Fabrication of the aspherical mold inserts by the laser-assisted diamond turning

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Binderless tungsten carbide (BTC), as the mold insert material, is widely applied in the field of optical components due to its excellent thermal stability, high wear resistance, and superior chemical resistance. However, the ultra-high hardness significantly affects its machinability, particularly when machining the aspherical surface. To address this issue, this study proposes a laser-assisted diamond turning method to enhance the machinability and surface quality of the BTC. Experimental results showed an aspheric surface with high machining quality was fabricated on BTC surfaces. The characterization results showed the average surface roughness Sa and Sz obtained by the laser-assisted diamond turning method are 1.2 nm and 31.5 nm, respectively. The comparative experiment using traditional single-point diamond turning shows the laser-assisted diamond turning method reduces the surface roughness Sa and Sz by 40% and 37.4%, demonstrating its effectiveness. Therefore, this paper provides an effective machining method for fabricating high-quality aspherical mold inserts, which can be applied in the manufacturing of optical components in the future.

NOMENCLATURE

R = curvature radius of the spherical surface
p = distance from the optic axis Z
K = the conic constant
A_i = aspheric deformation constant

1. Introduction

Binderless tungsten carbide (BTC) is a typical mold insert material, which has widespread application in the field of optics, particularly in the manufacturing of precision optical components. They are used to create molds for shaping and forming optical elements such as lenses, mirrors, prisms, and other components used in imaging systems, lasers, and scientific instruments. In the realm of optic, BTC mold inserts offer several advantages, such as excellent thermal stability, high wear resistance, and superior chemical resistance. The excellent thermal stability allows it to withstand high temperatures without significant deformation or degradation encountered during molding processes. This is crucial for optical applications, as temperature changes can affect the dimensional accuracy and quality of the molded components. The exceptional hardness of the BTC makes it have high wear resistance, which ensures that the mold insert maintains its shape and remains resistant to wear, even after prolonged use. Superior chemical resistance helps it withstand exposure to solvents, cleaning agents, and other chemicals commonly used in injection molding or other molding processes. Besides, although BTC mold inserts may have a higher initial cost compared to other materials, their exceptional durability and wear resistance often results in long-term cost savings. Therefore, BTC has garnered significant interest from both academia and industry.

However, how to fabricate optical components, particularly optical aspherical surfaces, continues to pose challenges. Extensive research efforts have been dedicated to addressing this issue. Luo et al. investigated the vertical dry grinding of P10 grade tungsten carbide by employing a resin-bonded diamond wheel. Experimental results found that the predominant type of abrasive cutting edges found on the worn surface of the wheel were primarily protruding (favorable) particles [1]. Yin et al. presented the results of ultraprecision grinding of tungsten carbide for the production of spherical mirrors with high machining quality. Experimental results that the machined concave and convex spherical surfaces had the form accuracy of the 83-104 nm peak-to-valley (PV) values and the surface roughness Ra 5 nm [2]. To address the machining difficulty of freeform molds, Yan and Fang combined the wheel normal grinding and the slow tool servo to prevent the transfer of wheel errors to the mold surface. This approach ensures the attainment of the necessary machining accuracy [3]. Polishing is another machining approach to obtain optical aspheric surfaces. Zhang et al. employed the electrorheological fluid with varying viscosity to polish the micro dies of tungsten carbide and used multi-variable linear regression and Taguchi orthogonal array to establish the empirical model, which was utilized for evaluating the influences of the machining parameters on the surface roughness and material removal depth [4,5]. To enhance the accuracy of the molds, Suzuki et al. developed an ultrasonic two-axis vibration-assisted polishing device. Experimental results show several micro-aspheric molds, constructed from BTC, underwent a polishing process and its surface roughness Rz can reach 8 nm [6]. Grinding or polishing are often restricted by the low material rates. With the rapid advancement of laser heating assistance, turning has emerged as a promising technique for machining BTC material. You and Fang proposed an in-process-heat laser-assisted cutting method and performed the numerical simulation and experimental investigation on machining parameters, machining quality, and tool life [7,8]. However, the fabrication of optical aspherical surfaces on BTC mold inserts remains unknown.

