A Study of Magnetic Field-assisted Batch Polishing on Structured Surfaces

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With the increasing demand for structured surfaces in different fields such as optics, biomedical, physics etc., a cost-effective and highly efficient polishing process is needed to increase the productivity in removing defects on the machined structured surface, as well as meeting the surface quality and accuracy requirements for functional purpose. A magnetic field-assisted batch polishing (MABP) was proposed to polish a batch of structured surfaces simultaneously with high efficiency. Experimental studies were conducted on four types of structured surfaces which were fabricated by milling, including v-grooves, sinusoidal grooves, rectangular grooves, and micro-channels. The surface roughness, form accuracy and surface topography before and after polishing were compared and analyzed. The results indicated that MABP can achieve nanometric surface roughness and remove machining tool marks in the abovementioned structured surfaces while maintaining surface form accuracy within 1 µm, demonstrating the high efficiency and feasibility of MABP on superfinishing of structured surface polishing.

1. Introduction

Structured surfaces, characterized by their patterned or textured features, have gained significant attention in various fields, including microelectronics, optical fiber communication, biomedical devices, imaging and illumination, and aerospace engineering [1]. Typical applications of structured surfaces include compound eyes for 3D imaging, micro-Fresnel lens arrays for imaging, micro-grooves for cooling system and metrology etc. [2]. However, the fabrication of structured surfaces usually creates defects such as machining tool marks and burrs on the surfaces, while achieving high-quality surface finishes on these structured surfaces is crucial for their optimal functionality and performance. Thus, post process polishing is usually required on the structured surface components.

To improve the surface quality of the machined structure, various types of polishing process have been proposed including vibration assisted polishing [3-5], magnetic field-assisted finishing [6-8], laser polishing, abrasive jet polishing [9,10] etc. Brinksmeier et al. [11] compared the polishing performance of pin- and conical wheel- shaped polishing tool with laser polishing and abrasive flow machining for surface finishing of V-grooves structures in electroless nickel, the results show that arithmetic roughness R_a at 4.5 nm was achieved in copying shape polishing tool as compared with 520 nm and 65.2 nm in the laser and abrasive flow machining processes respectively. Zhao et al. [12] applied ultrasonic vibration assisted polishing to finish cylindrical groove-structured surfaces using a polishing wheel of the same geometry and achieved arithmetic roughness at R_a 4.3 nm. Guo et. al. proposed a vibration-assisted magnetic abrasive polishing method [4-5,13], the arithmetic roughness R_a was reduced to 7 nm and machine tool marks were removed with microfeatures well maintained in both V-groove and Fresnel lens structures. Zhang et. al. [14] proposed to use non-Newtonian fluids for microstructured surface polishing, and the surface roughness of V-grooves achieved R_a 53 nm and height variation less than 2 µm. However, most of the above-mentioned processes usually process the workpiece one-by-one, leading to relatively high production cost and time consuming with the increasing demand for different applications of structured surfaces.

Recently, a novel magnetic field-assisted batch polishing (MABP) process was proposed by the authors for polishing a number of components simultaneously while achieving nanometric surface finish and micro-scale surface form accuracy [15,16]. However, the feasibility of MABP process for polishing different types of structured surface was still far from complete understanding. Therefore, a feasibility study of MABP on various types of structured surfaces was performed to examine the performance of the process.

2. Methodology

2.1 Working principle of Magnetic field-assisted batch polishing

In the magnetic field-assisted batch polishing (MABP) device, a minimum of two pairs of permanent magnets were mounted on a rotary table with an annular chamber fixed in between as shown in Fig. 1(a). Workpieces were fixed on the fixtures as shown in Fig. 1(b) and six or more components can be polished simultaneously in this setup. Magnetic abrasives were added into the annular chamber forming abrasive brushes under the effect of magnetic field, by driving the magnets to rotate about the chamber, the generated abrasive brush continuously impinges the workpiece surface inducing material removal as presented in the schematic diagram in Fig. 1(c). The magnetic abrasives were a mixture of loose abrasive slurry such as alumina, silicon carbide, diamond particles etc. and magnetic particles.

