Novel method for fabrication of monolithic multi-cavity molds and wafer optics

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ABSTRACT

One lens at a time on axis diamond turning or grinding of lens arrays with a large number of lenses is conventionally impractical because of the difficulties to shift and balance the substrate for each lens position. A novel method for automatic indexing was developed. This method uses an innovative mechatronics tooling (patent pending) that allows dynamic indexing at constant work spindle speed for maximum productivity and thermal stability of the work spindle while the balancing condition is maintained. In this paper we shall compare the machining capabilities of this method to free-form machining techniques, discuss about the main issues, present the concept and design of the working prototype and specific test bed, and present the results of the first cutting tests.

Keywords: indexing, positioning, wafer level manufacturing, micro lens array, monolithic mold, multi-cavity, diamond turning, grinding, free-form machining, diamond micro milling

1. INTRODUCTION

Monolithic lens array masters are used in applications such as wafer level smartphone camera manufacturing and lens replication molding. Ultra precision diamond cutting has become the reference machining technology for such lens arrays with aspheric shape whereby lens-to-lens registration is critical. Traditionally these lens arrays would be machined by on axis diamond turning, one lens at a time, requiring the substrate to be shifted sequentially for each lens position. Nowadays mostly free-form machining techniques are used allowing a single setup of the substrate, thus overcoming the difficulties and time losses of micron accurate substrate indexing and balancing. Although diamond micro-milling (DMM) allows for the machining of surfaces with steep edge slopes, limitations are faced such as the residual surface form error, the long processing time, the impossibility of Fresnel and diffractive features or the incompatibility with ultrasonic vibration assisted cutting.

It is well known that turning is more efficient and produces smoother surfaces than milling. This is inherent to the cutting process that is continuous for turning while it is interrupted for milling, causing vibration of the tool and of the part. Therefore generally turning is used wherever possible. In the case of optical surfaces that are mostly axisymmetric or near to it, ultra-precision turning and grinding machines have been developed and operated since more than 30 years. For lens arrays, in order to avoid the need of shifting the substrate, DMM is used since a few years, iteratively compensating for the form errors resulting from the micro-milling process such as spindle errors, machine kinematics errors, tool misalignment to the spindle axis, tool cutting edge waviness. But even if a major part of systematic errors can be compensated using a correction cycle, the surface quality of a micro-milled surface is generally lower than the surface quality of a diamond turned surface. Another important drawback of the DMM process is the significantly longer machining times that may take up to several days of continuous machining for a large array containing hundreds or thousands of lenses. Considering the limitations faced with micro-milling and other free-form machining techniques such as Slow Tool Servo (STS) or Fast Tool Servo (FTS), that cannot handle steep slopes, there is no technique that allows to machine large lenslet arrays to ultra precision with industrial efficiency.

With these considerations in mind, WIELANDTS UPMT has developed an innovative positioning tooling to automatically shift the substrate allowing efficient on-axis diamond turning of large lenslet arrays. This
tooling aims to overcome the above-mentioned difficulties of accurate positioning and balancing. The technology is called Dynamic Part Indexing (DPI). In table 1 the capability of this technology is compared to three well known free-form machining technologies: STS, FTS and DMM. The values in the table are to be considered as typical values.

Table 1. Typical monolithic array machining capabilities of DPI compared to free-form machining techniques.

<table>
<thead>
<tr>
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<th>STS</th>
<th>FTS</th>
<th>DMM</th>
<th>DPI</th>
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<tbody>
<tr>
<td>Maximum slopes</td>
<td>20 deg</td>
<td>20 deg</td>
<td>60 deg</td>
<td>60 deg</td>
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<tr>
<td>Process speed</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
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<tr>
<td>Form accuracy</td>
<td>-</td>
<td>-</td>
<td>+</td>
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<td>Diffractives</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
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<td>Ultrasonic turning</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Grinding</td>
<td>N</td>
<td>N</td>
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2. MAIN ISSUES AND SPECIFICATIONS

The main issues that arise with automatic indexing for an ultra precision application are: the accurate positioning, the balancing of the work spindle, the mechanical and thermal stability, the total machining process time including the duration of the indexing and of course the limitations of mass on the work spindle.

