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# Fabrication of sub-millimetre aspheric WC moulds for glass moulding process

C.L. Chao[1], W.H. Wang[1], Z.X. Xu[1], W.C. Chou[1], K.J. Ma[2], W.H. Fan[3]

[1]*Mechanical and Electro-Mechanical Engineering, Tamkang University, No.151 Ying-Chuan Rd., Tamsui Dist., New Taipei City 25137, Taiwan*
[2]*Department of Mechanical Engineering, Chung-Hua University, Hsin-Chu, Taiwan*
[3]*Department of Mechanical Engineering, Taipei Chengshih University of Science and Technology, No. 2, Xueyuan Rd., Beitou, 112 Taipei, Taiwan*

*clchao@mail.tku.edu.tw*

## Abstract

As the demand for precision optical components with sub-millimetre feature size steadily increases, numerous efforts have been made in developing new techniques and in improving the existing approaches to efficiently and economically produce those components. Glass moulding process (GMP) is considered to be a cost effective way for mass fabricating glass lenses. However, only a handful of materials such as tungsten carbide, silicon carbide and glassy carbon can sustain the chemical reaction, mechanical stress and high temperature involved in the glass moulding process and, almost all of these mould materials are classified as hard-to-machine materials. Precision diamond grinding is by far the principal choice used to machine the GMP mould. As the feature size of optical component gets smaller, the size of mould and grinding wheel used to fabricate the mould gets smaller too. This makes the precision grinding of mould a very time consuming and costly process. This research aimed to improve the small mould fabrication processes. Since the targeted aspheric lenses have 0.5 mm or less in diameters and very few commercial available diamond wheels have dimension in this range, a feasible way of producing small diamond wheels has to be developed before any grinding operation can be carried out. A non-contact precision tool monitoring system using edge-detection and image processing techniques is used in this study to measure the wheel wear and a modified tool path is then generated to minimize the profile error. Diamond wheels of around 0.4 mm in diameter after truing were successfully fabricated and WC aspheric mould inserts of form accuracy and surface roughness of 0.1 μm (P-V) and 10.6 nm (RMS) respectively were successfully produced in this research.

Keywords: Sub-millimetre, aspheric, WC moulds, glass moulding process

## 1. Introduction

With the rapid development of optoelectronic, semiconductor and consumer electronics industry, products are required to be better integrated, reacting faster, more accurate and performing better. While precision and integration get higher, components usually get smaller and, in many cases, get even more complicated. For instance, optical components have evolved from spherical, aspheric to free-form geometries to meet the demand of advanced applications. Owing to the technological difficulties and cost issues in the production of components made of glass, plastic lenses are still the majority to be used in many optical systems. However, plastic optics has many drawbacks such as: degradation when subjected to long term UV exposure, lower scratch resistance, relatively big variation of refraction index with temperature and relatively lower refraction index value in comparison to glass [1-3]. Glass moulding process (GMP) has provided answer over the past decades for many precision optical components to be mass produced in an effective manner. High precision spherical and aspheric glass lenses are now routinely fabricated by GMP. However, GMP has problems of its own. Apart from needing durable anti-stick coatings [4-6] and a suitable set of moulding parameters, mould inserts have to be machined to a superb surface finish and sub-micrometre form accuracy. Only a handful of materials can sustain the chemical reaction, mechanical stress and temperature involved in the GMP and almost all of these mould materials are classified as hard-to-machine materials. This makes the precision machining of these materials a rather tough and expensive task. It gets even tougher when the size of mould or feature size on mould gets smaller. This research aimed to improve the small mould fabrication process. An aspheric lens of 0.5mm in diameter was used as the targeted sub-millimetre component to be produced and tungsten carbide was selected as the mould material. In order to generate the small WC mould insert for glass moulding, an even smaller grinding wheel was produced and wheel profile was constantly monitored during the grinding process.

## 2. Grinding of tungsten carbide mould

### *2.1. Fabrication and truing of small grinding wheel*

Diamond powders of various grit sizes are well mixed with UV curing polymer and applied onto a WC pin of 0.05~0.15mm in diameter. On a layer-by-layer basis, diamond wheels of various diameters and diamond grit sizes can be generated. A truing process, however, has to be conducted to minimize the run-out and to shape the wheel to specified diameter. Shown in Fig. 1(a) and Fig. 1(b) are SEM micrographs of the diamond wheel after truing operation and detailed view of the "cutting edge" respectively.

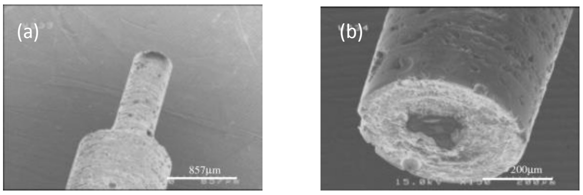

**Figure 1.** A truing process has to be conducted to minimize the run-out and shape the wheel to specified diameter as shown in SEM

micrographs: (a) wheel after truing and (b) detailed view of the "cutting edge".

### 2.2. *Grinding operation*

Grinding is conducted on a precision grinding machine and the grinding parameters used in the study are listed in the Table.1. Tungsten carbide of 0.5 µm averaged particle size and 1wt% cobalt concentration was used as the mould material. To avoid the grinding wheel interfering with the workpiece, the grinding was carried out in a slant (inclined for $45^0$) manner. Considering the low stiffness of the slim grinding wheel, 0.5 µm and 0.3 µm were used as cut-depth for roughing and finishing respectively.