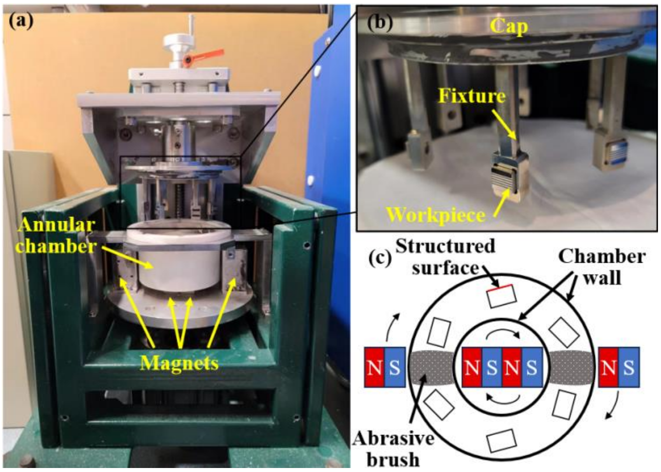


Fig. 1 MABP Experimental setup for structured surfaces (a) MABP machine (b) workpieces mounted on the fixtures and the cap (c) schematic diagram of MABP process.

2.2 Design of Experiment

Three types of structured surface were designed and fabricated including V-grooves, sinusoidal-grooves, and micro-channels on an 8×8×6 cm cube; detailed geometric information of the machined structures is shown in Fig. 2. The workpiece material was 304 stainless steels, and the structures were fabricated by Toshiba UVM 450C micro milling machine.

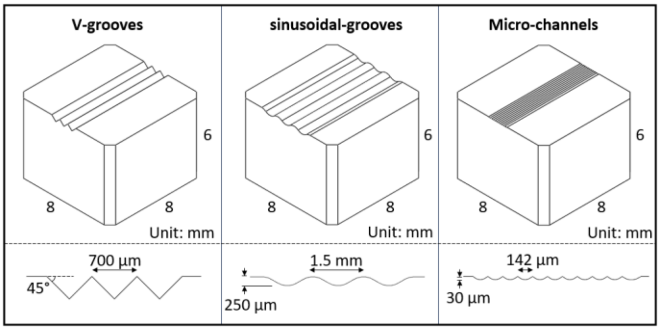


Fig. 2 Geometric information of structured surface workpieces

A series of experiments were conducted to validate the performance of MABP on different types of structured surfaces as shown in Table 1. Carbonyl iron particles (~2 μm in average, 75 wt.%) were mixed with alumina abrasives (~150 nm in average, 25 wt.%) to form the magnetic abrasive brush. Six workpieces, two from each structure, were polished in one batch for 20 minutes. The impinging angle of workpieces were kept at 15° according to the authors' previous research [16] to maintain better polishing uniformity in consideration of the magnetic field strength and the linear velocity. The grooves were aligned tangentially with the polishing direction. Surface roughness measurements were taken every 10 minutes by Zygo Nexview Whitelight Interferometer at 40× magnification, a total of nine points were measured with each measurement area as 214 μm × 214 μm, uniformly distributed over the structured surface. The surface profile before and after 20-minute polishing were measured by Form TalySurf PGI1240. Finally, the surface topography was observed by Hitachi Tabletop Microscope TM3000.

Table 1 Polishing conditions for structured surface

Condition	**Value**
Rotational Speed	1500 rpm
Polishing slurry	Alumina abrasive 150 nm, 25 wt.%
Magnetic particle	Carbonyl iron particle 3 μm, 75 wt.%
Impinging angle	15°
Polishing time	10, 20 min
Workpiece	V-groove, sinusoidal groove, micro-channels

3. Results and discussions

3.1 Surface topography

Fig. 3 shows the surface roughness change in arithmetic mean height (*Sa*) over 20-minute polishing of the three different structures. V-groove and sinusoidal groove structures had similar initial surface roughness at around 30 nm, while micro-channels workpiece have a higher value at approximately 70 nm. A significant decrease in surface roughness was found in the first 10-minute polishing to about 10 nm and 30 nm respectively, and gradually reduced to 8-10 nm despite the structure type. Snapshots and surface roughness contours at the valley of the structured surfaces before and after polishing were presented in Fig. 4, clearer reflective image could be observed after MABP polishing for 20 minutes, and the rainbow-like streaks reflected on the machined surface were diminished.