In this study, laser-assisted turning is applied to investigate the optical aspheric surface on the surfaces of BTC mold inserts. Experimental results demonstrate its effectiveness and the machined surface quality was quantitatively characterized in this paper.

2. Experimental setup

Fig. 1 depicts the fabrication setup of optical aspheric surfaces when using laser-assisted diamond turning. The workpiece (M78, NJS Co.,Ltd SPS Center, Japan) with the hardness of 2600 HV and the grain size of less than 0.2 μm was fixed on the C-axis of the ultraprecision lathe via a fixture, as shown in Fig. 1. In the roughing fabrication, the cutting depth and feed rate were 5 μm and 4 μm /rev. Two samples were initially machined to remove the primary material of the workpiece. Then two new diamond cutting tools were used to perform the finishing fabrication using the cutting depth of 2 μm and feed rate of 1.6 μm /rev. One was used to perform laser-assisted diamond turning via the laser-assisted machining device (Optimus T$_2$, Micro-LAM, USA) [9], and the other one that has the same geometrical parameters was used to perform the comparative experiment. The setup of the comparative experiment is shown in Fig. 2.

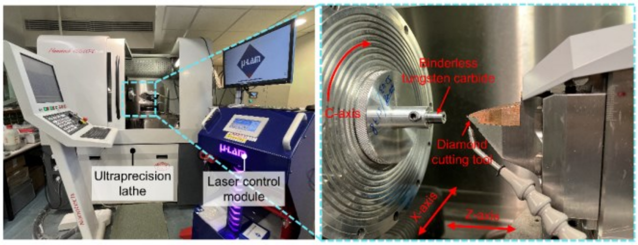

Fig. 1 Fabrication setup of aspherical BTC mold inserts by laser-assisted turning.

After fabrication, the machining surface quality and the cross-sectional profile of samples are characterized by the white light interferometry (Nexview^{TM}, Zygo Corp., USA) and optical surface profilometer (Form TalySurf PGI 1240, Taylor Hobson, England), as shown in Fig. 3.

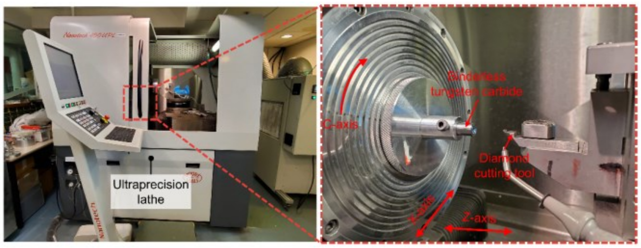

Fig. 2 Fabrication setup of aspherical BTC mold inserts by traditional single-point diamond turning.

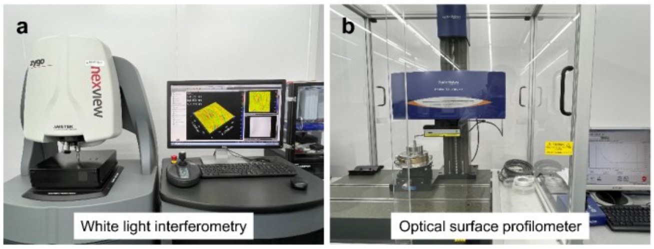

Fig. 3 Characterization equipment of the machining quality.

3. Results and discussion

3.1 Characterization of the machining quality

In general, the aspheric surface can be described, as follows:

$$z(p) = \frac{Cp^2}{1+\sqrt{1-(K+1)C^2p^2}} + \sum_{i=1}^{n} A_i p^i \quad (1)$$

$$p = \sqrt{x^2 + y^2} \quad (2)$$

where $C = 1/R$, and R is the curvature radius of the spherical surface. p is the distance from the optic axis Z. K is conic constant. A_i is the aspheric deformation constant. In this study, R=12.5 mm, K=-0.135, A_2 =0.00105, A_4 =0.00288, A_6 =7.28×10^{-5}, and other parameters=0.

