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RESEARCH ARTICLE

Magnetorheological finishing of optical surface combined with symmetrical tool function

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Abstract This research is aimed at the development of computer-aided polishing technology for optical surfaces using magnetorheological (MR) fluid as medium. The mechanism of a dual-axis polishing wheel and the mathematical model combined with a symmetrical tool function are demonstrated. The effects of speed, gap, time and geometric parameters of the tool have been experimentally evaluated by polishing a parabolic BK7 mirror in 120 mm diameter. The surface topography presented an obvious amelioration, and the shape accuracy decreased to 0.067λ from 0.519λ ($\lambda = 632.8$ nm, RMS) after 75 min finishing.

Keywords magnetorheological finishing (MRF), material removal, symmetrical tool function

1 Introduction

Magnetorheological finishing (MRF) is a deterministic polishing technology for optical surfaces [1]. Researchers focused their efforts on magnetorheological (MR) theory, MR fluid, and the development of MRF system. A single motion MR tool was investigated, and its removal function was analyzed [2]. Then, Finishing experiments on various kinds of glass materials have been implemented and resulting the achievements of high accuracy optical components [3–5]. However, in these reports, the removal function is characterized as an asymmetrical profile. According to the Preston hypothesis, material removal is convolution of a unit removal function and the dwell-time, and the unit removal function reflects the performance of the polishing tool, which had better present a symmetrical Gaussian profile. To achieve an optimization on the finishing process, a symmetrical removal function is necessary for tool-path planning and dwell-time distribution [6].

In this paper, a dual-axis wheel with internal magnets is designed and mounted on a fix-axis polishing machine. A symmetrical tool function is established based on the MRF machine, and the processing parameters are confirmed by MR polishing a parabolic mirror.

2 Mechanism of MRF tool

MR fluid will stiffen significantly and vary from Newtonian to visco-plastic Bingham fluid under the action of a magnetic field. Therefore, one precondition for successful MR polishing is the generation of suitable gradient of magnetic field. The previous works, however, all adopted tools that rotate about only one axis (the self-rotating axis). Little work was reported on using other wheel tool design. The present work serves to advance in this direction. Figure 1 shows a home-made MRF tool, which is characterized as a dual-axis wheel driven by gear case and guaranteed the transmission accuracy. The rotation of the wheel around the horizontal axis is driven by one motor, while the revolution of the wheel around vertical axis is driven by another motor. A pair of ring magnets arranged symmetrically on the two sides of the wheel tool. The orientation is such that the tool's self-rotating axis is normal to the ring magnets at their centers. N-pole of one magnet is placed on the outer periphery while S-pole of the other on the outer. And the flexible polishing ribbon is generated when MR fluid applied in the magnetic gradient field of the wheel.

3 Mathematical modeling

Figure 2(a) shows the MR polishing tool with MR fluid.

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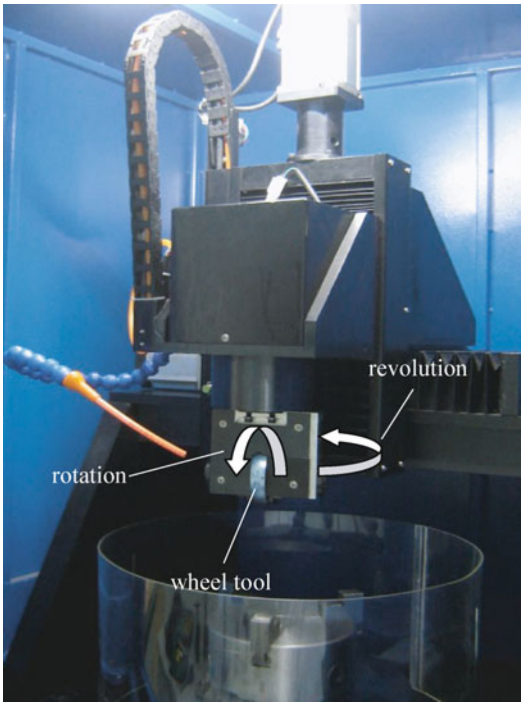

Fig. 1 Photo of MRF tool

Different compositions of MR fluid in the gradient magnetic field show different viscosities. The viscosity affects the shape of MR fluid. For the same MR fluid, viscosity increases significantly along with the magnetic field strength. And experimental results show that the MR fluid shape varies with the magnetic field strength. Furthermore, the different velocities are also associated with the shape. Conclusively, the MR fluid shape is associated with the magnetic field strength.

