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Fundamental performance of Magnetic Compound Fluid (MCF) wheel in ultra-fine surface finishing of optical glass

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ABSTRACT

This study investigates a new semi-fixed-abrasive, ultra-fine finishing method for optical glass using a magneticcompound fluid (MCF) wheel. This MCF wheel generates a thin, uniform MCF slurry layer on the entire circumferentialsurface of a ring-shaped permanent magnet placed between two non-magnetic plates. The MCF slurry is composed ofnano-sized magnetite particles, micron-sized iron particles, several 10 μm-sized α-cellulose fibres and sub-micron-sizedabrasive particles that react to the magnetic field. Following modifications to the design of the MCF, experiments wereconducted to evaluate the performance of the modified wheel in spot-polishing fused silica glass. This paper describes themodifications to the MCF wheel and the experimental setup used to measure its performance. The improvement of themodified wheel over the unmodified wheel in terms of material removal and surfaces roughness is experimentallyconfirmed. The effects of the wheel rotational speed and the clearance between the wheel and the workpiece on materialremoval and the workpiece surface roughness are investigated. The polishing forces are measured, the structure of the MCFslurry is examined and the magnetic field distribution is analysed. A model of material removal in polishing with themodified MCF wheel is developed. The results indicate the following: (1) more material was removed, i.e., greater spotdepths, and better surfaces were obtained in the regions that were near the edges of the magnet; (2) the modified MCF wheelperformed much better than the unmodified wheel in terms of material removal and surface roughness, e.g., 3.1 μm vs. 1.7μm for the maximum spot depth, 0.04 mm3 vs. 0.0088 mm3 for the volume of material removed and Ra = 5.624 nm vs.14.67 nm for the surface roughness; (3) a better work surface and greater material removal were obtained with smallerworking clearances and higher wheel rotational speeds.

1. Introduction

Fused silica glass is widely used in scientific research and in industry for applications including semiconductors, optical communications and astronomical telescopes because of its excellent mechanical and chemical properties. In the manufacturing process of optical devices, optical glass is generally polished with a loose abrasive to eliminate breaks, cracks and damaged layers on the work surface caused by the previous process, which is typically grinding. However, to achieve the desired surface quality, the conventional loose-abrasive technique is time-consuming and therefore costly [1,2]. The causes are mainly the difficulties in maintaining an effective amount of the abrasive slurry and a uniform distribution of abrasive particles in the polishing area. In addition, because the cerium oxide (CeO_2) abrasive employed for highly efficient polishing of optical glass is a rare earth element, it is crucial to maximise the amount of active abrasive in the polishing area to minimise consumption of the abrasive. Therefore, novel polishing methods in which the abrasive particles can be distributed uniformly in the polishing area and which consume the minimum amount of active abrasive are in great demand.

Magnetic-field-assisted polishing has been recognised as an advanced finishing technique that can produce a mirror surface without causing surface or subsurface damage. This technique overcomes the fundamental limitations of traditional finishing techniques because the behaviour of the abrasive particles can be controlled by adjusting the magnetic field. Tani and Umehara [3,4] investigated fine polishing using magnetic fluids (MFs) in the presence of a magnetic

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field and reported an appreciably improved surface roughness on a flat polypropylene workpiece. Prokhorov and Kordonski [5,6] proposed a novel polishing technology using a magneto-rheological fluid (MRF) that consisted of magnetic carbonyl iron powder (CIP), abrasive grains, a carrier fluid, and stabilisers. With the application of a magnetic field, the MRF becomes viscous and acts as a type of Bingham fluid [7]. Kordonski and Gorodkin [8] proposed a concept of material removal based on the principle of conservation of particle momentum in a binary suspension to analyse material removal in magneto-rheological finishing and magneto-rheological jet processes. Cheng et al. [9] studied the polishing of optical aspheric components with MRF using a 2-axis, wheel-shaped tool supporting dual magnetic fields. Dai et al. [10] established a calibrated and predictive model of the removal function based on an analysis of the MRF process. Sidpara and Jain [11] measured the normal and tangential forces in an MRF-based finishing process. Singh et al. [12] proposed a nano-finishing process using a ball-end MR finishing tool that was used to finish flat and 3D ferromagnetic work surfaces. However, in a magnetic field the magnetic pressure and the apparent viscosity of MFs are lower than those of MRFs, but the stability of the particle distribution in MFs is better than that in MRFs.

To overcome the respective disadvantages and benefit from the respective advantages of MFs and MRFs, Shimada and Akagami [13,14] developed a Magnetic Compound Fluid (MCF) by mixing an MF and an MRF that had a higher magnetic pressure and apparent viscosity in a magnetic field and a more stable distribution of particles while maintaining the behaviour of a fluid. Shimada et al. [15] developed a new type of magnetic abrasive compound named MCF polishing liquid, which they created by blending abrasive particles and α-cellulose fibres with an MCF, and it was confirmed experimentally that the MCF polishing liquid performed well in constant-contact-force polishing. Furuya et al. [16] proposed a new contact-free surface finishing method for metal surfaces with a micro-3D structure using an MCF polishing liquid. Wu and Sato [17,18] researched the fundamental characteristics of an MCF polishing tool for metal surface finishing and three-dimensional workpieces.