For aspheric lenses the upper and lower lens surfaces need typically to be aligned within ten microns or better. For molding applications, the closing of the mold may contribute to as much as four to five microns. Therefore the lens-to-lens registration at the level of each mold half may be specified as low as two or even one micron. For DMM the lens-to-lens registration depends mainly on the accuracy of the main axes of the machine. In case of an indexing device mounted onto the work spindle the lens-to-lens registration depends almost exclusively on the positioning accuracy of the indexing device. This key issue is further developed in chapter 4 where the principal contributors to the error budget of the lens-to-lens registration are described.

Perfect balancing of the work spindle is a key condition to ultra precision machining. Ultra precision work spindles generally have air bearings that have the advantage of near zero friction so that the rotation is very smooth while heat generation is minimized. However these spindles are sensitive to unbalance because of the limited stiffness of the air bearings. The allowable shape irregularity of a diffraction limited imaging lens surface is typically 200 nm p-v. The corresponding acceptable value of residual unbalance depends on the rotation speed as centrifugal forces are proportional to the square of the rotation speed and will typically be below 50 gmm at 500 RPM.

The system and the workpiece are submitted to gravitational and centrifugal forces. Considering that the system is mounted onto a workspindle with horizontal axis, the workspindle sees a constant gravitational force acting on the rotor generating a constant tilting moment. This results in a small but constant tilting angle of the workspindle rotor that has to be taken into account when aligning the cutting tool bit but has further no significant effect on the machining. However the gravitational forces on the indexing system have a frequency of once per revolution (the gravitational force's direction changes as the spindle rotates) and may therefore cause a once per revolution deformation that will in turn cause a displacement of the workpiece. Note that a configuration with vertical spindle axis would be favorable as then the gravitational forces on the system would be constant. Any static or dynamic unbalance (misalignment of the principal axis of inertia with the spindle rotation axis) will cause the axis to wobble. This wobbling again has a once per revolution frequency that will cause a displacement of the workpiece. Any displacement of the workpiece due to deformations or spindle wobbling during the machining will result in a form error.

As it is well known, the work spindle thermal stability is always critical when it comes to high precision machining as any fluctuation will modify the distance of the tool to the workpiece surface and directly affect the
surface form quality. Therefore it is common practice to let spindles rotate at constant speed for some time before starting to machine. For thermal stability it is clear that the system should be capable to operate dynamically i.e. with the work spindle rotating at constant speed without the need of stopping it to perform the indexing. A dynamic operation is also very advantageous from an economical point of view as it eliminates the deceleration and acceleration times that may make up a significant part of the total process time because of the large inertia of the tooling. Machining time is not only an important economical factor but it may also have its effect on the surface, shorter machining cycles generally resulting in lower irregularities.

The following principal specifications were defined for the design of the system: it should be designed as an add-on tooling to a standard ultra-precision lathe and work spindle with minimal hardware and software integration actions, it should be capable to operate at medium rotational speeds, it should be capable to hold and position workpieces up to 200 mm in diameter to conform to standard wafers of 8 inches, it should allow for diamond turning of lenses with form irregularities of less than 200 nm p-v and surface roughness of less than 5 nm Ra and it should have a positioning repeatability of 1 micron. The maximum mass of the system should be less than 36 kg with a maximum distance from the center of mass to the spindle nose not exceeding 100 mm. These values correspond to the load capacity of the well-known Professional Instruments ISO 5.5F air bearing spindle.

3. CONCEPT AND DESIGN

The engineered solution is a 2 axis positioning system for holding and automatically indexing a workpiece, that is added as a tooling to the rotor of the workspindle of a classical 2 or 3 axis ultra precision lathe. This system mainly consists of a chuck with two rotary axes called Alpha and Beta that are parallel to each other and to the work spindle axis. The Beta axis is mounted eccentric to the work spindle axis and carries the Alpha axis that is itself mounted eccentric to the Beta axis, preferably with the same eccentricity. The particularity of using rotary axes instead of linear axes is that each rotary axis can be perfectly balanced on its own rotation axis. Then the workspindle rotor with the complete system mounted onto it with the uppermost rotary axis holding the workpiece, can be itself perfectly balanced onto the workspindle axis so that the balancing condition is independent of the angular positions of the rotary axes.

Figure 1 shows the demonstrator/prototype that was designed and built. It has an outer diameter of 420 mm and a total mass of 30 kg with a center of gravity positioned at 80 mm from the workspindle nose. An interface plate contains the attachment to the spindle and incorporates slip rings to feed the system with electrical 24 V DC power. The brush contacts are held radially on a pneumatic actuator so that there is no contact to the rotor during the machining operations.
The eccentricity between the Beta rotary axis and the workspindle is 50 mm so that for the maximum Beta angle of 180 deg the workpiece is shifted by 100 mm. It is thus possible with this tooling to position any point of the substrate surface within a diameter of 200 mm on the axis of the workspindle.

