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Viscosity behavior of magnetic suspensions in fluid-assisted finishing

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Abstract

Magnetic fluid-assisted finishing has been verified both theoretically and experimentally as an effective fabrication technology for optical mirrors and lenses. The purpose of this paper is to introduce a novel design of polishing tool and demonstrate the possible applications of this technology. The work includes studying the viscosity of the magnetic suspensions of micrometer-sized Carbonyl iron particles under the influence of a magnetic field. Both the cases of magnetizable suspension with and without abrasive cerium oxide particles are studied for their ensuing polishing effectiveness. Determination of material removal function is conducted using a Wyko Nat1100 interferometer. Experiments to reduce surface roughness with the proposed tool are also performed using a K9 mirror as the work-piece. Results show that the surface accuracy is improved over three times to less than 0.5 nm after two cycles of polishing.

Keywords: Surface roughness; Micro-structure; Super-smooth; Fluid-assisted finishing; Material removal rate

1. Introduction

Magnetorheology fluid is essentially suspensions of micrometer size magnetizable particles immersed in a non-magnetic liquid. The fluid shows a unique ability to undergo rapid, significant, and near completely reversible changes in both mechanical and optical properties upon the application of an external magnetic field [1]. Magnetic fluid-assisted finishing is a technique that utilizes magnetic-field stiffened magnetorheological fluid ribbons for the polishing of a work-piece. Material removal occurs through the created shear stress when the fluids are dragged into the converging gap between the polishing tool and the work-piece [2]. The zone of contact is restricted to a spot much smaller than the work-piece's diameter, and the removal spot constitutes a sub-aperture pad that conforms perfectly to the local topography of the work-piece.

Applications of magnetorheological fluid have so far been largely focused on developing equipments such as controllable shock absorbers, vibration isolators, electromagnetic clutches and brakes, control valves, and artificial joints [3]. Other micro-fluidic devices involving lower concentrate magnetorheological suspensions have also been reported, especially in biomedical applications areas [4,5]. Relations between the microscopic structure and the mechanical and optical properties of these systems have also aroused considerable interest from a scientific point of view in the past decade or so [6,7]. In recent years, magnetorheological finishing (Mrf) of optical components has emerged as a popular research area of interest. Indeed, the above-mentioned sub-aperture pad occurred in Mrf is uniquely desirable in that it is adjustable through the magnetic field, and it carries away heat and debris from the working zone. Moreover, the pad does not lose its shape due to wear and tear. For these reasons, pioneering experimental studies on Mrf theory [8–13], systems [14], and

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processes have been actively pursued [15,16]. The present paper will further the study in this direction. Our study aims to introduce a novel design of polishing tool for Mrf and demonstrate its possible applications. Various experiments on micro-structures and viscosity behaviors of the magnetic suspensions under the influence of varying external field are also included.

2. A novel tool design

Mrf experiments have previously been carried out using more primitive tools [17–19], such as permanent magnets distributed symmetrically on the sides of an (nonmagnetic) aluminous plate. Given the performance intended here, a novel tool capable of providing an adjustable magnetic field with easy control of intensity is desired. Fig. 1 shows a wheel-shaped polishing tool designed for the present study. Fig. 1(a) presents the specific components comprising of a rotating wheel and electric coils made of brass wires distributed regularly along the direction of the self-rotation axis. Fig. 1(b) shows the rotating axes of the tool and the resulting magnetic field lines produced according to the laws of electromagnetism. Table 1 gives the design specifications of the coil.

3. Experimental studies

3.1. Fluids viscosity

Magnetorheological fluid is a stable mixture, whose the internal structure can be reversibly changed under the action of an external field. One of the intrinsic rheological properties that can be manipulated as such is the viscosity.

