Development of a 45 Degrees Tilted On-Machine Measuring System for Small Optical Parts

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Abstract

A new contact type of on-machine measuring system is developed in order to measure aspherical optical parts with steep surface angle for large numerical aperture (NA). A ceramic air slider made of SIALON is adopted for the measurment probe because of its low thermal expansion coefficient, high rigidity and light weight. A high accuracy glass scale is employed to reduce the thermal drift of the displacement gauge. The air slider or the measuring probe is tilted for 45 degrees against the aspherical workpiece axis, and the probe is scanned over the workpiece surface, so as to keep the contact angle between the probe axis and the contact surface constant in order to reduce the change in the probe friction force.

Keywords:

Measuring instrument, Ultraprecision, Mold

1 INTRODUCTION

Demands are increasing for micro aspheric glass lenses to be installed in various optical devices, such as DVD pick-up systems of blue laser, digital cameras and optical transmission devices in order to improve the optical performance. The micro aspheric glass lenses are generally molded by the glass press molding process with micro aspheric ceramic molding dies or molds made of tungsten carbides (WC) or silicon carbides (SiC). These dies/molds are mostly ground with micro diamond grinding wheels [1] and finished by the micro aspherical polishing process with loose super abrasives [2,3]. The dies/molds are ground and polished through the compensation process based on the measured form deviation profile. In the conventional measurement process, the contact type of measurement instruments with small diamond stylus are used to compensate the NC program.

As the optical system becomes more compact and complicated, it becomes more difficult to manufacture the aspherical shapes of lens molds. It is also difficult to measure them because of their high accuracy and large numerical aperture (NA), which results in large sweep angle of the aspherical surface. Generally, machining and measurements of the die/mold workpiece are repeated to obtain the final accuracy. In doing so, it is practically impossible to set the workpiece on the machine accurately, once it is unloaded for measurement. Therefore, on-machine measurement technology is required to guarantee high accuracy of machining. In this study, a new probe scanning method using the 45 degrees tilted air probe system is proposed and a new on-machine measuring system is developped to precisely measure the aspherical surface of large NA with use of a new air slider made of ceramics which have a low thermal expantion coefficinet. Fundamental properties of the proposed measuring method are evaluated and the measuring accuracies are compared with the conventional method.

2 CONVENTIONAL ON-MACHINE ASPHERICAL MEASUREMENT METHOD

The conventional on-machine measuring system is shown in Figure 1. The measurement error caused by the deformation of the contact probe becomes larger as the measurement deviation increases when the sweep angle of the aspherical workpiece surface is increased. The drift of the measurement scale of the LVDT (linear variable differential transformer) or Laser beam increases with the changes in the temperature, pressure and humidity [4]. In the conventional measurement method, the measurement probe scans along the workpiece surface by keeping the probe axis parallel to the workpiece axis as shown in Figure 2(a). As the sweep angle of the workpiece surface increases, the tangential component of the probe contact force F_x increases and the deformation of the probe increases, which results in the increase of the measurement error as shown in Figure 2(b). The error caused by the deformation of the probe is a serious problem, as some of the optical lenses have large sweep angle to increase NA.

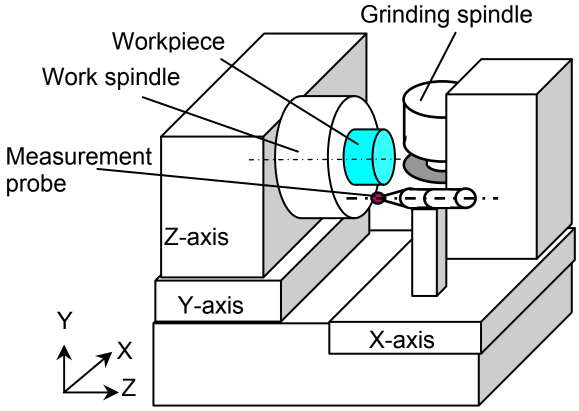
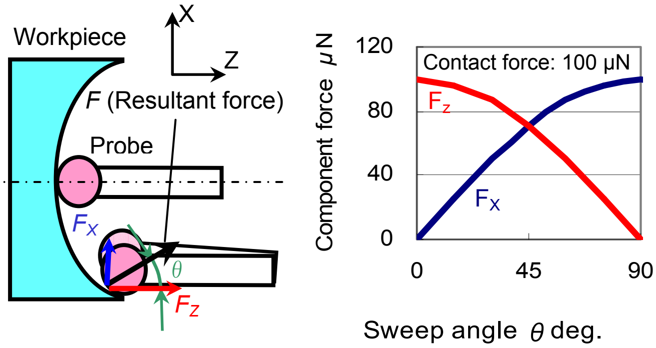


Figure 1: An example of conventional on-machine measurement system.