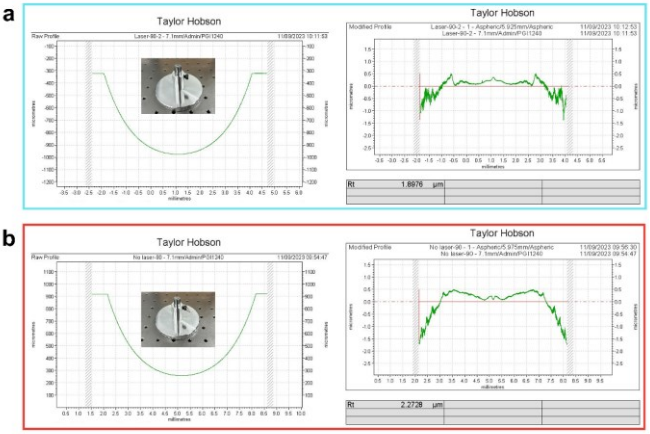

Fig. 4 The cross-sectional profile and profile error of the machined aspheric surfaces. (a) Laser-assisted diamond turning and (b) traditional single-point diamond turning.

Fig. 4 shows the cross-sectional profile (which passes through the center of the aspherical surface) and the profile error of the machined aspheric surfaces obtained through laser-assisted turning and traditional single-point diamond turning. It was found both methods achieved a good cross-sectional profile. The corresponding profile errors are 1.8976 μm and 2.2728 μm, respectively.

In addition to the cross-sectional profile, surface quality is also of paramount importance, as it directly impacts the performance of the machined aspherical surfaces. Randomly selected areas of the aspherical surface, measuring 179.96 μm × 179.96 μm, were extracted. The surface quality of these extracted areas was quantitatively characterized using a white light interferometer. When employing the laser-assisted diamond turning method, the average value of the surface roughness Sa and Sz, as illustrated in Fig. 5, were measured as 1.2 nm and 31.5 nm, respectively.

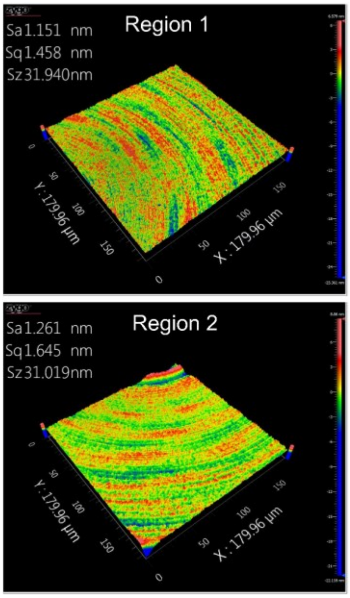

Fig. 5 The surface roughness of the machined aspheric surfaces when using the laser-assisted diamond turning method.

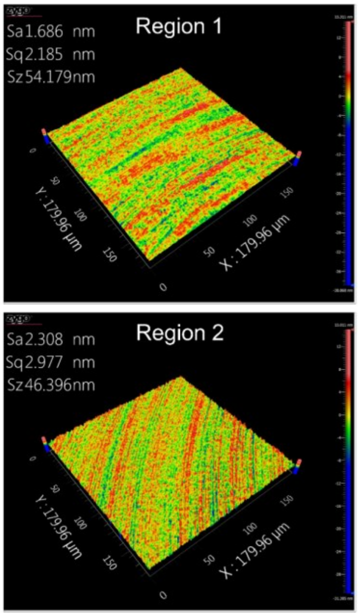

Fig. 6 The surface roughness of the machined aspheric surfaces when using the traditional single-point diamond turning method.

On the other hand, when using the traditional single-point diamond turning method, the corresponding values, as illustrated in Fig. 6, were found to be 2.0 nm (Sa) and 50.3 nm (Sz). It can be observed that compared to the traditional single-point diamond turning method, the laser-assisted diamond turning method reduces the surface roughness values of Sa and Sz by 40% and 37.4%, respectively. These results demonstrate the superiority and effectiveness of the laser-assisted diamond turning method in generating high-quality aspherical surfaces on mold insert material BTC. The significant reduction in surface roughness highlights its potential for enhancing the overall performance and functionality of optical components.

3.2 Characterization of the tool wear

When machining the BTC mold inserts, tool wear easily occurs due to the extremely high hardness of the workpiece material. In this study, two new diamond cutting tools, which were used to perform laser-assisted diamond turning and traditional single-point diamond turning, were characterized after finishing fabrication of the aspheric surface. Fig. 7 shows the SEM images of tool wear. When using laser-assisted diamond turning, there is small tool wear at the cutting edge. However, the traditional single-point diamond turning method causes larger tool wear, as shown in Fig.7 (b). Therefore, it indicates that the proposed laser-assisted diamond turning method is very appropriate for fabricating aspheric surfaces on BTC surfaces.

