated by improving these midspace frequencies and surface roughness. Many applications, including lithography, defense structures, and reference spheres, require high-precision optics [1]. The polishing of different types, shapes, and sizes of materials without causing surface harm is possible by magnetorheological finishing (MRF) [2] process. Many researchers used the MRF technique to polish a variety of materials up to the nanometer level. It has turned out to be an essential tool for the manufacture of over-precision optics. MR polishing fluid (MRPF) is a clever, viscosity-changing, controllable material under the application of a magnetic field. MRPF is composed of magnetic particles, liquid carrier and abrasive, non-magnetic sharpening particles. Many of the common materials used during the polishing process are carbonyl iron particles (CIPs), alumina [3], diamond [4] and ceria [5] as abrasives while deionized water is utilized as a carrier medium.

In terms of performance, the surface roughness is more important but includes not only traditional goals like figure precision, but also high-precise dimensions, small medium-excessive frequency fluctuations and low surface defects [6]. Recent developments enable more polishing of off-axis and free-form optics. These developments also allow the effective correction of wavelengths even having the space of ~1mm [7]. The development of a new liquid option for ultra-low roughness [8] has also resulted in the development of MR Fluid [9]. These recent progress in MRF technology enables even more precise optical production to meet the requirements for medical, industrial, defence and aerospace applications. The MRF efficiently polished hard glasses, silicon wafer, knee joint implants and hard crystals [10]. The process is carried out by interacting with the optical surface of magnetically stiffen MRP fluid particles under a magnetic field. The process of polishing aids the material removal mechanism [11].

The MRF process has successfully polished different kinds of optical materials like borosilicate glass [2], cordierite Ceramics (NEXCERA) [12], glass-ceramic [13], aluminum [14], etc. This process has now a big effect in the optical industry. The important rheological characteristics of MRP fluid are in the area of polishing, such as yield stress and flexible viscosity, on which magnet field has a high impact. Other methods, such as grinding, chemical etching, mechanical finishing, electrolytic finishing or ultrasonic finishing, etc. are not capable of effective finishing of complex surface characteristics such as micro grooving [15]. The polishing media can refill the vacuum and polish the complex surfaces with MRF. This literature presents significant information on the contribution of the MRF process inside the discipline of optics.

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2. Magnetorheological finishing

MRF process was developed and marketed by QED Technologies, Inc. [16], as a magnetic field-assisted finishing method [17]. The manner in which optics are manufactured has changed, and most of the major optic sectors have received wide recognition. A wide range of brittle metals, from optical glass to difficult crystals, were polished using the MRF process [18]. MRP fluid is employed in this method to polish distinct products. MRP fluid consists of carbonyl iron particles (CIPs), abrasives, surfactant particulate matter and de-ionized water or another fluid carrier. The MRP fluid constitutes a compliant polishing device, which enables it to polish a range of forms, including flat, rectangular and concave. A range of products has been effectively finished to the sub-nanometer level surface roughness with a suitable preparation of MRP fluid [17]. The MRP fluid behaves as a Newtonian viscous fluid in the absence of a magnetic field [19].



Figure 1. Magnetorheological effect: (a) MR polish fluid without magnetic field, (b) applied magnetic field strength H and (c) applied magnetic field strength H and shear strain γ [20].

The MR fluid strengthens and acts as a visco-plastic fluid depending on the strength of the magnetic field. In order to generate MR effects, the magnetic field and CIPs are essential, while non-magnetic abrasive constituents are accountable for MRF suppression. CIPs are drawn to the magnet and generate a chain-like framework along the rows of the magnetic field when the magnetic field is applied [20]. The energy needed to counter and break the chains is accountable for the start of broad, limited yield stress [21]. This yield stress is increasingly resistant to a transmitted shear strain (Fig. 1(c)). The particles return to the random condition (Fig. 1(a)), when the field is removed, and the fluid again displays the original Newtonian behavior. If non-magnetic agents are attached to the MRP fluid, they will be grabbed by magnetic chains. The stiff MR fluid creates an affinity point in the ribbon-working part by using a magnetic field with the help of a permanent magnet or an electro-magnet. In material removal mechanics through MRF processes, normal and tangential forces are accountable for transmission and cutting of high peaks during polishing. This literature reports on a majority of experimental work, for which various device configurations are created, based on the size and shape of the job to be finished. This paper also looks at these elements of MRF method, MRP fluid rheological characterisation and growth in MRF polishing of optical components.

