Optik 124 (2013) 4406–4411

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

# Discussions on on-machine measurement of aspheric lens-mold surface

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ARTICLE INFO

*Article history:*
Received 25 September 2012
Accepted 10 January 2013

*Keywords:*
On-machine measurement
Aspheric lens mold
Ultra-precision machining
Instantaneous shearing interferometry

ABSTRACT

At present, regarding to the machining of aspheric lens mold, there are two major methods to carry out the on-machine measurement (OMM) — contacting method (CM) and non-contacting method (NCM). Here such two methods are reviewed in detail. CM is mainly based on the contacting probe which is scratching aspheric surface of lens mold to achieve profile data. To be efficient, an idea with 45° tilt of probe is proposed for OMM of lens mold by Suzuki. But generally speaking, the contacting OMM is not so efficient and can only deal with axisymmetric aspheric lens mold. On the contrary, NCM mostly uses laser to achieve aspheric profile without any contact. On ultra-precision lathe, laser scanning system or laser interferometer is mounted on the frame of lathe and transfers measurement data to machining system efficiently. However, most NCMs need stable environment and low working noise except instantaneous phase-shifting shearing interferometry (IPSSI). Therefore, a new idea about IPSSI is proposed in this paper to realize OMM of lens molds. Unfortunately, it's also difficult to test the high numerical aperture aspheric or free-form lens molds. By comparison, the newly-developed fringe reflection (FR) method is becoming the promising method because it features the high efficiency and high accuracy. However, this method has not been used for OMM system yet. Much research should be conducted for FR OMM technology.



## 1. Introduction

Classical polishing methods used for spherical surfaces of lens mold are not applicable to general aspheres and freeforms [1]. So currently, the aspheric lens-mold shape are formed mainly by computer-controlled local polishing method, magneto-rheological finishing process (MRF), single point diamond turning (SPDT) or precision diamond grinding method. In every manufacturing process, the achievable precision is only as good as the measurement method. For a high-end aspheric optics processing environment, important characteristics of a measurement method are: (a) high accuracy; (b) universal; (c) non-contact; (d) large measurement volume; (e) short measurement time [2]. That is to say, the on-machine measurement (OMM) of aspheric lens mold should be highly efficient, accurate and universal. Up to now, there are two major kinds of OMM methods: probe contacting method [3–12,14–16] and laser-based non-contacting method [13,17–30]. The contacting method uses the stylus or probe to scratch the surface of lens mold to achieve the section profile. In this case, the probe will damage the smoothness of lens-mold surface to some degree. Suzuki [5] proposed a 45 degrees tilted OMM system for small optical parts, by which the contact angle between the probe axis and the contact surface is kept constant. The probe friction force on lens-mold surface is changed smoothly so that the damage on the surface of lens mold becomes much less. Anyway, the contact between the probe and lens-mold surface is unavoidable. Therefore, the laser-based non-contacting OMM method is proposed to avoid the disadvantages of contacting method. References [18–28] have proposed some non-contacting OMM methods based the laser interferometry or laser holographic technology to realize the nondestructive testing. The other non-contacting OMM methods include the laser-triangle method [17], the laser-scanning method [2] and the fringe reflection (FR) method [29,30]. All the non-contacting OMM methods share the common advantages of non-destruction and high accuracy. But they are very different in efficiency and universal. The OMM laser interferometry is highly limited in measuring different shapes of aspheric lens molds. Meanwhile, most of non-contacting measurement systems need the stable environment and low working noise except the instantaneous phase-shifting shearing interferometry (IPSSI). Here a new concept about IPSSI is proposed in this paper to realize the OMM of lens molds. Unfortunately, it's also difficult to test the high numerical aperture (NA) aspheric or free-form lens molds. Comparatively speaking, the laser-scanning OMM method is highly universal and accurate, but not so satisfactory in efficiency, especially its cost

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http://dx.doi.org/10.1016/j.ijleo.2013.01.106