The profile of the MR fluid in Fig. 2(b) is similar to a parabolic curve [7]. Parabolic equation can be described as

$$z = ax^2 + bx + c, \tag{1}$$

where a, b, and c is the equation coefficients identified by the coordinates L_1, L_2, and L_3. Since the parabola is symmetrical about the Z-axis, b is consequently zero. Revolution of the MR polishing tool introduces three-dimensional symmetrical tool function which is

$$z = a_1(x^2 + y^2) + c_1, \tag{2}$$

where a_1 and c_1 are the coefficients. Let Eq. (2) transform into another form which is

$$f(x,y,z) = a_1(x^2 + y^2) + c_1 - z, \tag{3}$$

where $f(x,y,z)$ presents the three-dimensional symmetrical tool function, z is approximately a const in the contacting region D.

MR fluid will become Bingham fluid under the effect of a magnetic field, and an MR ribbon is formed on the outer surface of the wheel. Analysis the polishing area shown in Fig. 3, because of the rotation and the revolution, the relative velocity is

$$V^2 = r_1^2\omega_1^2 + r^2\omega_2^2 = \alpha r^2 + \beta = \alpha(x^2 + y^2) + \beta, \tag{4}$$

where r_1 is the radius of wheel, ω_1 is the angular velocity of rotation, ω_2 is the angular velocity of revolution (ω_1, ω_2, r_1 are constants, $0 \leqslant r \leqslant D/2$), α and β are the coefficients.

Generally shear stress of Bingham fluid is proportional to the related velocity ($\tau = kv$). According to Preston equation, the removal function is

$$R = KPV = K\frac{\tau}{\mu}V = K_0\tau V = K_0K_1V^2$$
$$= K_2(ar^2 + b) = A(x^2 + y^2) + B, \tag{5}$$

where μ, K, K_0, K_1, K_2, A, and B are the coefficients.

Equation (5) is similar to Eq. (3). Therefore, symmetrical tool function in some cases can be used as removal function. The coefficient A, B (or α and β) is related to

