Research Progress of Magnetorheological Finishing Technology at CIOMP

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Abstract The history and current situation of magnetorheological finishing (MRF) at home and abroad are presented. The principle, characteristics and merits of MRF are introduced. Recent investigations of MRF at Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP) are described in detail, and several key techniques of MRF are resolved. Our research findings include: A new-style magnetorheological (MR) polishing fluid is prepared, and the rheology and polishing power of this MR polishing fluid are improved evidently; dwell time algorithm of MRF based on matrix algebra is studied; in order to increase the area of removal function (polishing spot), improve the material removal rate, and polish large aspheric mirror, a new MRF concept, named Belt-MRF, is presented.

Key words optical fabrication; magnetorheological finishing; magnetorheological finishing polishing fluid; removal function; dwell time; belt magnetorheological finishing

OCIS codes 220.4610; 220.4840; 220.5450; 220.1250

磁流变抛光技术在长春光机所研究进展

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摘要 简述了国内外磁流变抛光技术的研究历史和现状。介绍了磁流变抛光技术的抛光原理、特性及优点。着重阐述了长春光学精密机械与物理研究所近几年来在磁流变抛光技术研究方面的最新进展,解决了磁流变抛光的若干关键技术,主要包括:研制出一种新型磁流变抛光液,这种磁流变抛光液具有优良的流变性和较高的抛光效率;研究出一种基于矩阵代数运算模型的磁流变抛光驻留时间求解算法;为了增加去除函数(抛光区)面积、提高材料去除效率,研制出适合大口径非球面反射镜加工的带式磁流变抛光机。

关键词 光学制造; 磁流变抛光; 磁流变抛光液; 去除函数; 驻留时间; 带式磁流变抛光

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1 Introduction

Magnetorheological finishing (MRF) is a typical deterministic finishing technique for fine figuring various shape optical components such as flat, spherical, aspheric, and freeform. MRF was invented at the Luikov Institute of Heat and Mass Transfer in Minsk, Belarus in the late 1980 s by a team led by William Kordonski. In the early 1990 s, Kordonski and his colleagues were invited to work at the Center for Optics Manufacturing of the University of Rochester in New York to refine MRF technology[1-2]. Soon after, a "preprototype" MRF machine was prepared, and many MRF experiments were carried out on this machine[3-4]. In 1996, they recognized the commercial potential of MRF and founded QED Technologies to research and develop MRF technology. MRF machines were commercialized in the late 1990 s[5], and these commercial MRF machines were widely used for fabricating ultra-precise optics[6]. The Q22-2000F MRF machine has the ability for polishing optical components with the size up to 2.3 m. However, the price of MRF machine is very expensive.

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Some researchers in others country, such as Belarus, Germany, Japan, South Korea, also engaged in the study of MRF technology and obtained favorable research results.

The MRF technology was the first to be studied in China by some researchers at Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP) in the late 1990 s[7]. The early research works included studying magnetic field used in MRF[8], founding mathematics model of MRF[9], and preparing MR polishing fluid[10]. These research works provided the necessary support for further studying MRF technology. Recently, we studied an effective dwell time algorithm of MRF[11] and prepared a new type MRF fluid[12], and also we cooperated with researchers of Belarus building several MRF machines.

The MRF technology was also studied at National University of Defense Technology by some researchers. Their research work was as follows: establishing the material removal model of MRF[13], presenting an algorithm of MRF with spiral scan mode[14], and studying removal of subsurface damage in grinding by MRF[15] . A diameter of 80 mm K9 glass flat mirror was finishing by MRF technology at National University of Defense Technology. The figure error of the mirror had been improved from the initial rms value 0.031λ to root mean square (RMS) value 0.01 λ just through one iteration[16]. In addition, some other research groups in China are also working on study of MRF technology, and some beneficial results were achieved[17-18].