The balancing means partially consist of fixed counterweights and partially of adjustable counterweights on both the Beta rotary axis and the base plate of the system. Using a combination of plates with different thicknesses the counterweight mass can be adjusted precisely to balance the system to 50 gmm. The counterweight mass and height position can be calculated easily from the mass and dimensions of the workpiece knowing the exact mass and geometry of the system.

Because of the potential damage to the workspindle in case of incorrect balancing, the balanced condition is checked statically for different indexing positions of the workpiece before starting the rotation of the spindle, e.g. for the position Beta 0 deg where the workpiece is centered and for Beta 180 deg where the workpiece is shifted maximum. Fine balancing adjustments may be required depending on the surface form specifications. For this, classical methods can be used using accelerometers or analyzing the induced following errors on the machine axes (X or Y).

The system comprises embedded actuators, high precision on-axis absolute encoders, in position clamping means and a controller.

4. LENS TO LENS REGISTRATION

As mentioned above lens-to-lens registration is critical for most monolithic lens array applications. In contrast with other machining techniques the lens-to-lens registration accuracy does not depend on the accuracy of the machine tool axes, each individual lens of the array being machined on-axis using an identical toolpath. Instead, the lens-to-lens registration depends on the accuracy of the indexing device itself. The following sections describe the main contributors to the positioning error.

4.1 Angle positioning errors

The angle positioning error is the sum of the positioning repeatability and the angle accuracy. Using 26 bit absolute angle encoders, the encoder resolution is 0.09 µrad or 0.02 arcsec. The positioning repeatability including the clamping effect is less than 25 encoder counts, i.e. maximum 2.25 µrad or 0.5 arcsec. The angle encoder accuracy before mounting is ±3 arcsec as specified by the encoder manufacturer, while after mounting of the encoder the accuracy was measured to be ±15 arcsec. Finally the encoders were calibrated to a master encoder (Renishaw XR20-W) to ±1 arcsec (5 µrad) as shown in figure 2. The effect of angle positioning errors on the lens-to-lens positions depends on the eccentric positions of the rotary axes. For the Beta rotary stage the eccentricity is a fixed value (50 mm) so that 1 arcsec of angular error results in 0.25 µm of lens position error. For the Alpha rotary stage, the eccentricity to the work spindle axis varies between 0 and 100 mm so that 1 arcsec of angle error results in 0 to 0.5 µm of lens position error.

4.2 Runout and alignment errors

Radial runout of the rotary axes impacts directly the lens-to-lens position. The runout of the Alpha rotary axes was measured to be 0.3 µm p-v, the runout of the Beta rotary axes was measured to be 0.7 µm p-v.

Alignment errors of the system to the workspindle axis are multiplied by the Alpha and Beta angles. For an alignment error of 0.5 µm the cavity position error is maximum 2 µm for 180 deg angles of Alpha and Beta. The knowledge of the eccentricity between the rotary axes Alpha and Beta is measured with an accuracy of 0.5 m so that its effect is limited to 1 µm for a 180 deg angle of Beta.

Maximum care was taken for the parallelism and flatness of all the stacked components. The parallelism of the Alpha axis to the workspindle axis was measured to be 43 µrad p-v (9 arcsec). The effect on the lens-to-lens position in the XY plane is negligible. The effect on the sag of the lenses is ± 2 microns on a diameter of 100 mm.
4.3 Deformations and Unbalance

In addition to the effects on the machining that will result in form irregularity, deformations of the system due to centrifugal forces and gravity may impact the lens-to-lens registration. These deformations are almost perfectly repeatable. By correct FEM design the cumulated effect of the deformations are less than 0.8 $\mu$m.

Residual unbalance of the workspindle will cause the axis to wobble. This motion of the spindle axis has no significant effect on the lens position.

Thermal variations of the machine environment and of the system with its embedded actuators and control system will lead to dimensional changes of the system components. The principal concern is the value of the eccentricity of the axes. Temperature variations have been measured at the Beta axis below 0.2 C. By proper selection of materials the effect on the lens positions is evaluated to be maximum 0.3 $\mu$m.

4.4 Compensation

Except for the thermal effects all other position error factors are almost perfectly repeatable and can be compensated. The measurement of the positions with true micron accuracy is here the greatest difficulty.

