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Development of magnetic polishing method with 5-axis machining center for aspherical shape

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Abstract
In the fabrication of an aspherical mold, the workpiece is typically fabricated into the desired shape with a machining center, and the workpiece is polished using a polishing machine to obtain a smoother surface. Additionally, the mold fabrication process is "high-mix low-volume production," thereby significantly increasing the requirement for process integration. This paper proposes a magnetic polishing method that uses a small ball end-mill type tool on the machining center. In the polishing process of a mold, the form accuracy of the mold must be maintained. However, using the traditional loose-abrasive method results in the deterioration of form accuracy, because it is difficult to control the loose abrasives. In the proposed magnetic polishing method, the abrasives in a magnetic paste are controlled by a permanent-magnet tool, thereby making it feasible to maintain the form accuracy. Consequently, this study proposes a novel four-axis controlled magnetic polishing method to polish an aspherical mold, which uses a five-axis machining center. In this method, the contact position of the magnetic polishing tool is constantly maintained at all polishing points on the workpiece. Therefore, in order to obtain the effectiveness of the polishing force, this report proposes a novel polishing method that avoids the use of a tool center. The stainless steel (X30Cr13) was polished with the novel method and a general contour method. The novel method was able to polish the mold uniformly.

magnetic polishing, mold, aspherical shape, machining center

1. Introduction

The aspherical plastic lens has been used in various fields. The mold that fabricates these lenses is typically generated with a molding. This mold is generally machined by cutting or grinding into a desired shape. The mold is then polished using a loose abrasive method that uses a slurry, such as lapping or buffing, in order to improve the surface integrity. Recently, microlens array molds that have a small aspherical shape and are used to fabricate wafer-level lenses are required. However, the loose abrasive method has several problems. It is difficult to maintain the form accuracy, because controlling the polishing pressure or the movement of the abrasives is difficult. In addition, the environment deteriorates easily because the slurry is scattered. Furthermore, a specific machine for polishing is needed. Therefore, this study proposes a magnetic polishing method that uses a small ball end-mill type tool [1]. In this report, an improved novel polishing method that avoids contact of the tool center is proposed, to achieve high-accuracy and high-efficiency polishing. Moreover, in order to verify the generality of the proposed method, the stainless steel (X30Cr13) was polished.

2. Proposed four-axis controlled polishing method

A magnetic polishing tool (radius 1 mm) made of a permanent magnet is attached to a tool spindle of the five-axis machining center, as shown in Figure 1. In addition, the magnetic polishing paste adhering to the polishing tool consists of magnetic particles (Fe, diameter 100 µm), white alumina (diameter 0.1 µm), surfactant, and kerosene [2]. Because this magnetic paste is lightly affixed to the tool by the permanent magnet, the paste does not scatter.

In this report, a four-axis controlled magnetic polishing method for aspherical shapes is proposed, as shown in Figure 2. Because this method constantly uses a given point other than the tool center, the polishing pressure becomes constant at all polishing points. In addition, since the tool center is not used, its effectiveness is obtained by tool rotation. In Figure 2, P is the coordinate value of the aspherical shape, and calculated by Eq. 1, where Cv, K, and Ci (i = 1~n) are aspherical constants. ϑw is the workpiece inclination angle. ZAO is the distance between the workpiece center before rotation and the C-axis center. RA is the distance between P and the C-axis center, and rt is the tool radius. g is the distance between the tool and workpiece; it becomes zero when ball end-milling is carried out. If the given point of the tool surface is inclined by ϑ from central axis of the tool, the workpiece is rotated $\vartheta+\vartheta w$ (command value of A-axis). From these rules, the command values of tool Pt are defined in Eq.2, where ψ is defined in Eq. 3. In actual machining, the tool is moved to Pt, and the workpiece is rotated by $\vartheta+\vartheta w$. Then, the workpiece is rotated by the C-axis.

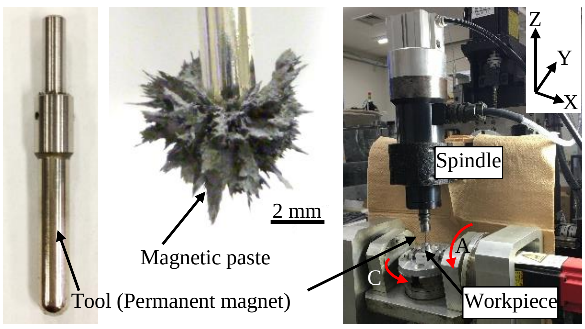


Figure 1. Magnetic polishing tool and paste, 5-axis machining center.

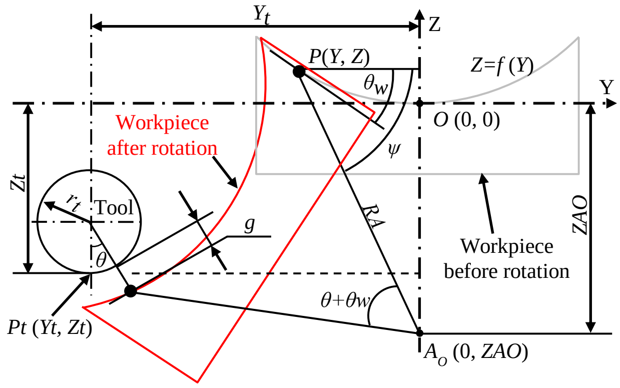


Figure 2. Model diagram of proposed 4-axis control method.

$$Z = f(Y) = \frac{Y^2 \cdot C_v}{1+\sqrt{1-(K+1)Y^2 \cdot {C_v}^2}} + \sum_{i=1}^{n} C_i \cdot Y^i \tag{1}$$

$$\left.\begin{aligned} Yt &= RA\{\sin(\theta+\theta w-\psi)+1\}+\sin(rt+g) \\ Zt &= -ZAO+RA\cos(\theta+\theta w-\psi)+\cos(rt+g)-rt \end{aligned}\right] \tag{2}$$

$$\psi = \tan^{-1}\left(\frac{Z+ZAO}{Y}\right) \tag{3}$$

3. Experimental results and discussion

The specifications of the desired aspherical mold were: effective diameter 1.0 mm, height 65 µm, maximum inclination angle 15°, and material stainless steel (X30Cr13), which is often used for plastic component molds. Form deviation and surface roughness were measured with a shape measurement laser microscope (VK-X210, Keyence Co., Ltd.). In order to evaluate the effectiveness of the proposed method, a simple contour line (3-axis) control method also generated the aspherical mold.