**Table 1.** Grinding parameters used in the study.

| **Grinding parameters** | |
|---|---|
| Work-spindle speed [rpm] | 100 |
| Grinding spindle speed [rpm] | 40000 (cutting speed~0.84 m/s @ ϕ0.4) |
| Coolant | Mineral oil mist |
| Depth of cut [µm] | 0.5 (roughing), 0.3 (finishing) |
| Feed rate [mm/min] | 0.5 (roughing), 0.3 (finishing) |
| Diamond grit [µm] | 30~40 and 2~4 |
| Grit concentration | 45%, 60%, 75% |

### 2.3. *Grinding wheel wear monitoring.*

Since tool wear is part of the machining process, especially when it is dealing with hard-to-machine materials. A non-contact precision tool monitoring system using edge-detection and image processing techniques is used in this study. The profile of a newly trued diamond wheel, as shown in Fig. 2(a), exhibits clear and sharp corners (cutting edge). As the grinding operation goes on, the sharp cutting edge gradually turns into a rounded edge with a small radius (Fig. 2(b)). This will generate a "deficit" in designed depth of cut and introduce an error in obtained profile. The longer the tool into the cutting process and/or the heavier the cutting force involved, the bigger the radius on the cutting edge and the greater the form error. Shown in Fig. 2(c) is the SEM micrograph of worn cutting edge. The SEM micrographs were used in this study for calibrating and checking the results acquired by optical tool monitoring system. The radius of the wheel cutting edge is in-process measured after each grinding pass and a modified tool path will be generated based on the "new" radius to minimize the profile error.

**Figure 2.** Optical micrographs of diamond wheel (a) just after truing, (b) after grinding and (c) SEM micrograph of the worn cutting edge.

## 3. Results and discussion

### 3.1. *Influence of grinding parameters*

Before conducting the mould grinding, a series of grinding experiments were carried out to study the influence of grinding parameters such as depth of cut and feed rate on the obtained surface. Grinding tests with depth of cut and feed rate ranged from 0.3 µm to 2 µm and from 0.3 mm/min to 2 mm/min respectively were performed on the targeted WC material. The results showed that it is better to keep depth of cut and feed rate smaller than 1 µm and 1 µm/min respectively if a good surface finish and form accuracy are to be achieved. Shown in Fig. 3 are the surface generated by grinding with a wheel of #4000 grit size, a work spindle speed/grinding spindle speed of 100rpm/40000rpm, a depth of cut of 0.3 µm and with a feed rate of (a) 0.3 mm/min and (b) 2 mm/min. The corresponding surface roughness (Ra) are (a) 9 nm and (b) 30 nm. As a result, 0.5 µm and 0.5 mm/min; 0.3 µm and 0.3 mm/min were used as cut-depth and feed rate for roughing and finishing respectively during the mould grinding process.

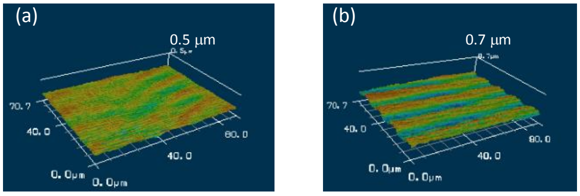

**Figure 3.** Surface generated by a wheel of 2~4 µm grit size, depth of cut = 0.3µm and with a feed rate of (a) 0.3 mm/min and (b) 2 mm/min.

### 3.2. *Mould grinding*

An aspheric surface was generated on a tungsten carbide mould of 0.5 µm averaged particle size and 1wt% cobalt concentration. The effective diameter is ϕ0.48mm and the sag is around 16 µm. Grinding was carried out in a slant grinding mode. Wheels of 30~40 µm and 2~4 µm grit size with various concentrations were used for roughing and finishing respectively at a fixed work/grinding spindle speed of 100rpm/40000rpm. Shown in Fig. 4 is the roughness (RMS) and form accuracy (P-V) values of the surfaces generated by wheel with various grit sizes and concentrations. The form accuracy after primary grinding process was around 1.95 µm (P-V). This was mainly due to the tool wear at the cutting edge. Compensation cuts were then followed to modify the error and to improve the form accuracy to around 0.47 µm (P-V, 30~40 µm, 60%). High concentration wheels are more suitable for large material removal rate and show better results in roughing (Fig. 4). In the case of finishing cut, concentration of 60% achieved better surface finish (10.6nm RMS) and form accuracy (86nm, P-V) than those obtained by concentration 75% (Fig. 4).

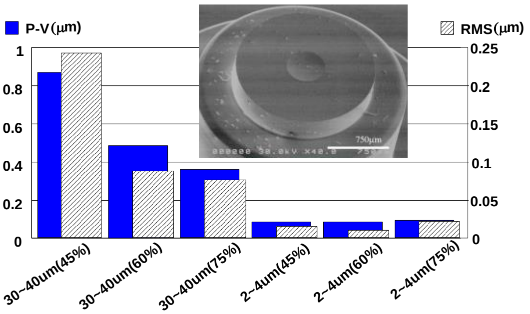

**Figure 4.** Roughness (RMS) and form accuracy (P-V) of the surfaces generated by wheel with various grit sizes and concentrations (inset: SEM micrograph of the obtained WC mould).

## 4. Summary

To meet the demand for precision optical components with sub-millimetre feature size, a new way of producing small diamond wheels and a non-contact, in-process wheel profile monitoring system were developed and applied in generating small mould fabrication processes. The grinding ratios of roughing (30~40 µm) and finishing (2~4 µm) wheels are around 12 and 30 respectively. WC aspheric mould insert of form accuracy better than 0.1 µm (P-V) and surface finish of 10.6nm (RMS) was successfully produced in this research.

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