5. CUTTING RESULTS

In this chapter the cutting results obtained by single point diamond turning using the DPI tooling for indexing of the substrate between cuts are presented.

The machine setup that was used was a classical 2 axis ultra precision lathe from Moore Nanotech type UPL 450. This machine tool has 450 mm diameter swing capacity that perfectly fits to the DPI demonstrator/prototype that has an outside diameter of 420 mm. The work spindle of this lathe is an air bearing spindle from Professional Instruments type ISO 5.5F. Because every cavity is cut on-axis the required travel of the X axis is limited to the radius of a single lens for cutting all the lenses.

In a monolithic 6082 aluminum disc with an outer diameter of 120 mm and a thickness of 20 mm, 37 concave lenses were cut with 6 mm diameter and 9 mm radius of curvature. The sag of the cavities was 0.515 mm and the surface slope at the edge was 19.5 deg. The spacing between the cavities was 8 mm. The lenses were cut spherical as this allowed to use straightforward interferometry to measure the irregularity of the surface.

A natural monocrystalline diamond toolbit with a controlled waviness of 0.25 $\mu$m from Contour Fine Tooling was used. The radius of the tool was 0.522 mm with a rake angle of 0 deg and a clearance angle of 12.5 deg. The
Figure 3. Closeup view of an on-axis diamond turned lens.

Figure 4. Zygo interferometer plots of on axis turned lenses Dia 6 mm, Radius 9 mm using DPI tooling technology for indexing.
cutting parameters were a depth of cut of 3 µm with a spindle speed of 350 RPM and a feedrate of 1 mm/min. The corresponding in-feed was 2.9 µm/rev and cusp was 2 nm.

Figure 4 shows the form irregularity of 3 lenses from the array measured by interferometry with tilt and power removed. The irregularity was measured to be consistently below 150 nm p-v. The astigmatism was measured around 30 nm.

The positioning repeatability was measured using an optical setup inside the diamond turning lathe (field of view of 610 by 470 µm), as shown in figure 5. Sub-pixel edge detection software was developed to track the outer diameter of lenses in the array, moving the DPI tooling with respect to the microscope using the X and C axes of the machine. The positioning repeatability was evaluated for each of the two rotary axes individually. For the Alpha axis, 8 angles were measured over 360 deg and repeated 5 times over. The axis was brought to position and clamped at a rotational speed of 350 RPM. An edge of a lens on the array was then tracked using the optical microscope and measured over 12 points (form tolerance within 0.4 µm). The p-v repeatability was evaluated to be 0.2 µm. The same method was used for the Beta axis but with 8 angles over 180 deg. The p-v repeatability was evaluated to be 0.6 µm.

6. CONCLUSIONS

A novel method for automatic part indexing was presented that allows for on-axis machining of each individual lens of a lens array. This method aims to overcome the difficulties of manual workpiece shifting that is considered impractical for arrays with many lenses in terms of micron accurate positioning, balancing and total process time. The originality and advantage of the method are to make use of eccentric rotation axes so that the balancing conditions of these axes are maintained independently of the part shift position.

This method allows to machine large lens arrays with on-axis machining techniques such as turning and grinding. This has many advantages over interrupted cutting techniques such as milling. The indexing being automated and dynamic, i.e. while the workspindle is rotating at constant speed, the indexing times from lens to lens are very short, only a few seconds which is only a fraction of the total machining time. The power dissipated in the tooling is negligible as the system is disconnected electrically between indexing instructions.

For the tested prototype system, the work spindle rotation speed was limited to typically 300 to 500 RPM to minimize the deformations resulting from the centrifugal forces. Compared to turning of a single on-axis lens, the cutting speed is thus relatively low. However, with respect to DMM that is the current state of the art technology for machining lens arrays, the total machining time is reduced significantly, by a factor of 5 to 10. For grinding applications the workspindle rotation speed is perfectly matching.
It was shown that the form irregularity of the lenses is consistently under 150 nm p-v. Lens-to-lens registration repeatability was evaluated to be under 1 µm using edge detection inside the diamond turning lathe. The next step is to measure the absolute lens-to-lens registration accuracy and make use of the high repeatability for any compensation.

Further development is planned to make profit of the full potential of this innovative manufacturing technology. Next key areas of interest include diffractive structures, grinding, and vibration assisted hard turning of steel molds. It is expected that this new technology will contribute to further develop applications for lens arrays, monolithic multi-cavity molds and wafer optics.

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REFERENCES


