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Technical note

Magnetorheological polishing using a permanent magnetic yoke with straight air gap for ultra-smooth surface planarization

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ABSTRACT

A permanent magnetic yoke with a straight air gap was developed as the magnetic excitation unit, in order to improve the efficiency of magnetorheological (MR) polishing for ultra-smooth surface planarization. Finite element modelling was used to simulate the magnetic performance of the newly developed yoke, which was found to agree well with the experimental measurement. With the developed MR polishing apparatus, the effects of trough speed, work and excitation gap width, particle concentration within the MR fluid and workpiece size on the material removal rate were systematically investigated. Final tests were performed on glass specimens to examine the polishing performance. The polishing area in the developed process was much larger than that of the conventional MR finishing process with a carrier wheel and ultra-smooth surface of 1 nm in R_a was achieved.

1. Introduction

In most of the machining processes for achieving ultra-smooth flat surfaces, polishing is required at the final stage of planarization in order to eliminate residual stress and remove surface (or subsurface) damage. Among the existing planarization techniques, lapping or polishing using loose abrasives was often used, however, it was difficult to obtain a surface that is fully free of surface (or subsurface) damage and residual stress [1–3]. Chemical mechanical polishing (CMP) can meet the requirement, but the process is less effective on some materials [4]. Elastic emission machining (EEM) was recently used for planarization, but its removal efficiency was extremely low too [5]. Magnetorheological (MR) polishing demonstrated as a valuable tool to produce damage-free and ultra-smooth surfaces in a reasonably efficient way [6,7]. In this process, MR fluid was formed into a stiffened fluid ribbon in a magnetic field, which was acted as a tool for polishing [8–10]. The stiffness and shape of the MR fluid ribbon could be controlled by adjusting the strength of the magnetic field, which play important roles on the performance of a MR polishing process.

The previous works were largely concerned with the process improvement through developing different MR fluid ribbons [7–16]. For example, Kordonski et al. [11] investigated a MR polishing process using the electromagnet with arc air gap as the excitation unit for deterministic sub-aperture polishing of concave, convex and flat surfaces. The MR process made significant impact for the production of ultra-precision optics. Nevertheless, the "spot" removed from the workpiece material in an individual removal event in the process is small and the polishing efficiency would become an issue if large surfaces were concerned. Singh et al. [12] later proposed a ball-end MR polishing process using a rotating electromagnet tube as the magnetic source, in which the MR fluid was stiffened to form a small ball at the end of the electromagnet tube. The process could finish typical 3D surface point-by-point, similar to ball-end milling, but in a much less aggressive manner. Seok et al. [13] investigated a MR finishing process using a ring-shaped permanent magnet as the magnetic excitation unit to finish curved surfaces on silicon-based micro-structures. Jiao et al. [14] introduced a ring-shaped permanent magnet for magnetic compound (MC) fluid finishing. They demonstrated that the developed process was suitable for the spot-polishing of ultra-fine optical glass surfaces. Jang et al. [15] developed a MR deburring process that used a rotating electromagnet, where a fluid ribbon was formed to have a slot-like shape between the two coils of the electromagnet and metal burrs of 200 nm high were effectively removed. In the aforementioned processes, the stiffened MR fluid ribbons (or the MC fluid ribbon) were basically ring-shaped, and

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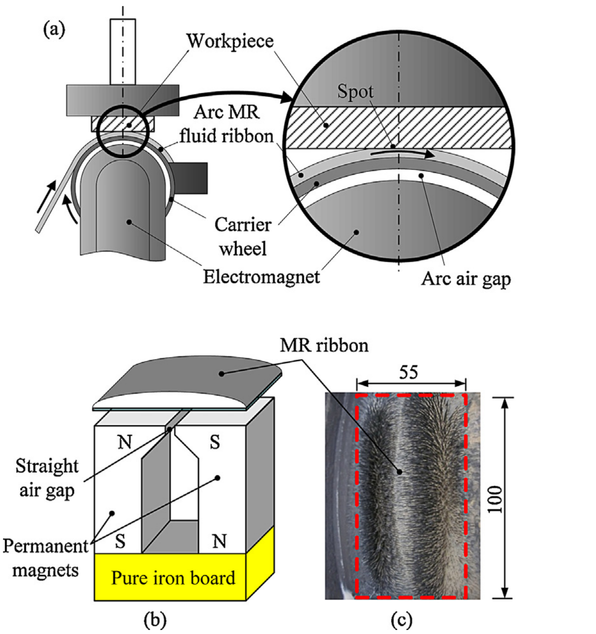

Fig. 1. Schematic illustrations of (a) the MRF apparatus that uses an electromagnet with an arc air gap [7] and (b) the new PM yoke with a straight air gap. (c) The optical image of the straight MR fluid ribbon formed.

the apical part of the ribbon was utilized for finishing. Jain and Sidpara [16] introduced a MRF process that used a rotating permanent magnetic block as magnetic source to finish silicon blanks for microelectronic applications, where the MR fluid was stiffened to form a MR fluid brush that rotates with the PM block.

