Fundamental research on aspheric surface polishing using doughnut-shaped MCF polishing tool

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Abstract. Previous researches have confirmed that MCF (magnetic compound fluid) slurry shows outstanding performance in the Nano-precision polishing of flat surfaces and V-grooves. However, no investigations have been conducted on the polishing of aspheric surfaces using MCF slurry. In this work, a novel method employing a doughnut-shaped MCF polishing tool and a 6-DOF manipulator has been proposed for the aspheric surface polishing. At first, the distribution of abrasive particles is detected by SEM and EDX mapping. Then, the time consumption for forming stable polishing tool and its final appearance are investigated. A plate-shaped aluminum alloy workpiece that can be considered as a kind of aspheric elements with infinite curve radius is adopted in the experiment. As a typical experimental result, the polished area and the profiles of cross section after every 30 min polishing are recorded in which a concentric circle polishing area is attained with almost Ø34 mm outer diameter and Ø15 mm inner diameter, the material removal is marked by maximum removed depth and the surface roughness $R_a$ decreases from 125 nm to almost 11 nm after 90 min polishing, confirming that the proposed method has the potential to polish aspheric surfaces.

Introduction

The surface profile of commonly used optical components includes plane, sphere and asphere. Especially, aspheric optical elements are of increasing importance in the optical field because of their prominent performance in improving the imaging quality of optical system and reducing the total cost compared with spherical optical elements [1]. The aspheric element could be classified into axisymmetric asphere and non-axisymmetric asphere. The latter is namely free-form surface and off-axis surface [2]. The traditional aspheric elements contain parabolic, hyperboloid and ellipsoidal mirror/lens. They are extensively applied in national defense military industry, aerospace, medical industry, laser industry and other commercial fields. The main products include Off-axis three mirrors optical system, astronomical telescopes, digital cameras, smart devices, and so on. Those optical instruments require materials with properties of low-weight, high-strength and stiffness, appropriate thermal conductivity, good manufacturability and low-cost. Hence, the conventional materials for aspheric optical elements and can be roughly divided into metals (e.g. aluminum, beryllium), optical plastics (e.g. TPX, SAN), optical crystals (e.g. alkaline earth fluorides, laser crystals), IR materials (e.g. metallic germanium, silicon, gallium arsenide) and Glasses [3]. However, The increasing demanding on performance, tolerances and capabilities have immensely prompted researchers to exploit new materials like CFC, SiC, CSiC and other specific materials. These materials are not only unaffordable but also unavailable or unreliable for all applications. Aluminum and aluminum alloys are eligible because of their heritage and the extensive knowledge of their properties, reliable and
predictable behaviors, which are essential for complex and accurate optical systems [4]. Hence, in this paper, the aluminum alloy 6061 will be chosen for the experiments.

The conventional methods to manufacture preliminarily high-quality aspheric elements made of crystals, metals, acrylic, and other materials are the single point diamond turning (SPDT) and the high precision grinding. The former is particularly appropriate for axisymmetric aspheric elements and the latter is capable of processing almost all kinds of aspheric elements [5, 6, 7]. However, these methods will remain tool marks and induce micro cracks and sub-surface damage on the work-surface. For the purpose of high precision, polishing process is required after SPDT and grinding [8]. Artificial polishing is an ancient method for polishing any kinds of surfaces, but it is hard to ensure the surface quality and form accuracy required. Instead of artificial polishing, Communication Computer Operating System (CCOS) is an ideal approach for modern asphere polishing for improving not only the surface quality but also the form accuracy. The CCOS improves the control accuracy in tool trace and pressure during processing with the codes programed in advance so that the process efficiency and precision can be enhanced tremendously compared with artificial polishing. Several creative methods have derived from the CCOS, for instances, bonnet polishing, magnetorheological fluid (MRF) polishing, etc. A. Beaucamp has polished a WC aspheric mold with a polyurethane polishing head and the surface roughness $R_a 1 \text{nm}$ is achieved finally, but the polishing tool is apt to be worn and needs to be repaired continuously to maintain the process accuracy during polishing [10]; A.K Singh has proposed a method to polish a Ø5mm stainless aspheric mold by a magnetic ball-tip polishing tool with the magnetorheological fluid for 20 minutes, eventually decreasing the surface roughness from $Ra 14 \text{nm}$ to $Ra 17.2\text{nm}$ [11]. Currently, polishing by using MRF as a smart slurry is the most promising and appropriate method for optical components because the polishing tool generated under a magnetic field has the most compatibility with the work-surface and can provide certain polishing forces to remove material. Therefore, many specific machines have been developed for commerce by utilizing MRF. Inspired by the advantages of MRF, the MCF slurry has been invented also for polishing. Our previous researches have confirmed that the MCF slurry shows outstanding performance in the nano-precision polishing of flat surfaces and V-grooves [9]; however, investigations have not been conducted on the aspheric surfaces polishing.