2.1. Magnetorheological polishing (MRP) fluid

The quality of the finishing process can be ensured through MRP fluid components and their volume fraction. Sidpara et al. [22] reported an enormous position of the various concentrations of CIP and abrasive particles in the removal of materials. Changes in the percentage of one fluid quantity lead to the rheological changes in the performance and properties of MRP fluid. High permeability and low magnetic residue of magnetizable carbonyl iron particles (CIPs) are preferable [23]. Few options, such as water, mineral and silicone oil have been reported for carrier liquid. The most suitable option for the polishing of ceramic-based surfaces is oil-based carrier liquid [24]. Deionized water is usually applied

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as a base fluid due to the formation of a weak hydrated tier on the skin of the surface of the workpiece as compared to the surface of an oil tier. Oil as a base liquid reduces the connection of the abrasives to the surface of the workpiece. The water-based fluid induces more friction due to the absence of lubrication compared to an oil-based fluid, leading to higher finishing performance [24]. One of the main contributors to the material removal rate (MRR) is abrasive particles. Round shape and smoothness of CIPs have the least contribution in MRR [25] as compared to MRP fluid having abrasives. Various types of abrasives used in MRP fluid are Al₂O₃, SiC, CeO₂ and diamond [26]. They are all ceramic particles with high hardness characteristics. The effect of the polishing of silicon from alumina and ceria was studied by Sidpara et al. [22]. Diamond particulates were used as abrasive in another study to deburr a brass metal surface [27]. Ceria based MRP fluid was used for polishing of silicone and the surface roughness value reduces from Ra of 1300 nm to 8 nm [10]. The stiffness and shape of the abrasives with sharp and irregular ridges give sufficient efficiency to remove materials on optical surfaces. Smaller abrasives show the sharpest and the most irregular ridges. Nagdeve et al. [28] indicated that the various sizes of abrasives affect the potency of the MRP fluid. This is because the non-magnetic abrasives trap between magnetic chains, when MRP fluid are driven by magnetic field. Low magnetic force interaction results in the greater range of abrasives trap into the CIP chains. If the volume of CIP and abrasive particles differ less, the power relationship shifts more and more in the raw ground proportion. The abrasive shape is irregular and the CIP shape is round. Abrasive is therefore essential in the MRF process for polishing mechanism. To suspend the solid particles in the base medium and for making the fluid as a corrosionresistant, additives were added to MRP fluid [29]. Anti-corrosion inhibitor is important since water is used as a carrier medium in most of the MRP fluid. MRF process includes additives such as grease, surfactant and glycerol [30].

3. MRF for flat, concave, convex, spherical, aspherical or freeform optical components

For accurate part handling, MR finish utilizes the MR polishing fluid. In Fig. 2, the experimental set-up of MR process is displayed. The MR polishing fluid shows Newtonian behaviour without magnetic field. An external magnetic field is applied to have an impact on MR behaviour [31]. Maloney et al. [32] has suggested a new C30 MRP fluid that can finish ultra-low rough (ULR) substrates and is optimum for good mid-space frequency adjustment in figures. C30 MRP fluid can attain less than 1.5Å RMS on Silicon substrate, CaF₂, Silicon fusion, and glass as well as other products. The new platform is designed in a modular manner to quickly switch to a wheel of diameter 150 to 20 mm in the lowest line and mid-space frequency adjustment.



Figure 2. Experimental setup of magnetorheological finishing process [31].

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Figure 3 shows the figure correction after finishing by Q-flex 300. The Q-flex 300 MRF polishes freeform, spherical and aspherical optics up to 45-degree angles. Hu et al. [6] presented the square aspheric window manufacturing process that combines grinding, magnetorheological finishing (MRF) and smooth polishing (SP). The pseudo-random-path technology of SP is used to eliminate the MRF defects having medium-excessive frequency and high-level errors on the surface. In addition, the reduction of sub-surface defects is examined for the ion beam figuring (IBF) and acid-etched method. It has been demonstrated that the machining and testing connection is a technology of processing which is highly efficient, deterministic and economic. The conventional sub-opening polishing has been modified to meet the requirements for errors in space Frequency. Simultaneously, IBF is used in the removal of scratches, mechanical filling and pollution from impurities. Figure 4 shows the manufacturing processing chain and aspherical window testing.