Table 1
Design specifications of the coil

Outer diameter of coil (mm)	Inner diameter of coil (mm)	Turn number of coil	Resistance (Ω)	Self-inductance coefficient (H)
65	28	2700	38	0.5

A commonly accepted model of magnetorheological fluid is the Bingham equation [20]

$$\begin{cases} \boldsymbol{\tau} = \boldsymbol{\eta} \cdot \dot{\gamma} + \tau_0 \cdot \mathrm{sign}(\dot{\gamma}), & |\boldsymbol{\tau}| \geqslant |\tau_0| \\ \dot{\gamma} = 0, & |\boldsymbol{\tau}| \leqslant |\tau_0| \end{cases} \tag{1}$$

where $\boldsymbol{\tau}$ and $\dot{\gamma}$ are, respectively, the shear stress and shear rate, $\boldsymbol{\eta}$ is the plastic viscosity, and τ_0 is a parameter dependent on the magnetic field yield stress. To deduce the shear stress $\boldsymbol{\tau}$, the viscosity of magnetorheological fluid $\boldsymbol{\eta}$ should be measured first. When the MR fluid with good fluidity is delivered into the working gap between the work-piece and the polishing wheel, it will become a plastic Bingham medium. An open viscometer is helpful to analyze the viscosity changing trend approximately although minor measuring errors exist. Fig. 2 shows the measuring device, which includes a NDJ-1 viscometer and a set of coils installed outside the columnar vessel filled with the magnetorheological fluid. The coil is constructed according to the specifications in Table 1. The magnetic field intensity is varied by adjusting the input voltage of the coil. This would in turn change the fluid viscosity, which is then measured by the rotor of the viscometer immersed in the fluid.

The present work utilizes Carbonyl iron (CI) particles (diameter @ 2 μm) with high saturation induction density

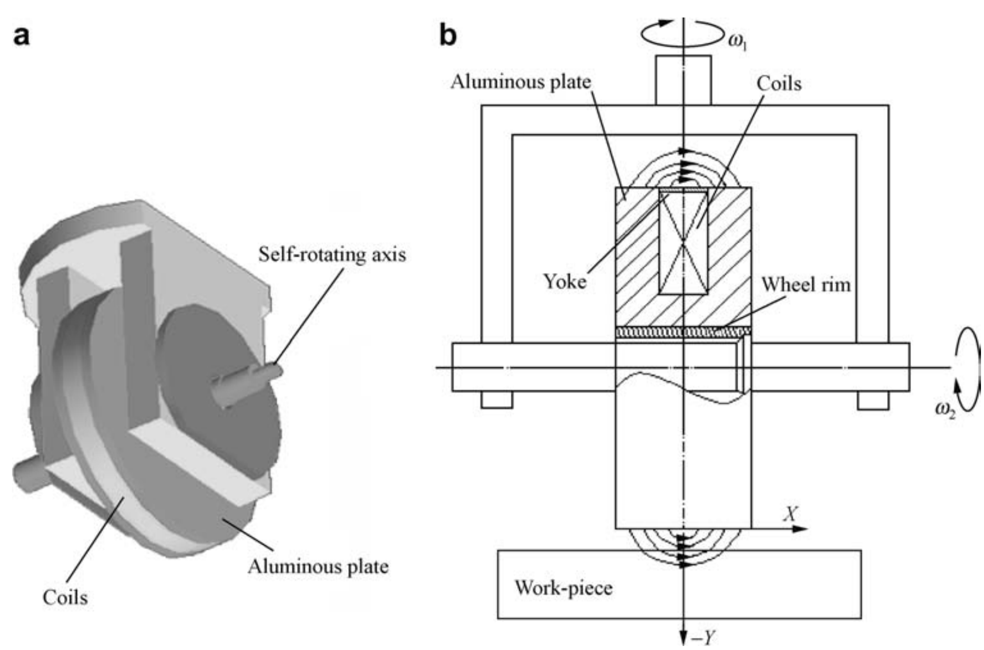

Fig. 1. Wheel-shaped polishing tool. (a) Three-dimensional structure; (b) rotating axes and magnetic field lines generated.

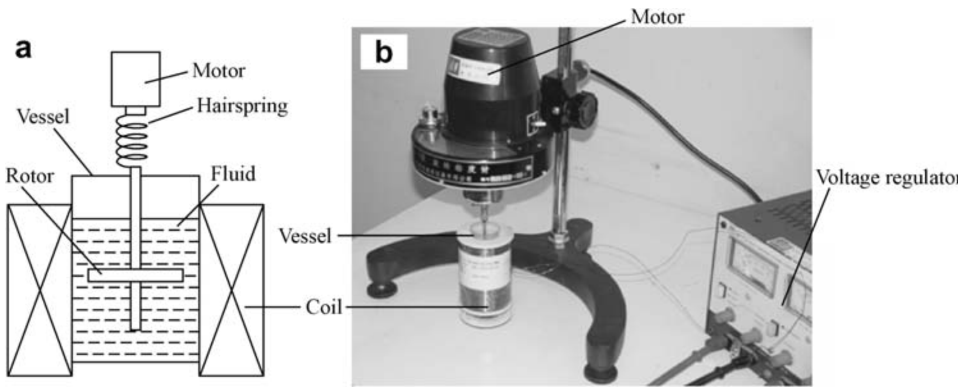

Fig. 2. Schematic diagram (a) and photo (b) of the testing device.

