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PRE-6259; No. of Pages 12
ARTICLE IN PRESS
Precision Engineering xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Precision Engineering
journal homepage: www.elsevier.com/locate/precision

Polishing characteristics and mechanism in magnetorheological planarization using a permanent magnetic yoke with translational movement

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 16 June 2015
Accepted 26 June 2015
Available online xxx

Keywords:
Magnetorhelogical planarization
Force
Roughness
Removal
Planarity

ABSTRACT

Translational movement was integrated into a magnetorheological planarization process that uses a permanent magnet yoke with a straight air gap as magnetic source in order to improve surface planarity. The effects of the process conditions, including stroke and velocity of the translational movement, work and excitation gaps and concentration of carbonyl iron particles, on the polishing forces, surface roughness and volumetric removal rate were systematically investigated. The results showed that translational movement had insignificant effect on the polished surface finish, but considerably improved the surface planarity. The surface quality and volumetric removal rate were found to be affected by carbonyl iron particles concentration, and work and excitation gaps. Based on the parametric study, theoretical and empirical models were established for predicting the polishing forces, surface roughness and volumetric removal rate in this magnetorheological process.

1. Introduction

The demand for ultra-smooth flat surfaces, such as those used for LED illumination, smart phone and tablet PC, has increased rapidly in recent years. Those surfaces need to be machined to have roughness at nanoscale and planarity of several microns without subsurface damage [1–6]. To date, ultra-precision lapping with loose abrasives has been the major technique to achieve such smooth and flat surfaces in mass production [1,7] because other processes, including chemical mechanical polishing (CMP) [8], elastic emission machining (EEM) [9] and ion beam finishing (IBF) [10] cannot meet the requirement for both efficiency and quality. Nevertheless, lapping often requires long processing time, as well as large and continuous supply of lapping slurry. Also, as the loose abrasives used are not always uniformly distributed during lapping, the resultant load concentration on the workpiece can easily cause subsurface damage [11,12].

Magnetorheological (MR) finishing has been widely used for polishing mirror surfaces [13–21] with promising removal efficiency. In our previous work, we developed a MR planarization process which uses a permanent magnetic (PM) yoke with a straight air gap [22]. The new MR apparatus allowed the instantaneous contact area for polishing being increased significantly. As a consequence, relatively large flat surfaces could be machined efficiently with satisfactory surface quality. Although the process demonstrated its potential for finishing relatively large planar surfaces, the uniformity of the magnetic field perpendicular to the air gap generated by the developed PM yoke need to be further improved [22]. To solve this problem, in this study a translational movement was integrated into the polishing process, aiming at improving the uniformity of material removal, hence the surface planarity.

In this work we systematically study the effects of the translational motion, including stroke and reciprocate velocity, and the process parameters, including work gap, excitation gap and particles concentration, on the planarity, roughness and removal rate of machined surfaces. In particular, the removal mechanism of the MR planarization process was discussed.

2. Experimental details

2.1. Experimental set-up

The schematic illustration and optical image of the MR planarization apparatus are shown in Fig. 1(a) and (b), respectively.

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http://dx.doi.org/10.1016/j.precisioneng.2015.06.014
0141-6359/

Please cite this article in press as: Wang Y, et al. Polishing characteristics and mechanism in magnetorheological planarization using a permanent magnetic yoke with translational movement. Precis Eng (2015), http://dx.doi.org/10.1016/j.precisioneng.2015.06.014