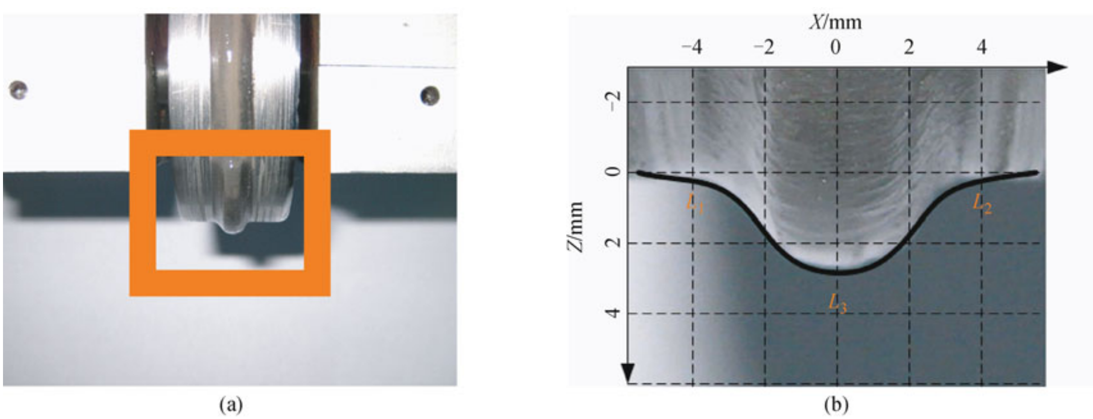

Fig. 2 (a) Photo of wheel tool; (b) establishment of coordinates

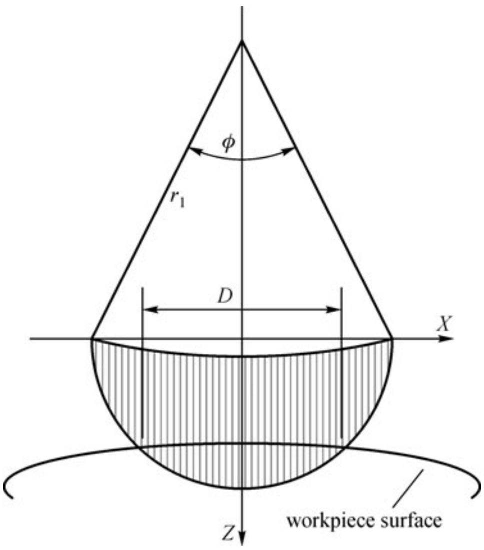

Fig. 3 Schematic of polishing area

magnetic field intensity, MR fluid, environmental temperature, work-piece material. As shown in Fig. 4, a typical symmetrical removal function was simulated, and compared with asymmetrical removal function.

4 Experiments and discussion

In order to obtain the actual removal function, a series experiments are carried out as shown in Table 1. The surrounding temperature is 20°C. The oil-based MR fluid includes 10% abrasive particle CeO_2, magnetic field strength is 860 kA/m, polishing time is 1 min.

The polishing area was measured by Zygo interferometer and data analysis has also been performed. Figure 5 shows the *YZ* and *XZ* cross-section profiles of the polishing area respectively. The polished area emerges a circle of diameter approximately from 5 to 6 mm. The resulting

Table 1 Experimental parameters

No.	material	gap/mm	magnetic particle fraction/%	(rotation/revolution) /(r·min^{-1})
1	BK7	0.8	30	250/30
2	BK7	1.0	40	300/30
3	BK7	1.2	50	200/30
4	BK7	1.0	40	300/40
5	BK7	1.2	50	200/40
6	BK7	0.8	30	250/40

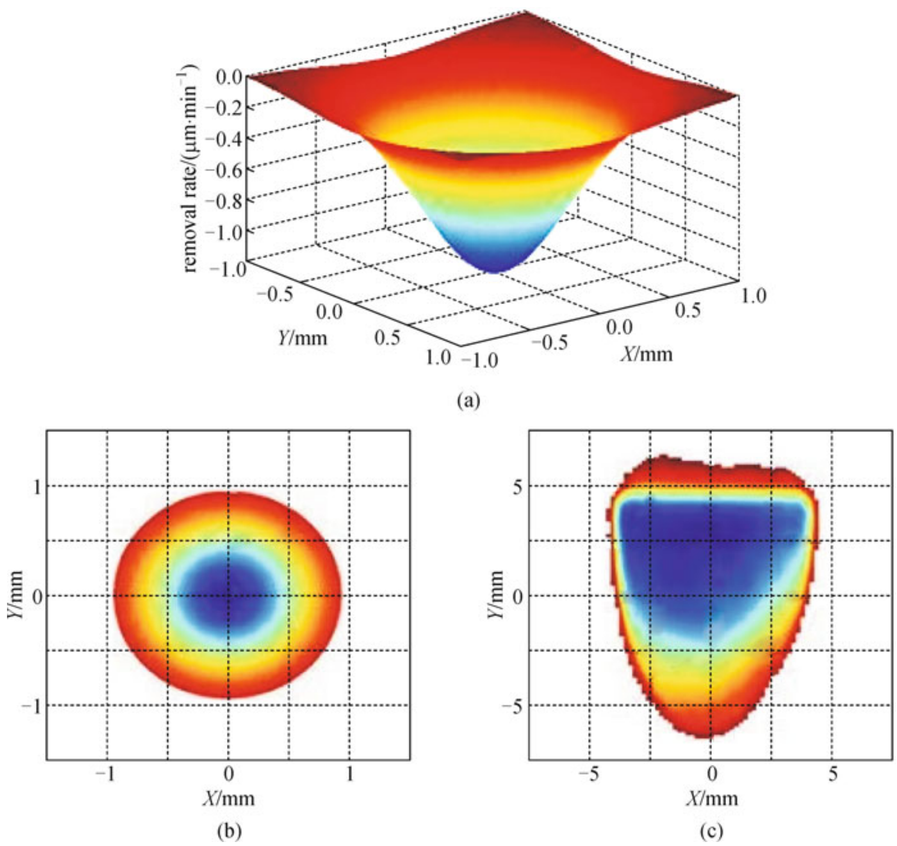

Fig. 4 Profile of simulated removal function. (a) Symmetrical removal function by authors; (b) top view of removal function; (c) top view of asymmetrical removal function by QED