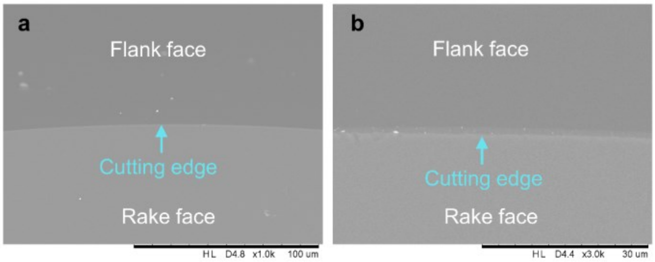

Fig. 7 SEM images of tool wear. (a) Laser-assisted diamond turning and (b) traditional single-point diamond turning.

3.3 Fabrication of the microstructure array

To demonstrate the flexibility of the laser-assisted diamond turning method, a microstructure pattern was also machined on the surface of the BTC mold insert. Fig. 8 shows its three-dimensional topography and corresponding cross-sectional profile. It was found that the microstructure array has a regular sinusoidal wave, and it radiates from the center of the microstructure surface to the outer of the sample.

The machining accuracy of the sine-wave microstructure array can be calculated based on their cross-sectional profiles, as displayed in Fig. 8(b). The average values of the measured amplitude and wavelength are 5.95 μm and 0.596 mm, which are in agreement with the designed values (6 μm and 0.6 mm). With regard to the machining quality of the machined microstructure array, the surface roughness Sa and Sz are 1.4 nm and 55.3 nm, respectively, also achieving the nanoscale surface finish.

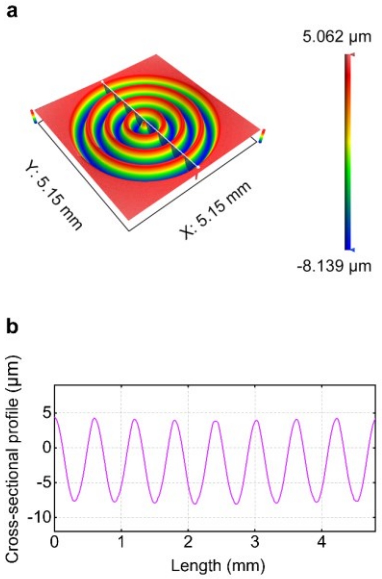

Fig. 8 The three-dimensional topography and cross-sectional profile of the sine-wave microstructure array.

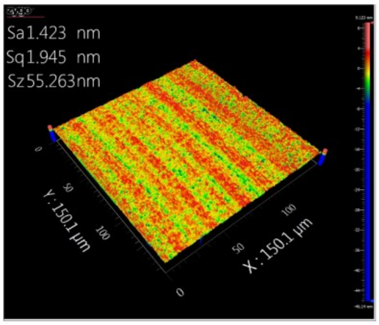

Fig. 9 The surface roughness of the machined sine-wave microstructure array.

4. Conclusions

In this study, a laser-assisted diamond turning method is applied to fabricate high-quality aspherical surfaces on mold insert material binderless tungsten carbide. The laser-assisted diamond turning method combines single-point diamond turning with in-situ laser-assisted machining, contributing to improving surface quality and effective material removal.

Fabrication results demonstrate the successful production of high-quality aspheric surfaces on binderless tungsten carbide surfaces. After measurement, it was determined that the surface roughness Sa was less than 2 nm, which signifies the exceptional machining quality.

Furthermore, a sine-wave microstructure array with the amplitude of 5.95 μm and the wavelength of 0.596 mm was also fabricated on binderless tungsten carbide surfaces. Its machining quality also achieves the nanoscale surface finish.

This achievement shows the capability and effectiveness of the laser-assisted diamond turning method in attaining aspheric surfaces with nanoscale surface roughness. Therefore, this study presents a valuable technology for fabricating high-quality aspheric surfaces on binderless tungsten carbide surfaces. This technology holds great potential for application in the manufacturing of optical components. It also will contribute to the advancement of optical engineering in the future.

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