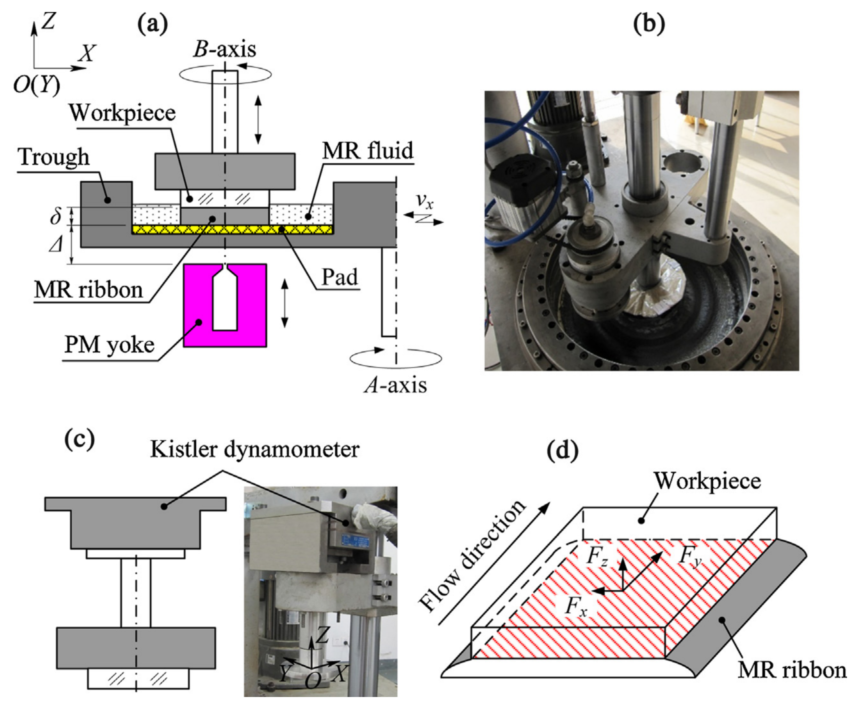

Fig. 1. (a) Schematic illustration of the MR planarization apparatus. Optical images of (b) the experimental apparatus. (c) The force measurement set-up. (d) Illustration of the force components acting on the workpiece.

It consists of a work spindle that rotates around *B*-axis, a nonmagnetic trough that carries MR fluid to rotate around *A*-axis, and a 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. To ensure the workpiece interacts with the MR ribbon, a work gap (δ) is maintained between the workpiece and the porous pad. The gap between the top surface of the PM yoke and the top surface of the porous pad, which is defined as the excitation gap (Δ), can be adjusted so that the field strength in the work gap can be varied. During polishing the PM yoke is elevated, so the excitation gap decreases and the magnetic flux density in the work gap thus increases. When MR fluid flows over the air gap, it is immediately stiffened to form a straight MR fluid ribbon. During machining, the ribbon is in contact with the workpiece. As the non-uniform flux distribution of the PM yoke prevents from achieving high surface planarity, a translational movement (v_x) is superposed onto the trough motion. The MR ribbon in the trough thus reciprocates relatively to the workpiece. The introduction of such movement allows a more uniform distribution of material removal and thus improves surface planarity.

2.2. Polishing conditions

K9 glass was used as the workpiece material. The glass substrates have a dimension of 50 mm × 50 mm × 4.6 mm. All the as-received samples (after grinding) have an initial surface roughness of ~430 nm in R_a. Four sets of experiments were arranged and the experimental conditions are summarized in Table 1.

The first set of experiments was a comparative study to show how trough movement affects surface planarity, where one sample was polished without translational movement but the other was polished by adding the translational movement (with a stroke of 80 mm and a reciprocate velocity of 0.1 m/min). The trough had a rotational speed of 20 rpm and the workpiece rotated at 80 rpm. The MR fluid used had carbonyl iron particles (CIPs, which have a thin SiO_2 coating of 0.4 μm in thickness on the iron core and a mean size of ~3.2 μm in diameter) of 35 vol.% and CeO_2 (with a mean size of ~2 μm in diameter) of 7 vol.%. The volume of the MR fluid used for polishing was 500 ml. During polishing the excitation and work gaps were kept constant at 7 and 1.5 mm, respectively.

The second set of tests systematically investigated the effects of translational movement, work and excitation gaps and CIPs concentration on the roughness, volumetric removal rate and planarity of polished surfaces. Different work gaps of 1, 1.5, 2 and 2.5 mm, excitation gaps of 7, 8, 9 and 10 mm, and particle concentrations of 35, 40, 45 and 50 vol.% were used. The stroke of the translational motion varied from 20 to 80 mm, and the reciprocate velocity was in the range of from 0.1 to 0.4 m/min.

In the third set of experiments, translational movement of the trough and rotational movement of the workpiece were intentionally stopped, so that the glass specimen being polished was rest, which enabled the measurement of polishing force. The force measurement was carried out using various work gaps of 1, 1.5, 2 and 2.5 mm, different excitation gaps of 7, 8, 9 and 10 mm, and different particle concentrations of 35, 40, 45 and 50 vol.%.

In the final set, the effect of polishing time on the integrity of polished surfaces was investigated. Three polishing periods of 30, 180 and 240 min were used. During polishing the excitation and work gaps were kept constant at 7 and 1 mm, respectively. The trough speed was kept constant at 20 rpm.

2.3. Measurements of surface quality, polishing force and material removal rate

Roughness values of the polished surfaces were measured using a white light interferometer (Zygo New View 7100). For each polished surface, five roughness measurements were taken at different locations. The average values and standard deviations were calculated. The planarity of the polished surfaces was measured using a laser interferometer (Zygo GPI XP/D).

To examine the sub-surface damage, a bonded interface sectioning technique [23] was used. In this method, the side surfaces of two pieces of glasses were well polished to make sure no polishing induced damage was generated. The polished surfaces