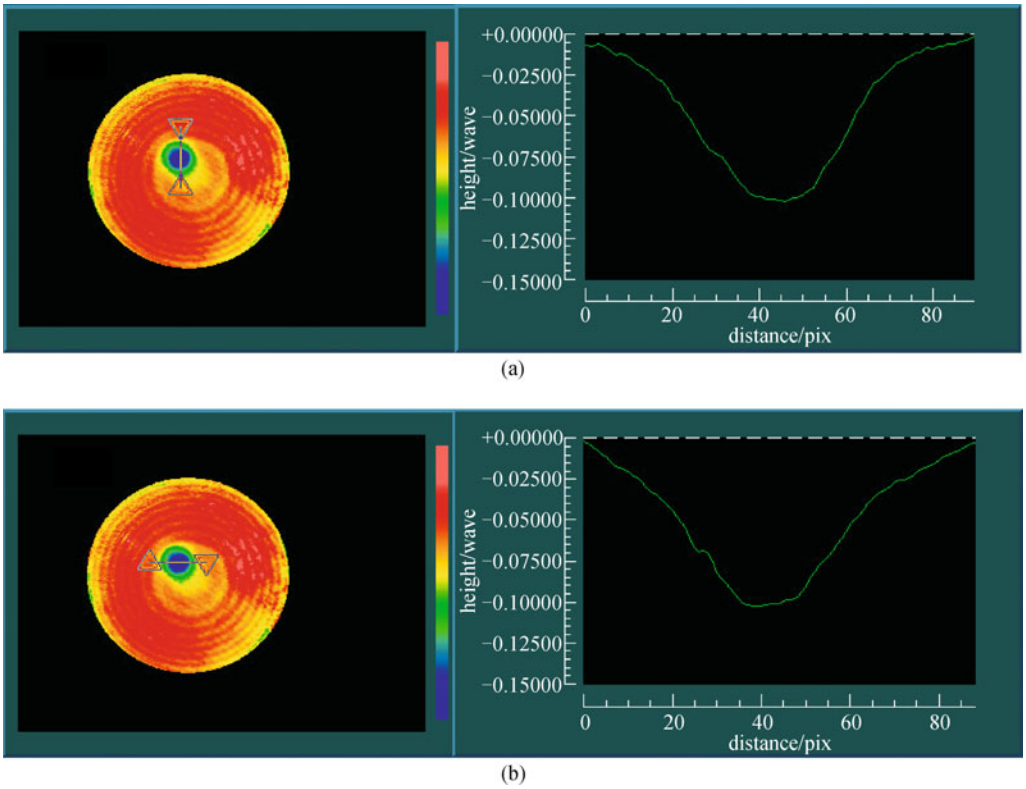

Fig. 5 Profile of experimental removal function. (a) *YZ* cross-section; (b) *XZ* cross-section

profile is close to Gaussian curve smoothly, which verify the mathematical modeling of the symmetrical removal function. Figure 6 shows the peak removal rates and volume removal rates. The results show the maximum rate of 0.068 μm/min and 1.34×10^6 μm^3/min, respectively, which means the efficient polishing for high accuracy processing. The experimental data accumulated in different conditions contribute to establish processing laws of Preston coefficient *K*.

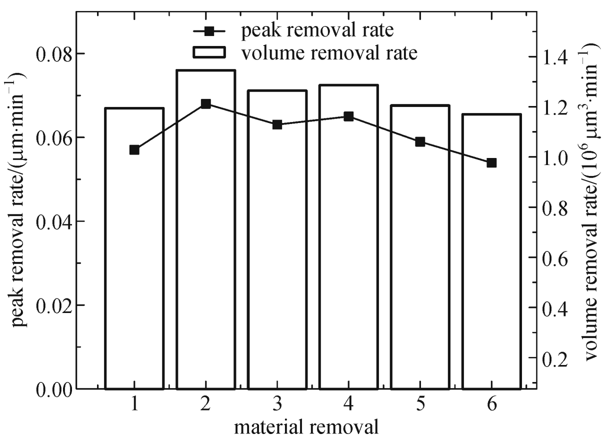

Fig. 6 Peak and volume removal rate of material removal

A 120 mm diameter parabolic BK7 mirror is polished using the MRF method, whose origin surface error as shown in Fig. 7(a). The dwell time of the spiral tool-path can be gained by the deconvolution calculation. The surface topographies after 75 min MR polishing is shown in Fig. 7(b). The PV value decreased from 1.726λ to 0.319λ and RMS value decreased from 0.519λ to 0.067λ (λ = 632.8 nm).