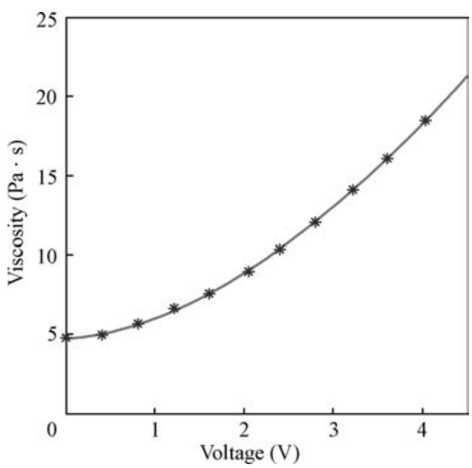

Fig. 3. Relation between input voltage and viscosity.

and low coercive force as magnetic particles. In order to avoid phase splitting and particles deposition, a surface pre-treating process is performed first. This includes mixing and whisking the CI particles with surface treatment solvent for 15 min at temperature 23 °C, putting the particles into an oven, and then heating and dring the particles until the solvent is absorbed completely into the surface of the CI particles. Volumetric component ratios of the magnetorheological fluid in the present study are 33.84% CI particles, 57.34% silicone oil, 2.82% stabilizing agent, and 6% cerium oxide (CeO_2) as abrasive particle. Such coefficients as hydrodynamic and magnetic pressure, shear stress and rate have previously been analyzed theoretically and experimentally [18]. In order to simplify the mathematic model and easily perform voltage controlling, effects of the magnetic intensity on the magnetic conductivity of the CI particles are neglected, and so the magnetic intensity $\boldsymbol{H}$ is proportional to the driving voltage $\boldsymbol{U}$

$$\boldsymbol{H} = k\boldsymbol{U} \tag{2}$$

where k is the distribution density function of the magnetic field.

The relation between the magnetic intensity $\boldsymbol{H}$ and the viscosity $\boldsymbol{\eta}$ of the fluid is [21]

$$\boldsymbol{\eta} = \boldsymbol{\eta}_0 + \alpha \boldsymbol{H}^n \tag{3}$$

where $\boldsymbol{\eta}_0$ is the original viscosity, α is a constant, and n stands for a coefficient in the range of 1–2 for different fluids. In the present study, we have $n = 1.725$. Combining Eqs. (2) and (3), we obtain

$$\boldsymbol{\eta} = \boldsymbol{\eta}_0 + \alpha(k\boldsymbol{U})^n = \boldsymbol{\eta}_0 + \alpha k^n \boldsymbol{U}^n \tag{4}$$

Using the measuring devices in Fig. 2, a curve describing the relationship between the driving voltage $\boldsymbol{U}$ and the viscosity $\boldsymbol{\eta}$ is obtained (Fig. 3). There is an obvious trend that viscosity would increase together with the driving voltage. Using regression analysis, the coefficients in Eq. (4) are determined as

$$\begin{cases} \boldsymbol{\eta}_0 = 4.72 \\ \alpha k^{1.725} = 1.24 \end{cases} \tag{5}$$

3.2. Magnetic suspensions

Fig. 4 presents several experimental results of the depositions of magnetorheological suspensions on the polishing tool to facilitate a better understanding of the behavior of magnetic and abrasive particles in the presence of an applied field. In the first study, silicon oil-based magnetic fluid without the mixing of abrasive particles CeO_2 is added to the tool. As the resulting pattern of the CI particles in Fig. 4(a) shows, the magnetic attractive force is the dominant factor in this situation. The particles hereby align with the lines of the magnetic force, resulting in a field-oriented structure.