The aspherical shape was generated with ball end-milling on the machining center by using both control methods, as shown in Figure 1. The cutting conditions were: tool radius 1 mm, ϑ = 5°, cutting speed 126 m/min, feed speed of C-axis 1080°/min, dividing pitch between machining points 20 µm, and depth of cut 20 µm. Figure 3 shows the comparison of form deviation for both control methods. These results did not carried out any corrective machining. Because the tool center or outer region of the tool does not interfere with the workpiece under this cutting condition, it is considered that the main factors that caused these deviations are tool run-out, position error of the tool from the C-axis center, or deviation the of measured *ZAO*.

These ball end-milled aspherical molds were magnetically polished under the following conditions: tool radius 1 mm, ϑ = 5°, circumferential speed 20 m/min, rotational speed of C-axis 360°/min, g = 0.3 mm, dividing pitch 0.2 mm, and total polishing time approximately 40 min. Figure 4 shows an overview of the polished mold. In the proposed method, all surfaces obtained a mirror face. However, in the 3-axis method, the center region did not obtain a mirror face. Figure 5 shows the comparison of polishing amount. With the 3-axis method, the polishing amount decreased with increasing radial position of the workpiece. Therefore, when using the tool center, the center region was found to be polished by pressing with abrasives that stagnated between the tool and workpiece. However, it is possible to restrain the deterioration of form accuracy with the proposed method. Figure 6 shows the surface roughness profile with proposed method that was processed with a high-pass filter (Cutoff value: 0.8 mm).The ball end-milled surface roughness is 1.0 µm *Ra*, 14.2 µm *Rz*. Thus, the surface roughness varies based on the radial position of the workpiece after polishing. Since polishing pressure becomes constant and the relative speed of the tool and workpiece is small, the primary factor is polishing time. If the tool is located on the workpiece center, as the polishing paste straddles the workpiece center, the polishing amount is considered to increase. Therefore, the polishing time must vary based on the radial position of the workpiece.

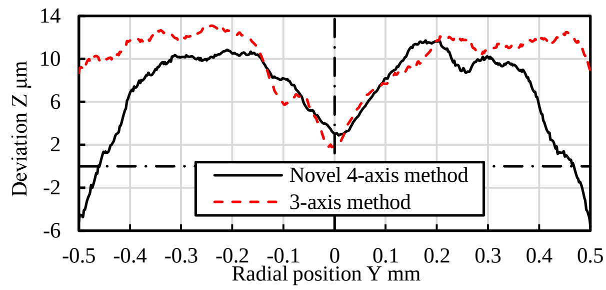
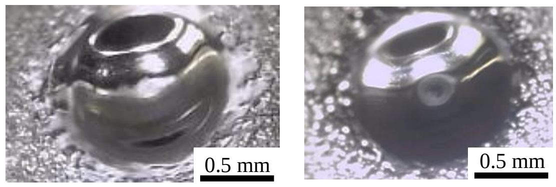


Figure 3. Comparison of form deviation after ball end-milling.



(a) With novel 4-axis method (b) With 3-axis method

Figure 4. Photographs of magnetic polished aspherical molds.

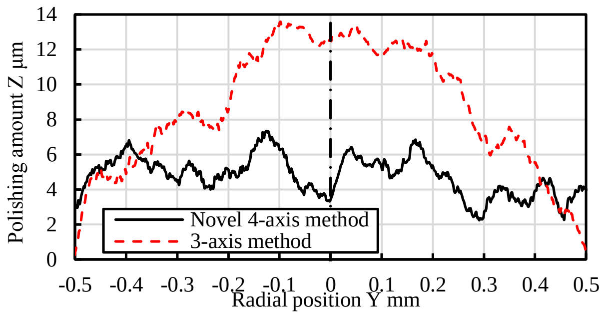


Figure 5. Comparison of polishing amount.

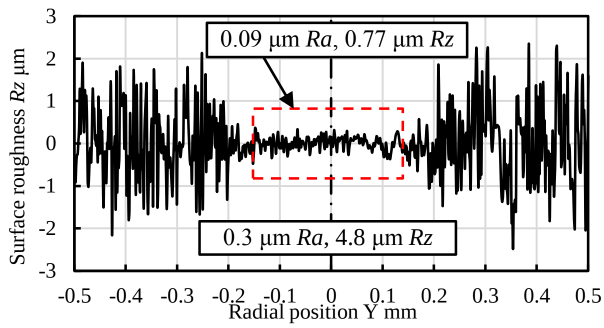


Figure 6. Surface roughness profile with novel four-axis method.

4. Conclusion

The proposed 4-axis method was found to be useful for uniformly polishing an aspherical shape. However, improvement of polishing conditions is needed to obtain further high accuracy. Moreover, it is expected that the total polishing time will decrease, because a necessity of the shape correction polishing is small compared with 3-axis method.

References

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