2 Magnetorheological finishing process

A typical MR polishing fluid consists of carbonyl iron (CI), nonmagnetic polishing abrasives, water, other carrier fluids, and stabilizers[19]. In the absence of a magnetic field, the MR polishing fluid has the viscosity less than 0.5 Pa·s. Once introduced to a gradient magnetic field, the viscosity of the MR polishing fluid increases several orders of magnitude. The MRF fabrication mechanism utilizes this rheological alteration of MR fluid in a gradient magnetic field to create a flexible and extremely stable "subaperture polishing lap" that is used to carry out a deterministic polishing process on optical components.

A photograph of a MRF machine is shown in Fig.1(a). Fig1(b) shows the schematic of this MRF machine. MR polishing fluid with viscosity of 0.2 Pa·s is pumped from the conditioner to the nozzle where it is ejected onto the rotating wheel as a ribbon. The rotation of the wheel drags the MR polishing fluid upon the optical component in region where it is acted by the magnetic field. The MR polishing fluid ribbon is stiffened by magnetic field and sequentially dragged by the rotation of the wheel to flow through the converging gap between the wheel and the optical component. The materials of the optical component are removed by shear forces that are created by the interaction among the wheel, stiffened MR polishing fluid, and the optical component. Rotation of the wheel continues to drag the MR polishing fluid from the gap over to the region near the scraper where the magnetic field does not act on the MR polishing fluid. Therefore, the MR polishing fluid recovers to initial state, and then pumped back to the conditioner where it is cooled to a setpoint temperature and any evaporative losses are replaced.

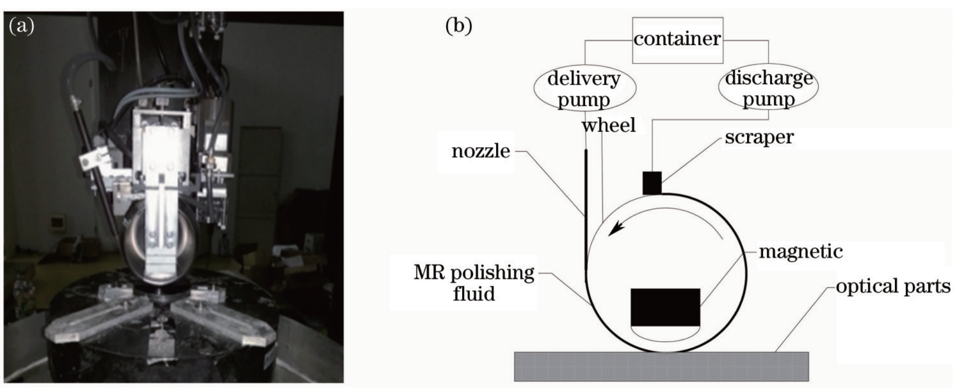

Fig.1 MRF machine. (a) Photograph of MRF machine; (b) schematic of MRF machine

The advantages of MRF mainly include:

1) flexible polishing tool conforming the various shape optical components;

2) no subsurface damage because of material removed by shear forces;

3) process parameters are extremely steady and controllable, hence MRF has in- variant material removal function;

4) high-efficiency material removal can be obtained by choosing suitable polishing powder;

3 Recent progress of magnetorheological finishing at CIOMP

3.1 Preparing of a new-style MR polishing fluid

Materials of optical components are removed by the rheological characteristic of MR polishing fluid in MRF process. Therefore, if a fine polishing result is expected to be obtained, a kind of excellent MR polishing fluid should be prepared firstly. Good performances of MR polishing fluid include excellent rheology, extremely physical and chemical stability, high polishing efficiency and so on. Based on study of mechanism of dispersion stability, we analyzed and optimized the ratio of MR polishing fluid additives and prepared a new-style MR polishing fluid. The composition proportion of MR polishing fluid is shown in table 1.