The ability to hold as many abrasive particles as possible in the working area for a time as long as possible is of primary importance in Mrf. High density of abrasive particles at the contact surface between the work-piece and the tool would greatly enhance the machining efficiency and surface quality. With this in mind, magnetorheological fluid mixing with 6% ultra-fine abrasive particles CeO_2 is adopted in the next study. As can be seen in Fig. 4(b), the white CeO_2 particles are dispersed in the silicon oil and suspended into the slits between the magnetic CI structure.

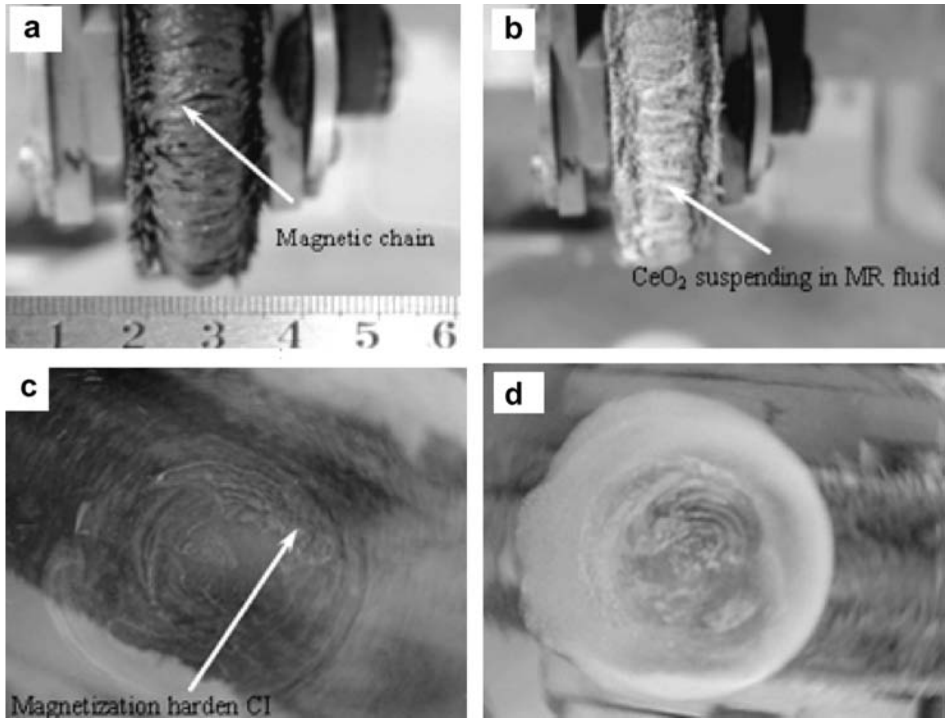

Fig. 4. Particles formation on the polishing tool. (a) A field-oriented structure of CI particles; (b) CeO_2 particles suspended in slits between magnetic CI chains; (c) polishing area created by CI particles directly scraping the work-piece; (d) vortex polishing pattern created by the presence of CeO_2.

To observe the pattern of the magnetorheological suspensions during the polishing process, a transparent glass plate is put in place as the work-piece, and a camera is installed underneath for direct observation. Fig. 4(c) shows the resulting behavior of the CI particles in a magnetorheological fluid without CeO_2 particles, under the condition that the wheel is self-rotating together with the co-rotating movements of the tool as in actual Mrf process. In this case, the magnetization hardened CI particles are observed to directly scrape the surface of the work-piece and take the form of a spiral arrangement.

For comparison, the CeO_2 particles with 1.5 μm size are put into the magnetorheological fluid. Both the self-rotation and co-rotation rates are kept 1× lower, creating a similar but not identical conditions to the above one. In this case, as the fluid is delivered to the surface of the tool during the polishing process, it is pulled against the tool surface by the magnetic field gradient and immediately attains a resultant velocity determined by the self-rotation and co-rotation. When the fluid reaches the small gap at the lower apex of the tool, it is squeezed between the surfaces of the tool and the work-piece, resulting in higher stresses. As shown in Fig. 4(d), most of the particles would not separate from the center of the polishing area as the tool rotates, and hence a vortex pattern is formed. This phenomenon results in an accumulation of CeO_2 particles and ensures a relatively higher concentration of the abrasive particles CeO_2 at the polishing area, producing a faster rate of material removal.