In this paper, a novel method for polishing aspheric surfaces is proposed by using a doughnut-shaped MCF polishing tool and employing a 6-DOF manipulator to control the MCF tool motion trace.

Processing principle and experimental details

Figs. 1 and 2 show the schematic drawing of aspheric surface polishing with doughnut-shaped MCF polishing tool using 6-DOF manipulator and an optic view of the experimental setup constructed. A MCF unit composed of a magnet holder, a hollow cylinder-shaped neodymium permanent magnet (Ø30 in outer diameter and Ø 9mm in inner diameter, t20mm, 0.5T), a slurry carrier (aluminum plate), two motors, a belt/pulley mechanism were developed and fixed onto a work-bench. In this unit, the carrier was located above the magnet and the magnet was fixed onto the magnet holder with an appropriate eccentricity $r$. When the magnet holder is rotationally driven by one of the motors, a rotary magnetic field is generated and a doughnut-shaped MCF polishing tool is formed. The other motor was connected to the slurry carrier via the belt/pulley mechanism to give the MCF slurry a revolution motion. On the end tip of the 6-DOF manipulator, a work-unit composed of a holder and a motor were mounted to hold and rotate the workpiece. The working gap $h$ and the workpiece tilt angle $\theta$ were determined by adjusting the position of the end tip of 6-DOF manipulator. Here, $n_w$, $n_c$ and $n_m$ are the rotation speeds of workpiece, slurry carrier and magnet holder, respectively. Fig.3 shows an illustration of material removal principle in which ferric clusters gathered by carbon iron particles under the rotary magnetic field that will stir and refresh those abrasive particles, and the $n_c$ mainly gives the relative motion between abrasive particles to workpiece surfaces to remove material.
composition of the MCF slurry used in the experiments is as followings: Water-based magnetic fluid (MF) wt.40%; 1μm size Al₂O₃ wt.12%; α-cellulose wt.3%; Carbonyl iron powders (CIPs) ~7μm size wt.45%.

In the preparation of the MCF tool sample for the abrasive distribution observation, the θ was set at 0°, the working gape was given at h=1mm, and the eccentricity was r=4mm. In addition, the magnet revolution speed, and the rotational speeds of the workpiece and the slurry carrier were set at \(n_m=500\)rpm in ccw, \(n_w=450\)rpm in cw and \(n_c=150\)rpm in cw, respectively. After a polishing operation has been carried out under these conditions for 2 min, the MCF slurry sample was dried naturally and the distribution of Al elements within Al₂O₃ abrasives on the sample working surface and cross section were investigated by SEM observation and EDX mapping.

The investigation on the final appearance of MCF polishing tool and the time consumption for obtaining the final tool appearance was conducted under different values of r, magnet revolution speeds \(n_m\) and supply volumes, but \(n_c\) was kept constant at 300 rpm in cw.

To confirm the feasibility of the proposed method in polishing, experiments were carried out with certain process parameters. After polishing, the workpiece was cleaned by water rushing and then dried for 15 minutes; surface roughness and its cross-section profile were measured by using Zygo white light interference and Taylor profile detector. During polishing experiments, MCF slurry was renewed every 5 minutes for guaranteeing the ability for polishing.

**Experimental results and discussion**

**Abrasive particles distribution**

Fig.4 (a) shows the top (left side) and cross section (right side) views of the MCF sample, and Fig.4 (b) shows the microscopic SEM images (upper sides) and EDX mapping images (lower sides) for different areas on the working surface and the cross section shown in Fig.4(a). The Al element within Al₂O₃ abrasives was marked by green color in EDX mapping images. It is obvious that the Al
elements can be observed either in the top surface or in the cross section, indicating that abrasive particles distribute evenly inside the MCF slurry. This demonstrated that the abrasive particles have been stirred and refreshed by abundant ferric clusters under the rotary magnetic field during processing.