Table 1 Composition proportion of MR polishing fluid

Ingredient	De-ionized Water	Carbonyliron powder	Polishing powder	Dispersant	Wetting agent	Thixotropic agent	Other agent	pH
Proportion	56%	40%	1%	1%	1.5%	0.2%	0.3%	10%

The new-style MR polishing fluid was placed for 7 days, we did not find precipitation and stratification in MR polishing fluid, which indicated that stability of the MRF fluid was very good. The viscosity of MR polishing fluid outside of the magnetic field was tested by viscometer (Brookfield), the test result was shown in Fig.2. Fig.2 shows that the apparent viscosity of MR polishing fluid decreases as the shear rate increases. The viscosity of MR polishing fluid at 100 r/min shear rate is 0.2 Pa·s. In MRF process, the viscosity of MR polishing fluid outside of the magnetic field is kept low so that it is pumped easily by the fluid delivery system.

The rheology of MR polishing fluid was tested by rheometer (MCR302), the test result was shown in Fig.3. Fig.3 shows that the dynamic yield stress of MR polishing fluid increases as the magnetic field intensity increases. The dynamic yield stress of MRF fluid is 42.5 kPa at 0.35 T of magnetic field intensity. In MRF polishing region, the dynamic yield stress of MR polishing fluid is big enough to carry out efficient polishing.

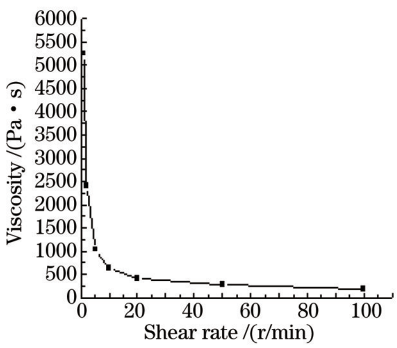

Fig.2 Viscosity test result of MRF fluid

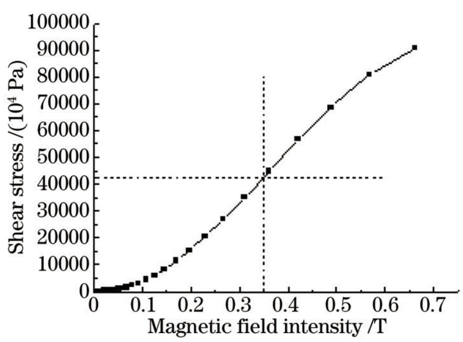

Fig.3 Shear stress of MRF fluid at different magnetic field intensities

In order to test the polishing stability of the new-style MR polishing fluid , 3 removal function (polishing spot) experiments were carried out on a Φ 80mm K9 glass flat mirror by MRF over a period of 2 hours. The polishing time of each polishing spot was 10s, and the two adjacent polishing time interval was approximately an hour. Process parameters were as follows: 1) the diameter of polishing wheel is 160 mm; 2) rotation speed of the wheel is 120 r/min; 3) the gap between the mirror and the wheel is 1.1 mm; 4) temperature is 22 ℃.

After polishing, these polishing spots were measured on Zygo interferometer. The test results are shown in Fig. 4. According to analysis of the test results of polishing spots, some conclusions are drawn as follows: the peak-valley polishing removal rate is 4.83 μm/min, the instability of the MRF process is less than 1%.

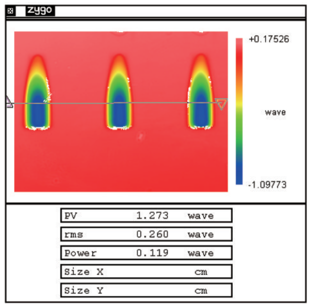

Fig.4 Test results of polishing spots

The above discussion indicates that our MR polishing fluid has extremely physical and chemical stability, good rheological property, and high polishing efficiency.