Figure 3. (a) Figure correction on 150 mm diameter asphere before and after MRF and (b) Q-flex 300 MRF set up [32].



Figure 4. Manufacturing processing chain and asphere window testing [6].

The consequence of operating variables on borosilicate glass (BK7) material removal has been examined by [2]. Data are gathered on an MRF set up with a standard MRP fluid. They found that shear stress does not depend on the magnetic field strength, nano-diamonds concentration, penetration depth, MR ribbon rotation and the relative velocity of the part. Shear stress controls material removal in MRF, which is primarily determined by the material mechanical characteristics. Due to brilliant mechanical and optical qualities, BK7 is a traditional optical glass commonly used in the industrial sector. This MR liquid included CI crystals (45%), deionized (DI) air (51%) and stabilizers (45%). The leveraging ideas used for freeform raster MRF capacities were investigated by Maloney et al. [33]. The use of B axis (rotating axis) in conjunction with a "virtual axis" using the polishing head geometry is included in their set up. Earlier hardware crashes with a concave half-angle boundary, can now be prevented, and the fresh feature is seamlessly incorporated in the software. This new MRF model overcomes previous constraints on the finishing of concentric surfaces, so as to now accommodate all concave hemispheres.

It is now possible to use MRF for a range of full concave hemispheres. This opens up a new regime of high-precision optics that can be processed using commercially-available, production-oriented equipment. Figure 5 shows the polishing region head rotation with respect to the wheel apex. The methods used for the production of asphere lenses were revealed by Luzio et l. [35] combining the micro-grinding process with the MRF process. Deficiencies in local shape caused by micro-grinding is removed by the MRF process. This method, therefore, enables commercial aspherical substrates to be produced. The membrane polishing is made of a narrow membrane like a polishing agent in this process. The polisher is a cylindrical chamber-forming brass tool. A membrane of a rubber blade and a polyurethane leaf (polyurethane rigid microcellular mousse), is locked into the chamber. Depression or overpressure in

the tank can be created through the valve. This gives the active surface (the polyurethane part) a concave or convex shape as illustrated in Fig. 6.



Figure 5. (a) Beginning of standard rotational MRF run, where the polishing region is normal to the wheel apex during the entire run, (b) Halfway through a standard rotational MRF run, and (c) End of standard rotational MRF run [34].



Figure 6. Simplified schematic of membrane polisher [35].

Sugawara et al. [36] conducted experiments on ultra-low thermal expansion ceramics, which is regarded as one of the potential candidate materials crucial for ultra-lightweight and thermally-stable optical mirrors for space telescopes. They developed a deterministic aspheric shape polishing and a precise figure correction polishing method for the cordierite ceramic. Magnetorheological finishing (MRF) was tested to the cordierite ceramic aspheric mirror from best-fit sphere shape. CD107 and D20 fluid, were developed and clarified that aspheric mirrors made of cordierite ceramic, can be corrected by the MRF to sufficiently high figure accuracy without degrading the surface roughness required for the space telescope mirror. They concluded that in the case of a solid substrate, as an upstream process of the MRF, aspherical figure accuracy of PV ~ $\lambda/4$ and RMS ~ $\lambda/24$ (λ : 633nm), and surface roughness of less than 1nm RMS were achieved in the mirror substrate. The result also suggests that a 5–10 mm relatively thick aspheric mirror sheet with lightweight structure might be able to be finished precisely only by the computer-controlled polishing without the MRF correction process. Figure 7 shows the surface finishing of cordierite ceramic after processing by MRF.



Figure 7. High precision hyperbola made of the cordierite ceramic processed by using the MRF[36].

Forbes et al. [37] described the process of magnetorheological finishing to enhance the manufacture of mirror segments in meters class tolerances for extraordinarily large telescopes. Shorey et al. [38] reported that the advanced surface-finishing methods, particularly the magnetorheological finishing process is a stable polishing technology that enables precision fabrication of flats and spheres as well as increasingly complex optics, such as aspheres and freeform shapes.

