Fundamental Investigation of Ultrasonic Vibration Assisted MCF (Magnetic Compound Fluid) Polishing

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Abstract. This research deals with the development of an ultrasonic vibration assisted MCF (Magnetic Compound Fluid) polishing technology for final polishing. This paper describes the fabrication of an experimental apparatus composed mainly of an ultrasonic polishing unit, and the experimental investigation of its performance in surface polishing. In addition, investigation of ultrasonic vibration assisted MCF polishing under different applied methods of ultrasonic vibration was also conducted. The experimental results indicate that applying ultrasonic vibration to the workpiece improves the surface roughness and the material removal rate when the ultrasonic vibrations are changed. In addition, over the range of polishing conditions employed in this paper, the precision surface roughness and high material removal rate can be easily obtained on the acrylic plate by using an elliptical vibration is applied to the ultrasonic vibration.

Introduction

In recent years, the demand for clean energy such as solar photovoltaic is increasing with the development and the increase in application of renewable energies. In order to concentrate sunlight and raise the efficiency of the power generation in the solar cell system, Fresnel lenses are commonly employed as the key parts in the system. This kind of lens is in general created by generating micro shape on optical glass or plastic, and in practice produced by injection molding or/and hot press process with micro structured molds/dies. As the transmitted light energy of lenses is closely related to the geometrical quality, i.e., the form accuracy and surface roughness of the lens, and the quality of lenses depends on that of the molds/dies used, the generation of high form accuracy and high precision micro structured molds is a stringent requirement.

Exiting precision machining processes such as diamond machining and precision grinding are well suited for the manufacture of micro structured surfaces. However, in some cases subsequent polishing of the micro structures must be performed to improve surface roughness and form accuracy or to remove cutter-marks caused by pre-machining which may result in light scattering effects [1]. One promising advanced finishing technique is abrasive polishing which is considered to be one of the effective manufacturing [2]. Gessenharter et al. [3] proposed abrasive flow machining method to improve the surface quality. Abrasive polishing using pin type and wheel type polishing tools made of polyamide was applied to improve the surface roughness of micro structured molds [4]. In these methods, however, it is hard to achieve the uniform distribution of abrasive gains within the polishing zone which blocks the further improvement of work-surface quality. Under this situation, magnetic fluid (MF) or/and magnetorheological (MR) fluid mixed with abrasives as a polishing tool was introduced for the finishing of three-dimensional surfaces [5-7]. However, magnetic field, magnetic
pressure and apparent viscosity of the MF are smaller than that of an MR fluid, whereas the particles are more stably distributed in the former than in the latter [8].

Against these problems, a novel slurry is produced by mixing the MF containing nanometer size magnetite particles and MR fluid containing micron size carbonyl iron powder (CIP) in the same base solvent, and exhibits higher magnetic pressure and apparent viscosity and a more stable and uniform distribution of particles under a magnetic field, while maintaining a fluid-like behavior [9]. Once a magnetic field is applied, chain-shaped magnetic clusters composed of nanometer sized magnetite particles and micron sized CIPs are formed along the magnetic lines of force immediately, and abrasive grains are entrapped into the clusters or distributed between clusters, and α-cellulose fibers have interwoven with the clusters. When a relative motion is given between the work-surface and abrasive grains, a polishing force is imposed on the workpiece owing to the induced friction between the workpiece and abrasive grains, and the micro-cutting action of abrasive particles occurs to remove materials. The MCF slurry has been successfully used for polishing flat surfaces with nano-precision and scratch-free work-surfaces under a static and/or dynamic magnetic field [10–11]. However, up to now, the machining efficiency in MCF polishing has not been satisfactory. Therefore, in this study, a novel MCF polishing method using ultrasonic vibration is proposed, and the effects of the ultrasonic vibration on MCF polishing are investigated. For these purpose, an experimental apparatus primarily consisting of an ultrasonic vibration unit are designed and manufactured, and investigations of ultrasonic vibration assisted MCF polishing under different applied methods of ultrasonic vibration is also conducted in this paper.

Polishing principle and experimental details

Fig. 1 schematically illustrates the ultrasonic vibration assisted MCF polishing process. A disk-shaped permanent magnet is attached on the end face of its holder with an eccentricity of $d$. An MCF carrier made of an aluminum plate is located the magnet with a clearance. When the magnet holder is rotated at speed $n_1$, the magnet revolves around the axis of the holder (hereafter called rotary magnetic field). The magnetic flux density is constant but the magnetic lines of force constantly revolve around the magnet holder axis.

Once the clearance $\Delta$ between the workpiece and the carrier has received a certain volume of MCF slurry, as shown in the right portion of Fig. 1, chain-shaped magnetic clusters composed of nanometer sized magnetite particles and micron sized CIPs (Carbonyl-iron-particles) are formed along the magnetic lines of force immediately; non-magnetic abrasive particles are entrapped into the clusters or distributed between clusters and α-cellulose fibers have interwoven with the clusters. Kim et al. defined magnetic levitation as force that is exerted on nonmagnetic bodies by a magnetic functional fluid. Therefore, under the combined effect of both magnetic levitation and gravitational forces, majority of nonmagnetic abrasive grains within the MCF slurry move towards the work surface. In addition, all of the clusters are collected forcibly by the magnetic attraction force and they are gathered in the area where the magnetic field is stronger. When the ultrasonic vibration is given to the
workpiece, a large polishing force is imposed on the workpiece owing to the induced friction between the workpiece and abrasive grains, and the micro-cutting action of abrasive grains occurs to remove materials.