3.3. Material removal and surface micro-characteristics

The Preston equation commonly accepted in optical manufacturing dictates that an optimal material removal function is inherently one with a peak at the center and decreasing fairly rapidly to zero on the sides. To actually obtain the material removal profile of our polishing tool, a fixed-point polishing experiment is carried out. In this case, a K9 glass mirror ($K = 4.8 \times 10^{-13}$ m^2/N) is adopted as the work-piece. Other experimental parameters include: the radius of the polishing wheel is 35 mm, the gap size between the tool and the work-piece is 1 mm, the rotating speed of the polishing wheel is 180 rpm, and the polishing time is 5 min.

Fig. 5 presents the material removal function measured by a Wyko Nat1100 interferometer. The resulting smooth and Gaussian-like distribution reflects the stable removal characteristic of the MR fluids. Fig. 6(a) and (b) show the spiral pattern of material removal orbits observed in a 60× micro-camera and the three-dimensional Wyko interference image on the polished surface with a sampling resolution of 7.8 μm, respectively. These phenomena reflected in Figs. 5 and 6 are consistent with the expected operations of our polishing tool.

Finally, to highlight the fine figuring capabilities of our tool, the K9 glass work-piece is polished in two separate cycles, in similar fashion to previous experiments using permanent magnetic-based tools [18]. The results are given in Fig. 7. Keeping a relatively high viscosity of 18.3 Pa · s and

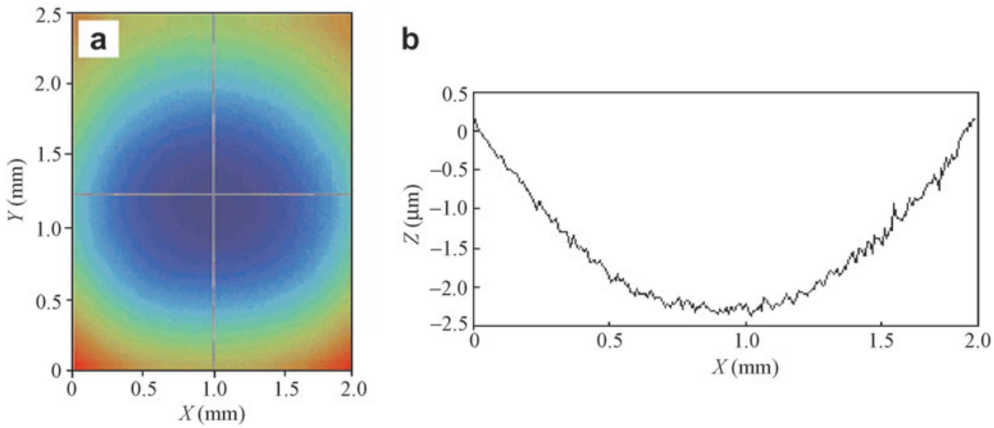

Fig. 5. Features of the material removal function. (a) Two-dimensional Wyko interference image demonstrating the contour of the polishing area; (b) a profile in the radial direction.

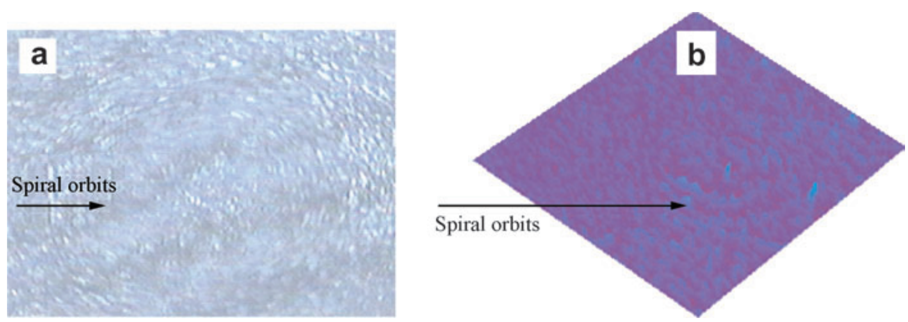

Fig. 6. Two- (a) and three-dimensional (b) images revealing the micro quality of the finished K9 medium.