Zhang et al. [39] developed magnetorheological brush finishing (MRBF) as the flexible MRF technique for overcoming the problems in designing and completing concave areas of conformal optics. MRBF is a very flexible method. Under the influence of an external magnetic field, the circulated magnetory fluid is extruded through the channel of the smooth ferromagnetic spindle to form an amenable circle with shear pressure to complete the whole concave floor with a spinning spin and the piece being rotating. The MRBF control algorithm has been developed and experiments have shown MRBF's performance in figuring and polishing concave complex areas.



Figure 8. Setup of MRBF experimental platform [39].

Figure 8 shows the experimental setup of MRBF for the polishing of a concave surface. Zhong et al. [40] investigated the magnetorheological finishing (MRF) techniques for the super-smooth processing on the nickel optics. The current fabrication technology for the nickel aspheric mainly adopts the single point diamond turning (SPDT) having the disadvantage of residual surface texture which will cause great scattering losses and fall far short from the requirement in the X-ray applications. Self-controlled MRF-fluid NS-1 was used to finish the high-precision surface figure lower than RMS $\lambda/80$ (λ =632.8nm) and super-smooth roughness lower than Ra of 0.3 nm on the plane reflector and roughness lower than Ra of 0.4 nm on the convex cone. Nickel is one unique material for X-ray optics. They concluded that MRF is a considerable potential technology for improving the surface error and roughness and broadening the applications for removing the cyclic signature caused by the diamond turning. Zhu et al. [41] investigated subsurface damage produced by the primary grinding process and grinding parameters will be changing in real-time in the processing of deep aspheric surface, so the depths of subsurface damage

of the workpiece are inconsistent. Subsurface damage depths under different conditions of grinding parameters were acquired by the method of magnetorheological finishing spot. Results show that the depth range from inside to outside along the radius of the workpiece is minimized by MRF.

Murphy et al. [42] used QED's SSI supplements next-generation processing technologies, like magnetorheological finishing. This workstation automatically stitches sphere, flat and mild aspheric measurements. In addition to corrections of sub-aperture positioning errors like tilts, optical potency and recordings, developed software is also responsible for the correction of imaging optics of the interferometer. The full opening of high domes can be measured automatically by SSI for interferometric precision. It enables the manufacture of domes to unprecedented quality with a deterministic finishing method. Experiment with steep local slopes on concave mirrors was performed by [43]. The jet of abrasive fluid (water abrasive jet machining) and MR jet was compared. Polishing results show that the MR jet finishing technique is more appropriate for the precise finalization of complex forms. It was also established that high precision surfaces can be manufactured by MR Jet with a roughness of < 1 nm range of materials, including glasses, single crystals, advanced ceramics, and metals. This technique offers a versatile solution for conformal optic imaging systems. With water, the jet only stabilizes for a diameter of~2 mm nozzle, as shown in Figure 9.



Figure 9. Jet photographs at the velocity of 30 m/s and on the nozzle diameter of 2 mm for (a) water, (b) MR fluid without magnetic field and (b) MR fluid with magnetic field [43].

Huang et al. [44] conducted a test of freeform polishing by the Q-flex 300 MRF machine. Simulation of the distortion of the lens through self-load distortion with semi cinematic mounting is done by ANSYS. The final lens cell surface form error after MRF is 0.042µm in the peak valley (PV). For glass-ceramic polishing [13] used the MRF process. A glass-ceramic surface performance screened with an atomic force microscope (AFM). The obtained surface roughness was Ra of 0.684 nm indicating that elevated ground performance can be achieved by MRF. The large, lightweight optics have been polished by [45], which has the further challenge of non-uniform assistance. Combining fluid stabilization, developed software allows complicated off-axis aspheres to be finished. It concluded that QED techniques are well placed to meet the potential requirements of optics while lowering polishing times and costs considerably.

Zheng et al. [46] reported a magnetorheological polishing technique controlled by software. The kernel module is designed using the Jansson-Van Cittert algorithm. Then the programming of software modularisation, modular testing, and integration testing were performed. The crystal element is examined with an overall opening of 500 mm and, following the software-controlled magnetorheological finishing, quick and efficient convergence is reached on the surface of the element. It has been shown that the software can accurately manage the entire completing process. CNC-controlled MRF for big sapphire optics and asphere glass meter optics were used by [47]. CNC monitoring allows it to prevent

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non-symmetrical errors, gravity and/or tracking impacts from prior polishing measures. It is well placed to respond to the evolving and potential requirements of defense programs.