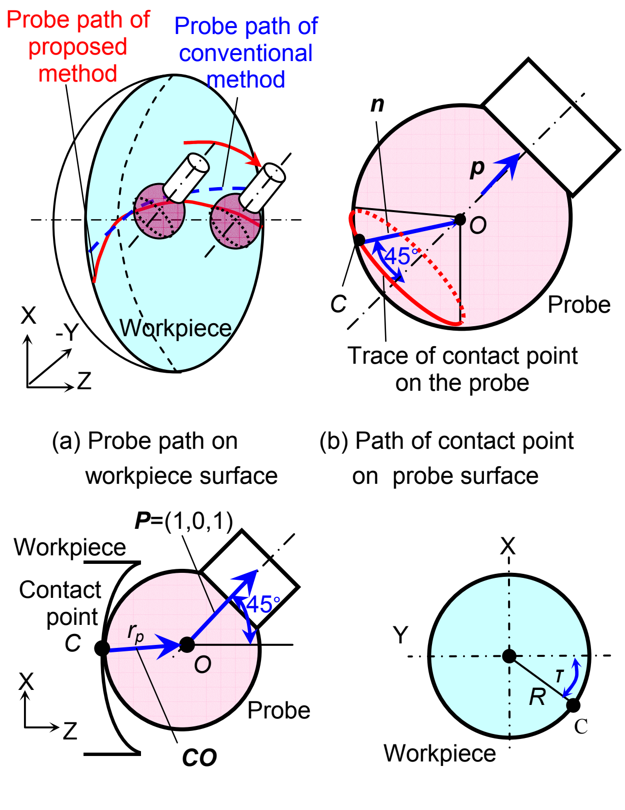
(a) Probe deformation (b) Probe force change

Figure 2: Problem of conventional measurement.

3 PROBE PATH OF PROPOSED ASPHERICAL MEASUREMENT METHOD AND ITS PRINCIPLE

3.1 Proposed scanning method

In order to decrease the measurement errors caused by the probe deformation mentioned above, a new probe scanning method is proposed here. As shown in Figure 3(a), the probe is tilted at 45 degrees from the workpiece axis on the X-Z plane and the probe scans 3-dimentionally so as to keep the contact angle between the probe axis and the contact surface constant in order to reduce the change in the friction force between the measuring probe and measured workpiece, while the probe scans 2-dimentionally on the Y-Z plane in the conventional scanning method.



(a) Probe path on workpiece surface (b) Path of contact point on probe surface

(c) X-Z plane (d) Workpiece surface

Figure 3: Calculation of the probe path.

3.2 Calculation method of probe path

The positional relationship between the ball probe and workpiece is shown in Figure 3(b) and (c). The aspherical function of the axi-symmetric aspherical shape is given by:

$$Z = f(R) = \frac{Cv\cdot R^2}{1+\sqrt{1-(K+1)\cdot Cv^2\cdot R^2}} + \sum_{i=1}^{n} C_i\cdot X^i \qquad (1)$$

Where, $R=f((X^2+Y^2)^{0.5})$. The normal vector $\boldsymbol{n}$ at the contact point between the probe and workpiece surface is given by:

$$\boldsymbol{n}\,(a,b,c) = \left(-\frac{\partial f}{\partial X},\ -\frac{\partial f}{\partial Y},\ 1\right) \qquad (2)$$

The vector $\boldsymbol{CO}$ between the probe center O and the contact point C is given by:

$$\boldsymbol{CO} = \left(r\frac{a}{l},\ r\frac{b}{l},\ r\frac{c}{l}\right) \qquad (3)$$

Where, $l=(a^2+b^2+c^2)^{0.5}$, and r_p is the ball probe radius respectively. As the probe is tilted at 45 degrees from the Y-Z plane, the directional vector of the probe $\boldsymbol{p}$ is given by $\boldsymbol{p}$=(1,0,1). From Equations (2) and (3), the following relation is obtained:

$$b^2 = 2ac \qquad (4)$$

The contact point coordinate $C\,(X_c,Y_c,Z_c)$ is expressed by the following equations as shown in Figure 3(d):

$$X_c = R\cdot\sin\tau,\quad Y_c = R\cdot\cos\tau,\ Z = f(R) \qquad (5)$$

Where, R is workpiece radial position of the workpiece, and τ is angle of the C from Y axis respectively.