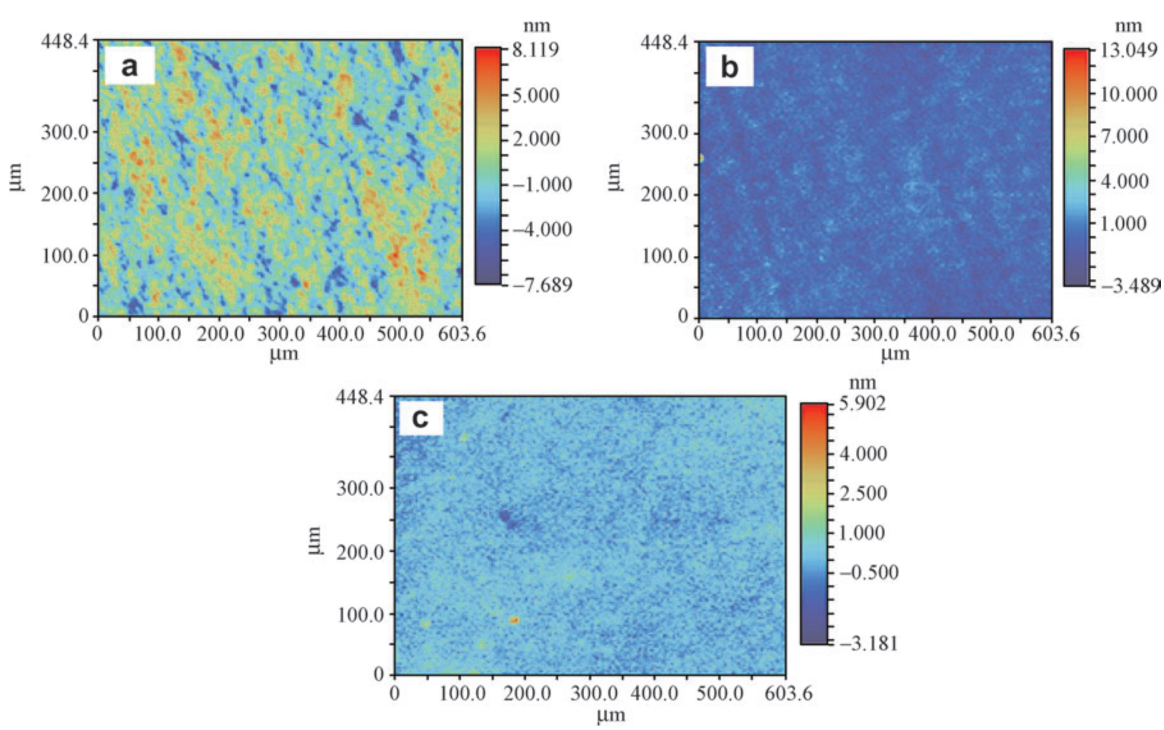

Fig. 7. Wyko measuring results revealing the nanometer surface roughness of the K9 glass test-part. (a) Original roughness: $Ra = 1.52$ nm; (b) roughness after 10 min polishing: $Ra = 0.61$ nm; (c) roughness after 30 min polishing: $Ra = 0.47$ nm.

a driving voltage of 4 V, the original surface roughness of 1.52 nm is improved to 0.61 nm after the first cycle of 10 min polishing. The surface roughness is further reduced to 0.47 nm upon a second run polishing of 20 min at a low viscosity of 8.9 Pa · s and a driving voltage of 2 V.

4. Conclusions

Magnetic fluid-assisted finishing is a promising technology for super-smooth fabrication of optical mirrors or lenses made of brittle materials. The technique is characterized by the rheology of suspensions containing micrometer size magnetic particles, whose properties can be rapidly modified by the application of a magnetic field. In this paper, we have introduced a novel design of polishing tool comprising of a self-rotating wheel and brass wire coils aligned to the direction of its rotation axis. The setup is capable of producing a magnetic field with the application of electric voltage to the coils. The work presents an experimental study to determine the magnetic fluid viscosity as a function of the applied electric voltage through the generation of magnetic field. The micro-structure and behavior of the magnetic fluids are also studied. Further experiments reveal the effects of magnetic field on the micro-quality of the polishing area between the work-piece and the polishing tool. Finally, polishing experiments are conducted using a K9 glass mirror as the work-piece. The surface accuracy of the mirror is improved from the initial roughness of 1.52 nm to the final value of 0.47 nm after a total of 30 min polishing. The present work demonstrates the feasibility of the proposed design tool in producing a controllable magnetic field for Mrf.

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