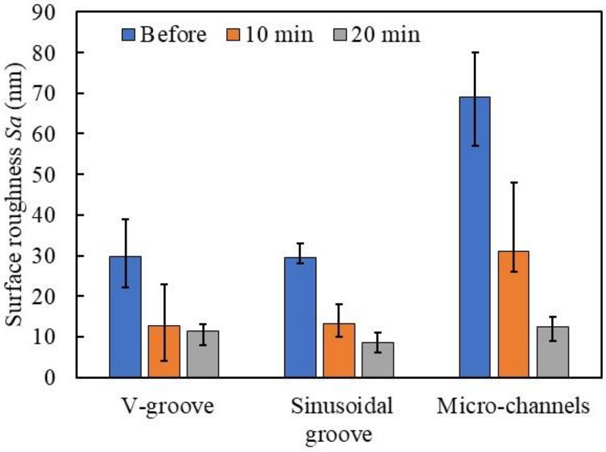


Fig. 3 Surface roughness change on different structures

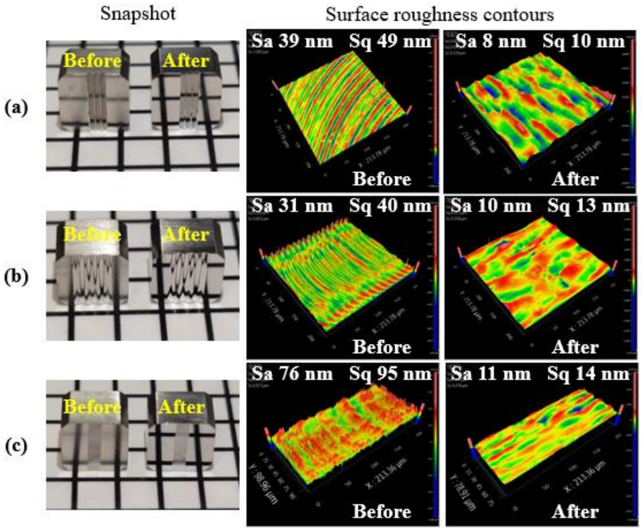


Fig. 4 Snapshot and surface roughness contours before and after polishing for (a) V-grooves (b) sinusoidal grooves (c) micro-channels

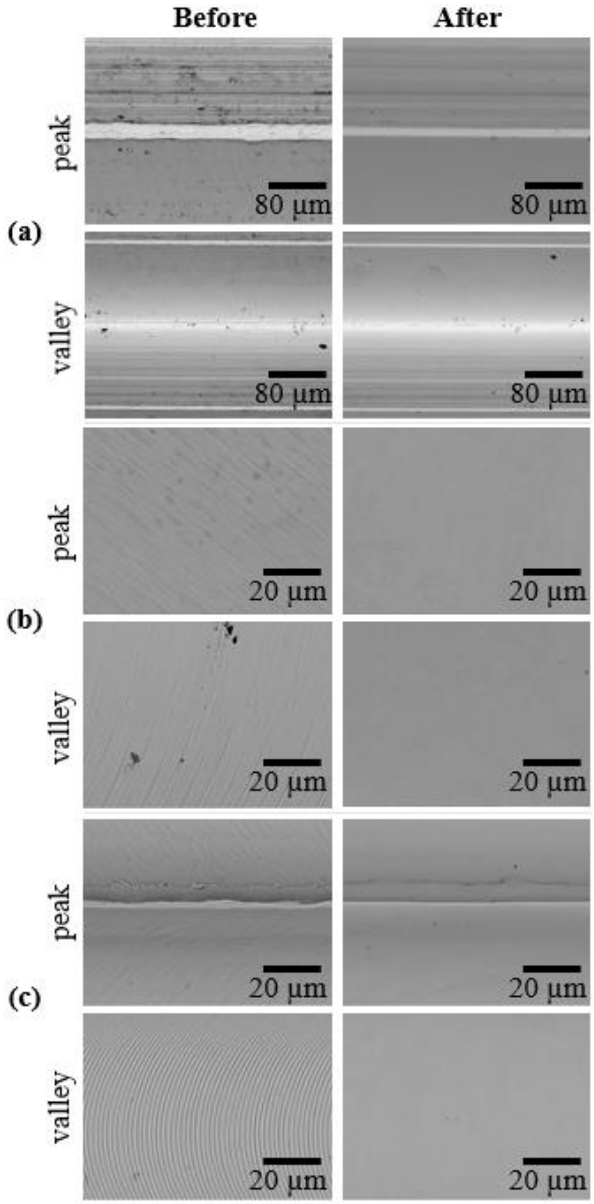
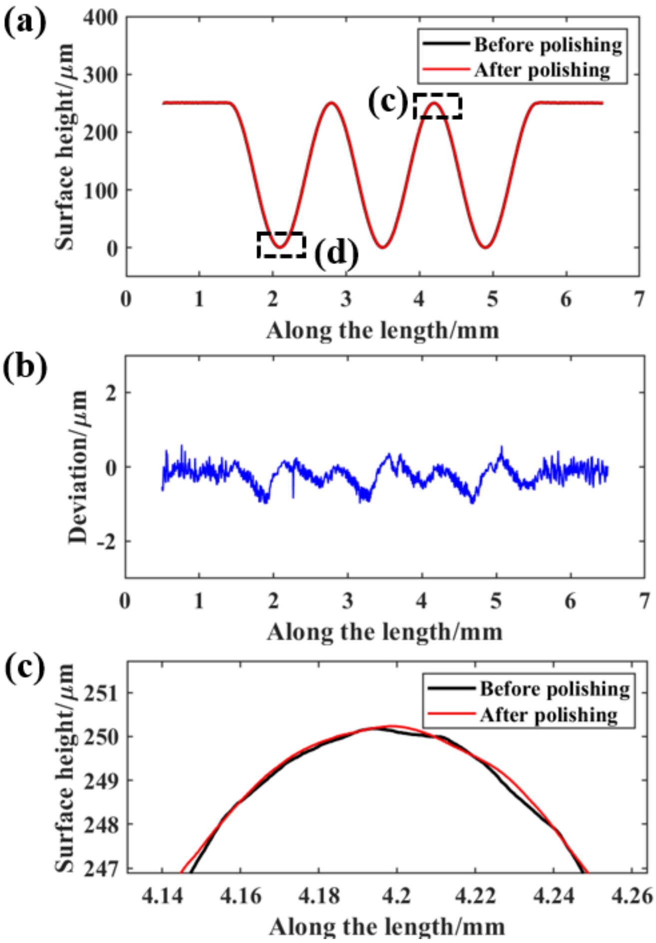