For realizing the polishing principle, an experimental rig was constructed as shown in Fig. 2. A polishing unit was composed mainly of an aluminum-made MCF carrier and a motor used for rotationally driving the MCF carrier via a belt/pulley mechanism is attached. In addition, another motor is employed as the magnet holder, on the end face of which a neodymium permanent magnet is attached with an eccentricity. The ultrasonic vibration unit is constructed by bonding a piezoelectric ceramic device (PZT) with two separated electrodes onto a metal elastic body (stainless steel, SUS304). When two alternating current (AC) signals (over 20 kHz) with a phase difference to each other generated by a wave function generator are applied to the PZT after bending amplified by means of power amplifiers, the 1st longitudinal vibration (L1-mode) and 2nd bending vibration (B2-mode) with their respective amplitudes are excited simultaneously, and the synthesis of vibration displacements in the two directions creates an elliptic motion on the end faces of the ultrasonic vibration unit. Consequently, the workpiece on the end face of the ultrasonic vibration unit moves elliptically.

Polishing experiments were performed on the constructed experimental rig. The purpose of this research was to investigate the effects of ultrasonic vibration. Therefore, the water-based MCF slurry was prepared with given compositions as shown in Table 1. Table 2 lists the experimental parameters; polishing experiments were conducted at different ultrasonic vibration motion.

![Fig. 2 Photograph of the experimental rig](image)

Table 1 Compositions of MCF slurry

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Abrasive : Alumina</th>
<th>12 wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbonyl Iron powder : CS</td>
<td>58 wt%</td>
</tr>
<tr>
<td></td>
<td>MF (MSGS60)</td>
<td>27 wt%</td>
</tr>
<tr>
<td></td>
<td>α-cellulose</td>
<td>3 wt%</td>
</tr>
</tbody>
</table>

Table 2 Experimental conditions

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Nd-Fe-B , B = 0.454T , ( \Phi 6.5 \times 5 \text{ mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revolution radius</td>
<td>( d = 5 \text{ mm} )</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>( n_1 = 800 \text{ mm}^{-1} )</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Acrylic plate</td>
</tr>
<tr>
<td>Supply of MCF slurry</td>
<td>0.7 ml</td>
</tr>
<tr>
<td>Clearance</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Polishing time</td>
<td>2, 5, 10, 20 min</td>
</tr>
<tr>
<td>Aluminum plate rotation</td>
<td>600 mm(^{-1})</td>
</tr>
<tr>
<td>Ultrasonic vibration</td>
<td>Frequency : ( f = 21.95 \text{ kHz} )</td>
</tr>
<tr>
<td></td>
<td>Applied voltage : ( V_{pp} = 50, 100, 150 \text{ V} )</td>
</tr>
<tr>
<td></td>
<td>Phase : ( \psi = -180 \sim 180 \text{ deg.} )</td>
</tr>
</tbody>
</table>
Experimental results and discussion

At first, the ultrasonic vibration unit tests were performed under different input variables to elucidate the influences of the ultrasonic vibration parameters. Fig. 3 shows the influences of applied voltage on amplitude of ultrasonic vibration motion. As is evident, the ultrasonic vibration amplitude increases as the applied voltage increases. It was also found that ultrasonic vibration occurs even when the workpiece is attached. Fig. 4 shows the influences of phase on amplitude of ultrasonic vibration motion. From the results, it was found that ultrasonic vibration motions generate three kinds of longitudinal vibration, bending vibration and elliptical vibration by changing the phase.

![Graph showing ultrasonic vibration amplitude under various applied voltage](image1)

**Fig. 3 Ultrasonic vibration amplitude under various applied voltage**

![Graph showing ultrasonic vibration motion under various phase](image2)

**Fig. 4 Ultrasonic vibration motion under various phase**

Fig. 5 shows the surface roughness Ra during polishing for different ultrasonic vibration motions, respectively. When ultrasonic vibration is applied, the surface roughness is improved as compared with the case without ultrasonic vibration. In addition, high precision results were obtained in the order of bending vibration, elliptical vibration, and longitudinal vibration in the ultrasonic vibration motion. Fig. 6 shows the influence of the polishing time on the material removal. As shown in Fig. 6,
the material removal increases gradually with an increase in the polishing time. Under the polishing conditions in this study, when ultrasonic vibration is applied, the material removal increases as compared with the case without ultrasonic vibration. Also, high efficiency results were obtained in the order of elliptical vibration, longitudinal vibration, and bending vibration in the ultrasonic vibration motion.

![Fig. 5 Surface roughness under various ultrasonic vibration motions](image1)

![Fig. 6 Material removal under various ultrasonic vibration motions](image2)

**Conclusions**

In this study, a novel MCF polishing method using ultrasonic vibration was proposed. In order to develop the polishing technology, an experimental apparatus primarily consisting of an ultrasonic vibration unit are designed and manufactured for the effects of the ultrasonic vibration on MCF polishing are investigated. Investigations of ultrasonic vibration assisted MCF polishing under different applied methods of ultrasonic vibration were also conducted. The obtained experimental results are summarized as follows.

1. The ultrasonic vibration unit capable of generating ultrasonic vibration was designed and manufactured.
2. The ultrasonic assisted MCF polishing apparatus consisting of ultrasonic vibration unit and polishing unit was prototyped.
3. The ultrasonic vibration assisted MCF polishing revealed that the surface roughness improvement and material removal increase as compared with the conventional MCF polishing.
4. Over the range of polishing conditions employed in this study, an elliptical vibration was most effective in the ultrasonic vibration assisted MCF polishing.

From the above results, the ultrasonic vibration assisted MCF polishing is effective.
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References