3.2 Study of an effective dwell time algorithm of MRF

The MRF principle is based on the Preston equation, which insists that material removal is the linear ratio compared to dwell time. MRF is a deterministic subaperture polishing process. It is common to employ a raster scan path and spiral scan path in MRF [20]. The amount of material removal of an optical component in MRF process can be expressed as:

$$E(x_i,y_i)=\sum_{j=1}^{N}R(x_i-\xi_j,y_i-\eta_j)\cdot T(\xi_j,\eta_j)\,, \tag{1}$$

where, $E(x_i,y_i)$ is the amount of material removal at coordinate (x_i,y_i), $R(x_i-\xi_j,y_i-\eta_j)$ is the removal function at coordinate (x_i,y_i) while the polishing spot dwells at coordinate (ξ_j,η_j), $T(\xi_j,\eta_j)$ is dwell time of polishing spot at coordinate (ξ_j,η_j), N is the total number of dwell coordinate points. For the actual process, the amount of material removal $E(x_i,y_i)$ is the surface residual error of optical component that can be known by measuring the component. The removal function $R(x_i-\xi_j,y_i-\eta_j)$ can be gotten by MRF experiments. In order to correct the surface error of optical component preferably, dwell time $T(\xi_j,\eta_j)$ should be solved accurately from equation (1) firstly.

In order to solve perfect dwell time $T(\xi_j,\eta_j)$ accurately, according to the actual physical meaning of equation (1), we transform the convolution expressed as equation (1) to a matrix that is expressed as:

$$\begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_M \end{bmatrix}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1N} \\ r_{21} & r_{22} & \cdots & r_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ r_{M1} & r_{M2} & \cdots & r_{MN} \end{bmatrix}\times\begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_N \end{bmatrix}. \tag{2}$$

The equation (2) may be simply described as $E=R\times T$. Where, E is the amount of material removal, R is removal function, T is dwell time, M is the number of removal coordinate points, and N is the number of dwell coordinate points. Such, the math model of MRF process changes from convolution to matrix product, and the calculation of the dwell time becomes a solution to linear equation. Traditional factorization methods such as Gaussian elimination and total least squares can't be used because the linear equations are severely ill condition. In order to solve the ill-posed problem caused by meterage error, the Tikhonov regularization is used, and the regularization parameter is determined by adaptive method. By comparing with other algorithms, the advantages of the matrix-based algorithm are obviously with the precision enhancing 30%[11]. The matrix-based algorithm for resolving dwell time is excellent, which can satisfy the requirement of MRF process very well.

3.3 A novel belt-MRF

The traditional MRF machine employs a polishing wheel to realize material removal. Restricted by the size of polishing wheel, the polishing spot area of this machine is relative small. Therefore, the application of traditional MRF machine is concentrated mainly on the small optics fabrication, and for polishing a large optical component, the traditional MRF machine has low polishing efficiency. The straightest way to improve the material removal rate is to increase the polishing spot area. Instead of using a large polishing wheel which is extremely demanding in terms of precision machining and assembly, we provided belt-MRF using a belt wrapping a permanent magnet box with large radius. The effect is equivalent to applying a polishing wheel with the same radius of curvature[21].

Figure 5 is a photograph of belt-MRF prototype. The operating principle of the belt-MRF machine is similar to that of the traditional MRF machine. MR polishing fluid is pumped from the conditioner to the nozzle where it is ejected onto the moving belt as a ribbon. The moving of the belt drags the MR polishing fluid upon the optical component in region where it is acted by the magnetic field. Then MR polishing fluid comes into a viscoplastic Bingham medium. As it flows through the converging gap between the wheel and the optical component, the materials of the optical component are removed by shear forces. As shown in Fig. 5, the bottom radius of permanent magnet box is 500 mm and according to the measured size, the chord length is about 68 mm. Therefore, a large polishing spot area may be produced in belt-MRF process.