5 Conclusion

Material removal function plays an important role in improving the optical surface quality. This paper described a two-axis MR tool, and a symmetrical removal function was also studied. The effects of the symmetrical removal function were verified by MR polishing a parabolic mirror, whose surface accuracy convergent to 0.067λ from initial 0.519λ (RMS) after 75 min finishing.

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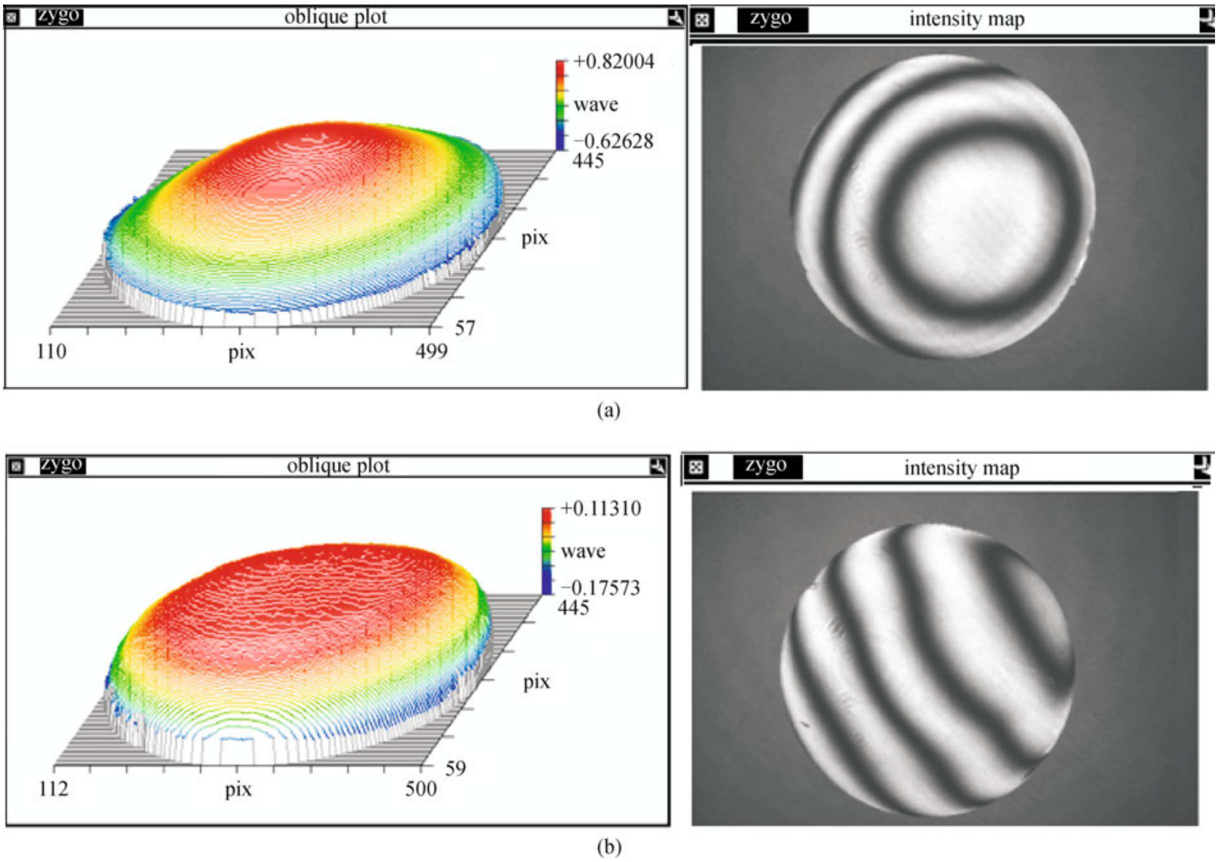

Fig. 7 Surface topographies. (a) PV = 1.726λ, and RMS = 0.519λ before MRF; (b) PV = 0.319λ, and RMS = 0.067λ after MRF

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