Fig.4 (a) The top and cross section views of the MCF sample, (b) the microscopic SEM images and EDX mapping images

Fig.5 Time consumption, width, height and final appearance of the polishing tool

**Polishing tool formation**

The time consumption and the final appearance of the polishing tool at different eccentricities $r$ are shown in Fig.5. Evidently, when the $r$ was larger than 2mm, the time consumption was shortened to less than 1s. Especially, at $r=4$mm, the final appearance of MCF polishing tool looks like a pretty doughnut. However, as the value of $r$ was increased or decreased from 4mm, the shape of doughnut was deteriorated, leading the volume of MCF slurry in the fringe of doughnut to becoming too big or too small; thus, the ability of polishing tool for polishing would be weakened. Consequently, in the polishing experiments, the eccentricity $r$ was set at 4mm. The effects of the $r$ on the final width and maximum height were also exhibited. As the increase of eccentricity $r$, the width increases slightly then decreases a little. As to the maximum height, it decreases first and then turns to increase. Obviously, it has a negative relationship with the width. This is because the volume supplied is a certain value (1 ml) so that it limits the height to increase when the width increases.

As shown in Fig.6(a), as the revolution speed of magnet increases the width and height almost keep constant, but the time consumption decreases sharply. In the initial appearance of MCF slurry (1 ml) (see Fig.6(a)) there remains a gap. Once the magnet has been rotated, the rotary magnetic field drives the MCF slurry to form a whole doughnut-shape polishing tool so that the gap is eliminated and the time for forming stable polishing tool depends totally on the revolution speed of magnet.

The supply volume of MCF slurry affects the width and height deeply; both of them have the positive relationship with the supply volume. The time for forming polishing tool decreases almost 62% when the supply volume increase from 0.5ml to 1ml, then the decrease trend reduces gradually as the supply volume increase. The more supply volume of MCF slurry induces the less gap occurred in the initial state, which directly leads to shortening the forming time.
Polishing feasibility

A plate-shaped aluminum alloy workpiece (Ø50mm x t5mm) that can be considered as a kind of aspheric elements with infinite curve radius is adopted in the experiment. As a typical experimental result, Fig.7(a) shows the optical image of polished area and the profiles of cross section A-A after every 30min polishing under the conditions of $n_c=250$ rpm in cw, $n_w=450$ rpm in cw, $n_m=500$ rpm in ccw, $h=3.5$ mm, $\theta=6^\circ$, the volume of MCF slurry $=1.5$ml. It is obvious that a concentric circle polishing area was attained with almost Ø34 mm in outer diameter and Ø15 mm in inner diameter. In the figure, the parameter $d$ means the maximum removed depth in the profile. Thus the material removal can be calculated by the $d$ based on the A-A section profiles. A 3D microscopic image of the polished work-surface and the variation of work-surface roughness $R_a$ during polishing are recorded timeously. Each plotted point for $R_a$ was the mean of five $R_a$ values measured at 5 different locations on the polished area. The surface roughness $R_a$ decreases 44% quickly in the first 15 min, and the work-surface continues to be smoothed during following polishing, finally it decreases from 125nm to 10.789 nm after 90 min as shown in Fig.7(b). Obviously, during polishing the depth of polished area, i.e., the material removal increased and the $R_a$ decreased. According to this experiment, it is demonstrated that this novel method has the certain ability to remove material and smooth work-surface to Nano level.
Conclusions

This paper proposed a novel polishing method for aspheric surface with a doughnut-shaped MCF polishing tool. Experiments were conducted and results can be summarized as following:

1) The dried MCF slurry sample has been made for observing the abrasive particles distribution. Those abrasive particles could be tracked evenly not only in the top surface of the sample but also in the cross section, demonstrating that the abrasive particles have the possibility to remove material and to be stirred and refreshed by the dynamic ferric clusters.

2) The time consumption and the final appearance of MCF polishing tool have been recorded at different eccentricity \( r \), magnet revolution speed and supplied MCF slurry volume. The eccentricity \( r \) is the most critical factor to achieve an appropriate doughnut-shaped MCF polishing tool. The revolution speed of magnet and supplied MCF slurry volume also can reduce time consumption for forming stable polishing tool and affect the width and height of the final appearance.

3) The experiment for verifying polishing feasibility has been carried out with a plate-shaped aluminum alloy workpiece. The material is removed by the single fringe of the polishing tool and a Nano level work-surface \((Ra=10.789\text{nm})\) has been attained after 90 min polishing. Therefore, this method has the certain ability for polishing aspheric surface and will be worth to be further studied in the future.

References