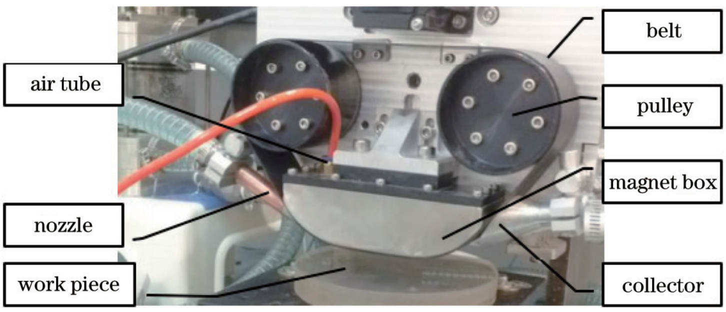

Fig.5 Photograph of core part of belt-MRF

Three material removal function (polishing spot) experiments of belt-MRF were carried out on a 100 mm diameter flat SiC specimen. The belt speed is 1, 1.5, 2 m/s, respectively, and each polishing time is 10 s. The detailed belt-MRF process parameters are shown in table 2.

Table 2 Process parameters of belt-MRF

Belt speed /(m/s)	Flow of MR fluid /(L/min)	Ribbon height /mm	Insertion depth /mm	Polishing time /s
1.0	1.70	3.5	1.8	10
1.5	2.55	3.5	1.8	10
2.0	3.42	3.5	1.8	10

Afterwards these polishing spots were measured on Zygo interferometer. The test results were shown in Fig. 6. According to analysis of the test results of polishing spots, some conclusions are obtained as follows: The maximum material removal rate of belt-MRF is proportional to belt speed. The polishing spot area of the traditional MRF machine (200 mm diameter wheel) is about 15 mm×6 mm, and the polishing spot area of the belt-MRF machine is approximately 52 mm×7 mm which is much larger than that of the traditional MRF machine. In addition, the magnetic field intensity at the polishing spot of the belt-MRF machine is similar to that of the traditional MRF machine. Therefore, the polishing efficiency of the belt-MRF machine is higher than that of the traditional MRF machine.

However, the stability of the belt-MRF machine is not as good as that of the traditional MRF machine and the shape of the polishing spot of the belt-MRF is too long and narrow, which is not conducive to correct surface residual error of an optical component fast and accurately. We are committed to the research of belt-MRF technology now and hope it can apply to the actual project early.

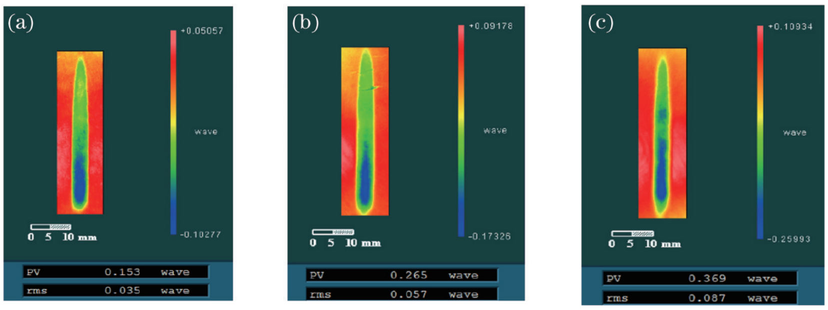

Fig.6 Test results of belt-MRF polishing spots. (a) Belt speed 1 m/s; (b) belt speed 1.5 m/s; (c) belt speed 2 m/s

4 Conclusion

MRF becomes an extremely effective technical method for fabricating optical asphere. Recent investigations of MRF at CIOMP include: we prepared a new-style MR polishing fluid, the polishing efficiency of MRF is improved evidently by using this new-style MR polishing fluid; we presented a dwell time algorithm of MRF based on matrix algebra, which dwell time of MRF can be solved accurately and rapidly by this method; in order to increase the size of removal function (polishing spot) and improve the material removal rate, we presented Belt-MRF, which is fit for polishing large aspheric optics. At present, the traditional MRF has been applied to the actual project, and we hope Belt-MRF can apply to actual polishing of large aspheric optics early.

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