In the existing MR polishing processes, the working area of the stiffened MR fluid ribbon is relatively small. Thus, they would be much less efficient when dealing with ultra-smooth planarization of relatively large surfaces. In order to develop a high efficient MR polishing process for planarization of large flat surfaces, this study attempted to use a permanent magnetic (PM) yoke that uses a straight air gap as the excitation unit. The new design of the yoke considerably enlarged the instantaneous contact area for polishing. The effects of excitation gap, work gap, trough speed, particle concentration and workpiece size on the polished surface and volumetric material removal rate were systematically investigated.

2. MR polishing apparatus and experimental details

2.1. The apparatus using a PM yoke with straight air gap

In conventional MR polishing, an electromagnet with arc air gap is often used as the magnetic source. As shown in Fig. 1(a) [7], MR fluid is stiffened to form an arc fluid ribbon when it is delivered over the air gap, and the workpiece interacts with the apex area of the arc fluid ribbon. Therefore, the contact area between workpiece and MR ribbon is small, which is thus inefficient for planarization of large flat surfaces. To enlarge the contact area between the workpiece and the MR ribbon, the commonly used arc air gap was replaced by a straight air gap on a PM yoke in this work. As shown in Fig. 1(b), the newly developed PM yoke consists of two permanent magnets that are made up of N50 grade NdFeB and a pure iron board at the bottom. The wedges of the two permanent magnets thus form a straight air gap, and thus the magnetic fields being generated are straight above the air gap. When MR fluid flows over the air gap, it is stiffened to form a straight MR fluid ribbon of 100 mm long and 55 mm wide, as can be seen in Fig. 1(c). During MR polishing, the flat workpiece surface is in contact with the ridge of the straight ribbon,

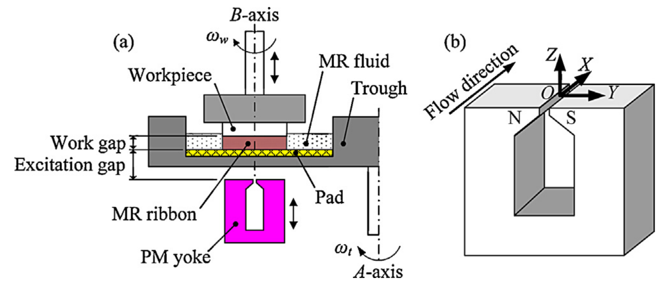

Fig. 2. (a) The MRF apparatus. (b) The coordinate system of the PM yoke for magnetic field analysis.

so a large rectangular area of polishing can be formed. It should be noted that although a much larger MR fluid ribbon was formed, the magnetic flux generated above the air gap was less uniform than the conventional process.

To examine the polishing performance of the new PM yoke, an experimental apparatus was developed. As shown in Fig. 2(a), the apparatus consists of a workpiece spindle that rotates around *B*-axis, a nonmagnetic trough that carries MR fluid and rotates around *A*-axis, and the PM yoke with a straight air gap underneath the trough. The trough bottom is covered with a porous pad that allows reliable mechanical adhesion between the MR fluid and the trough. A gap is maintained between the workpiece and the porous pad, which is named as the work gap. The gap between the top surface of the PM yoke and the top surface of the porous pad is defined as the excitation gap, which can be adjusted. During polishing when the PM yoke is elevated, i.e. the excitation gap decreases, the magnetic flux density in the work gap thus increases. When MR fluid flows over the air gap, it is stiffened to form a straight MR fluid ribbon. When the workpiece is in contact with the MR fluid ribbon, material removal takes place.

To analyse the magnetic field, a Cartesian coordinate system was established. As shown in Fig. 2(b), the original point (*O*) of the coordinate system is located at the centre of the air gap on the top surface of the PM yoke.

2.2. Polishing conditions

The first set of experiments was carried out to assess the performance of the new yoke. The volume of MR fluid used was 500 ml, in which the volume concentrations of carbonyl iron particles (CIPs, with a mean particle size of ~3.2 μm) and CeO_2 particles (with a mean size of ~0.5 μm) are 40 and 7 vol%, respectively. The excitation gap width was 6 mm and the working gap remained as 1.5 mm. During the polishing period of 60 min, the workpiece was kept at rest and the trough rotated at a speed of 40 rpm. The experimental conditions are summarized in Table 1.

The second set of experiments was carried out to study the effect of work gap and polishing time on polishing mark. In the first part, the work gap was varied from 1 to 2.5 mm at an increment of 0.5 mm while the polishing time was fixed at 30 min. In the second part, the polishing time was varied from 30 to 150 min at an increment of 30 min, but the work gap was fixed at 1.5 mm. The other conditions were kept the same as those in the first set.

The third set of tests was a parametric study, which was carried out to investigate the effects of trough speed, work gap, excitation gap, CIPs concentration, CeO_2 concentration and workpiece size on the volumetric material removal rate (*VRR*). Five tests were arranged and the experiment was designed based on the one-factor-at-a-time rule, i.e. if one parameter was varied the other parameters were kept constant. In the Test 1, *VRR* was studied as a function of trough speed. To reduce the influence of centrifugal force on polishing, the trough speed was set to be smaller than