In a previous study in which MCF slurry was used in surface finishing processes, the authors introduced a semi-fixed-abrasive polishing tool named the MCF wheel [19], which is illustrated in Fig. 1, for ultra-fine surface finishing of fused silica glass. An annular, i.e., ring-shaped, permanent magnet in which the magnetisation is parallel to the central axis of the annulus (X-axis) was fixed to a horizontal shaft that rotates with speed n_t. A workpiece was located below the magnet with a clearance δ. When a given volume of MCF slurry was introduced into the gap between the rotating magnet and the workpiece, a thin MCF slurry layer was generated on the circumferential surface of the magnet, resulting in the formation of an MCF wheel. Because of the edge effect, the magnetic field across the width of the magnet is stronger near the edges than in the middle. Thus, more of the MCF slurry was attracted to the edges and easily lapped the sides of the magnet because of the stronger magnetic force, decreasing the amount of MCF slurry in the middle and thus lowering the material removal rate to counter this effect, blades were placed on both sides of the magnet with a clearance Δ, which caused a thin MCF slurry layer to form on part of the side surfaces of the magnet in addition to the circumferential surface. Experiments were performed to determine the effects of the MCF wheel construction and process parameters on material removal and the workpiece surface roughness, and the performance of this new type of polishing tool for surface finishing of optical glass was confirmed.

However, there are still several practical weaknesses in this technique, such as the following: (1) a portion of the MCF slurry supplied is attracted to the sides of the magnet as before through the gap between the magnet and the blades and therefore does not contribute to material removal; (2) the clearance must be changed according to the composition of the MCF slurry and the processing conditions, which increases the processing cost; (3) the blades wear during polishing because of the abrasive action of the MCF slurry, which increases the equipment maintenance cost and the process time; and (4) the blades complicate the equipment, increasing the cost. Changes to the MCF wheel design are required to improve its performance in practical applications.

In this study, the design of the MCF wheel was modified, and the fundamental characteristics of the modified wheel in spot-polishing fused silica glass were investigated. The paper first describes the modifications to the MCF wheel design and the experimental setup. The performance improvement of the modified wheel over that of the unmodified wheel in terms of material removal and surfaces roughness is confirmed by the experiments. Next, the effects of the wheel rotational speed and the clearance between the wheel and the workpiece on material removal and the workpiece surface roughness are investigated. The polishing forces are measured, the structure of the MCF slurry is examined and the magnetic field distribution is analysed. A model of material removal through polishing with the modified MCF wheel is developed. Finally, the conclusions are presented.

2. Experimental setup, procedure and conditions

2.1. Experimental setup

Fig. 2 illustrates the experimental setup for polishing using the modified MCF wheel. To overcome the weaknesses in the technique used in the previous work [19] that were discussed in Section 1, the MCF wheel used previously was modified by installing ring-shaped, non-magnetic plates with the same diameter as that of the magnet on either side of the magnet, which is magnetised parallel to the central axis of the annulus (X-axis). Consequently, the two blades used in the unmodified MCF wheel (see Fig. 1) are no longer necessary (see Fig. 2). The magnet and the two plates are affixed to a horizontal shaft that rotates at a speed n_t. The workpiece lies below the magnet and the plates with a clearance δ. When a given

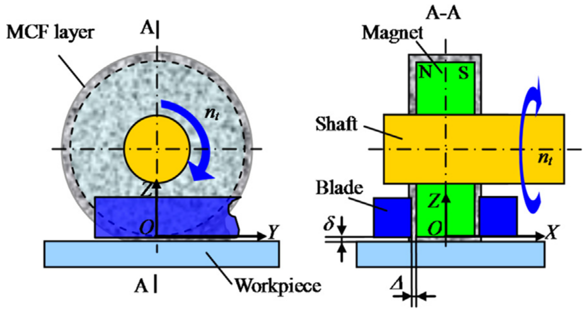

Fig. 1. Unmodified MCF wheel for surface finishing.

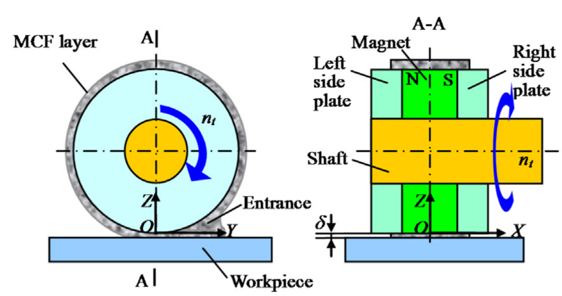

Fig. 2. Experimental setup for polishing using the modified MCF wheel.