A unique magnetic polishing liquid (MPL) made through a mixture of abrasives into the magnetic component fluid (MCF) has been presented by [48]. MCF is a smart fluid that is created by blending a solid-liquid into a solution and, therefore, reacts to the magnetic field. There were seven types of MPLs made from kerosene. An experimentation finding has shown that the surface roughness differs with the polishing moment and is reduced to a certain magnetic field force. For testing, metal freeform lenses were used. The magnetic clusters consist of the (Fe₄O₃), iron (Fe) and Al₂O₃. The experimental results show that a higher viscosity MPL is used for a better surface finishing. As a tool to figure out for aluminium diamond-turned lightweight mirrors with electroless nickel plating, Beier et al. [14] have used MRF. Freeform mirrors with greater aperture, fewer shape deviations are better components for MRF. However, owing to scatter failures for smaller wavelengths as a consequence of the residual periodical diamond rotating framework, uses are normally restricted to the invisible spectrum area.

K9 concave asphere finished with the MRF set up was presented by [49]. The surface accuracy of peak to valley (PV) has been increased in a single-process by about two hours from 0.216µm to 0.179µm. They concluded that an advanced optical production technique that can be used to smooth varied optics is a characteristic of high-precision deterministic MRF. In order to achieve computer-controlled deterministic finishing technologies, Pollicove and Golini [50] mixed computer-aided manufacturing and advanced MRF (magnetorheological finishing) technology, have demonstrated the ability to finish plane, sphere, asphere or cylinder optics with round or not round openings.

In order to minimize edge-wheel uncertainties, Zhang et al. [51] presented a new magnetorheological wheel with a perpendicular axis. By using the rotating wheel, a stable removal property can be achieved. Experiments have been carried on a square optical workpiece having a spherical surface. Found that the MRF can reduce polishing time and expense with the perpendicular axis polishing wheel. Sato et al. [52] studied the magnetic theory of finishing for the micro-cracks of glass. A secret issue of catastrophic glass breaking was identified as micro-cracks on the finer glass sheet surface. A shear force is applied to the thin glass sheet surface by magnetorheological fluid, magnetically supported by a specifically engineered magnetic wheel device. The surface roughness improved from Ra of 0.5 μ m to 0.03 μ m and all micro-cracks were finished from the glass sheet surface.

In the process of magnetorheological finishing, Shi et al. [53] employed elastic-plastic deformation theory in order to make elastic polishing feasible. They used components having laser-induced threshold damage (LIDT). The surface roughness of optical window polished with fused silica (FS) has improved from Ra of 1.793 nm to 0.167 nm and LIDT improves from 9.77 to 19.2 J/cm², following the polishing process with MRF elastics.



Figure 10. Distribution of abrasives in different MR fluid (a) standard (b) new [53].

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Figure 10 shows the abrasive distribution in standard and new MR fluid. The used MR Jet is provided by [54] especially when finishing within the steep concentric dome and other irregular forms. MR Jet has the ability to resolutely and precisely do the figure correction of the conformal domes. Figure 11 shows the improvement in surface roughness and figure error of the laser-irradiated component after each step of finishing by new MR fluid.



Figure 11. MRF a high-precision polishing process [53].

4. Conclusions

In this article, a study of the latest development of the MRF in the optic sector is attempted from the released reports on MRF. The composition of MRF should be determined by recognizing which component is going to be polished. A mixture of the appropriate composition of MRPF improves the material surface roughness. In MRF, rheology also plays a significant part. CNC controlled MRF, MR jet polishing, Magnetorheological brush finishing, Mixed technologies like MRF, grinding, etching, smooth polishing were used to finish the various flat, spheric, concave, convex, aspheric or freeform optics. General materials used for fabrication of mirrors are cordierite ceramics, glass ceramics, aluminium, laser-irradiated ceramics, nickel, and nickel-plated aluminium, etc. These mirrors are used in the field of X-ray, space telescope and defense systems, etc. Dependant on the structure of the MRPF, polishing parameters can be optimized. MRF has shown great success in nano-level polishing in the discipline of optics.

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