Fig. 5 SEM photos of structured surfaces before and after polishing for (a) V-grooves (b) sinusoidal grooves (c) micro-channels

Fig. 5 shows the SEM photos of the three types of structured surfaces before and after MABP polishing. As shown in Fig. 5(a), it can be observed that the surface of the V-groove on both the peak and valley was smoothened, the peak of the V-shape was also sharpened, burrs induced by machining were removed thoroughly. As shown In Fig. 5(b) and 5(c), machining tool marks on both the peaks and valleys of structure were diminished, a clean surface was achieved on all three types of structured surfaces. The results indicate that MABP is effective in improving the surface finishing and removing machining defects generated in structured surface fabrication and proved its feasibility in different types of structures.

3.2 Surface form maintainability

Fig. 6(a) shows the measured surface form profile of the sinusoidal structured surface before and after polishing. It was found that the profile was smoothened after polishing, and the deviation before and after polishing was less than 1 µm as shown in Fig. 6(b). The profile of the peak and valley of the sinusoidal groove after polishing mostly conformed with the original profile as presented in Fig. 6(c) and Fig. 6(d). The results indicated that the surface profile was maintained well, and the smoothening effect can be clearly observed.



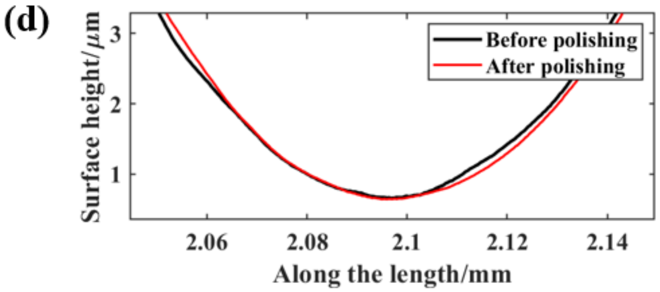


Fig. 6 Surface form comparison before and after polishing (a) profile comparison (b) surface deviation (c) surface comparison at peak of groove (d) surface comparison at valley of groove.

4. Conclusions

In this paper, the performance of MABP on various kinds of structured surfaces was examined. It was proven that MABP was able to improve the surface finish of different structures to nanometer scale while maintaining the surface form accuracy. Machining tool marks in the small gaps of micro-channels were removed thoroughly, indicating its high flexibility and adaptability to groove-type structured surface. The machined surface with surface roughness ranges from *Sa* 30-70 nm were improved to below 10 nm in 20 minutes, the surface form deviation was within 1 μm and the burrs on the peaks were diminished. The experimental results prove that MABP process is effective for post-process finishing of hard-to-reach structured surface.

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