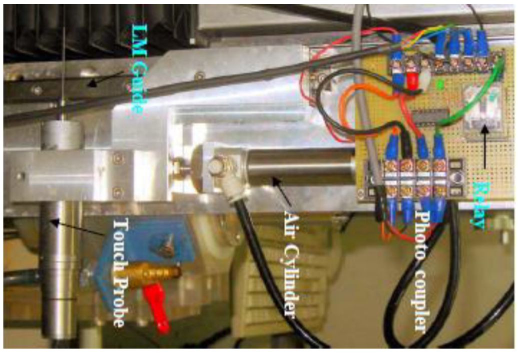



**Fig. 1.** Contacting OMM system by Mohammad (from Ref. [4]).

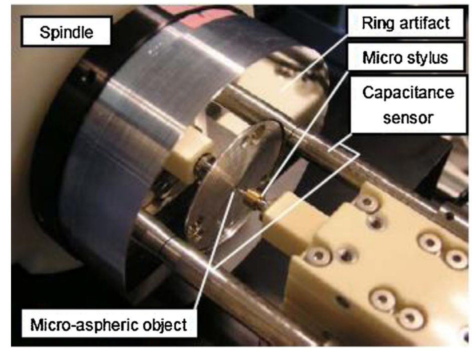



**Fig. 3.** Arai's scanning probe OMM system (from Ref. [10]).

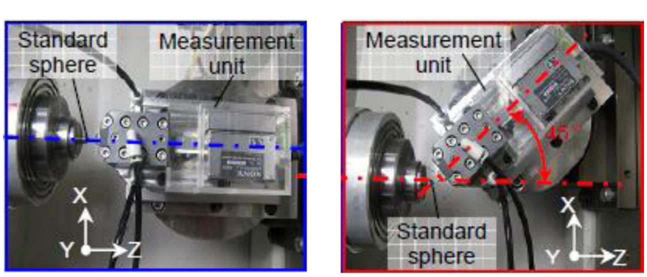
should be considered carefully. The newly developed FR method is becoming a promising OMM method to be used to seek the balance among high efficiency, high accuracy and universal.

## 2. Probe-contacting OMM method

As for the probe-contacting OMM methods, Mohammad [4] has developed a fully functional 4 axis CNC ELID grinding machine and an OMM system to measure the ground aspheric surface profile and diameter of grinding wheel. The OMM system was based on coordinate measurement machine (CMM) principle and checked the ground surface profile during machining. At the same time, the wheel wear could be also measured at some regular interval. Fig. 1 shows the OMM system.

In 2011, Huang [3] proposed a machining error compensation method using OMM system in 3-axis aspheric grinding. It aimed to providing the compensating profile data for large aspheric grinding. By use of this OMM system, the machining errors were reduced dramatically and the accuracy was improved by more than 45%, compared with the non-compensation machining. Additionally, Suzuki [5] proposed a 45° tilted contacting OMM system for small aspheric optics, especially for the large NA optics with steep surface angle. A air slider made of SIALON was adopted for the measurement probe and it was tilted for 45° against the aspheric workpiece axis so as to reduce the change in the probe friction force. Fig. 2 showed the real setup of OMM system and the conventional system. Through experiments, it proved that the measuring accuracy was much improved as compared to the conventional method.

Kim [7] realized diamond turning of large off-axis aspheric mirrors with OMM, and the machine axis errors were compensated in real time by using a fast tool servo. Its results showed that the proposed approach was capable of fabricating aluminum mirrors of 620 mm diameter with form accuracy of 0.7 μm in peak-to-valley (PV). On the other hand, Arai [10] presented a novel probe-scanning system to achieve the precise profile measurement of micro-aspheric mold. Fig. 3 showed the Arai's new OMM system. It consisted of a scanning stage and a sensor unit. The probe's contact force is less than 2.3 mN. Its experiments proved that the measurement repeatability of micro-aspheric scanning were smaller than ±20 nm.




(a) Conventional OMM method (b) the 45 degrees tilted OMM method

**Fig. 2.** the 45 degrees OMM method compared to conventional one (from Ref. [5]); (a) Conventional OMM method; (b) the 45 degrees tilted OMM method.

Chen [9] also developed a compensation method based on the OMM to conducting the grinding of tungsten carbide (WC) aspheric lens mold. The form error after grinding was achieved by subtracting the target profile from the actual ground profile. The experiments showed that the aspheric surface had an accuracy of 177 nm (PV) and roughness of 1.7 nm (Ra) after 3 compensation cycles. Yongjian [11] developed a low-cost OMM method used in fine grinding of large aspheric mirror. The OMM method was carried out on a common digital-controlled lapping machine tool and its accuracy was better than 5 μm. To improve the accuracy of OMM, Yoshikazu [12] put forward an accurate two-probe method to measure an aspheric lens on an ultra-precision grinding machine. Its results showed that the deviation of tested profile from the designed value was confirmed to be 0.35 μm. In addition, Changyu [15] provided an OMM method aiming at solving the complex aspheric surface. Its experiments showed that the measuring method had high accuracy, universal utility in the aspheric machining and measurement. Zhifang [16] had also made an OMM of aspheric workpiece surface by using a precise-calibrated, low-force and air-bearing LVDT.

According to the investigations of OMM methods, the probe contacting method is still popular for the ultra-precision machining although the scanning efficiency of probe is much limited. Its profile accuracy can be on the order of submicron. However, on the most cases, it's only suitable for the axisymmetric aspheric surface of lens mold.

## 3. Non-contacting OMM method

### *3.1. Laser triangle method*

Gao [17] firstly developed an in-process form error measurement device to deal with the opaque barrier and vibration. It was based on a single laser sensor of 50 nm resolution together with a damping technique and a moving average one. Fig. 4 showed the prototype for the OMM optical setup by Gao.

In Fig. 4, the proposed damping technique was able to improve vibration attenuation by nearly 21 times compared to the natural attenuation, and its moving average method was able to reduce errors by seven to ten times with no change of form errors. For a workpiece sample, the overall system measurement error could be as low as 0.3 μm.