From the Equations (2) and (5), the following relationship is obtained:

$$\boldsymbol{n}\,(a,b,c) = \left(-\frac{\partial f}{\partial X},\ -\frac{\partial f}{\partial Y},\ 1\right) = \left(-\frac{\partial R}{\partial X}\cdot\frac{df}{dr},\ -\frac{\partial R}{\partial Y}\cdot\frac{df}{dR},\ 1\right)$$

$$= \left(-f'(R)\cdot\cos\tau,\ f'(R)\cdot\sin\tau,\ 1\right) \qquad (6)$$

From Equations (4) and (6), the angle τ is given by:

$$\sin\tau = \frac{1}{f'(R)} + \sqrt{\frac{1}{f'(R)}+1}\quad \text{; for convex shape} \qquad (7.1)$$

$$\sin\tau = \frac{1}{f'(R)} - \sqrt{\frac{1}{f'(R)}+1}\quad \text{; for concave shape} \qquad (7.2)$$

In order to determine the probe scanning path, first, the angle τ is calculated at the radius position R by Equations (7.1) or (7.2), secondly, the contact point coordinate on the workpiece surface $C(X_c,Y_c,Z_c)$ is calculated, and finally, the ball probe center coordinate $O(X_o,Y_o,Z_o)$ is given. The paths of the probe center and the contact point on the ball probe are shown in Figure 3(a). The probe scans the workpiece surface 3-dimentionally in the proposed method, while it scans 2-dimentionally in the X-Z plane in the conventional method.

4 DEVELOPED MEASUREMENT SYSTEM

4.1 Air bearing slider

Figure 4 shows a schematic diagram and a view of the developed air slider for the measurement unit, which is made of SIALON ceramics. Table 1 shows physical properties of SIALON ceramics. The SIALON is a composite ceramic of Al_2O_3 and Si_3N_4. The density and the thermal expansion coeficient of SIALON are 1/2.5 and 1/10 respectively as compareed with steel. The air slider is supported by the air gap of 2 μm in both sides of the air bearings. In the center area of the slider, there is a gap of about 100 μm. The air is supplied through this port and released through one side of the port while there is no release port at the other side. The pushing force and the pulling force are generated by adjusting the air presure in both sides, so that the probe contact force is controled. Figure 5 shows a relationship between the supplied air pressure and the generated contact force. Low contact force of 0.1 mN can be obtained by this mechanism.

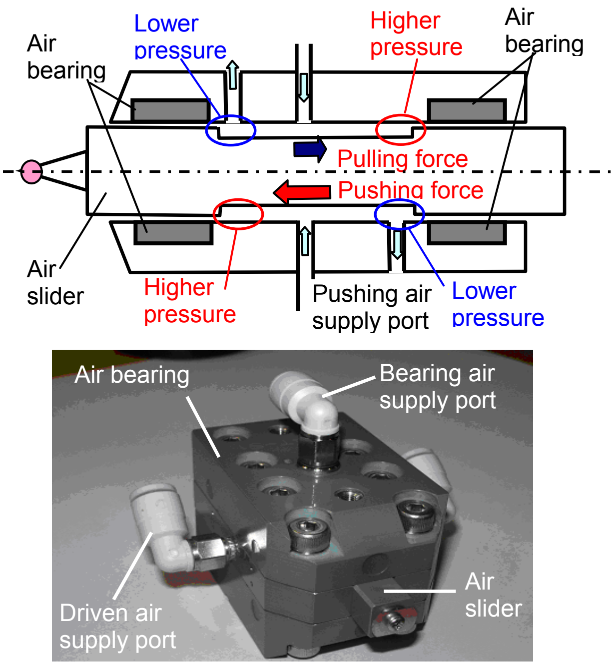


Figure 4: Schematic diagram and view of developed air slider for measurement unit.

Materials	SIALON S120	Steel S55C (JIS)
Density (g/cm^2)	3.2	7.9
Yong's modulus (GPa)	300	206
Thermal expansion coefficient (K^{-1})	1.3 x10^{-6}	12 x10^{-6}

Table 1: Properties of SIALON ceramics.

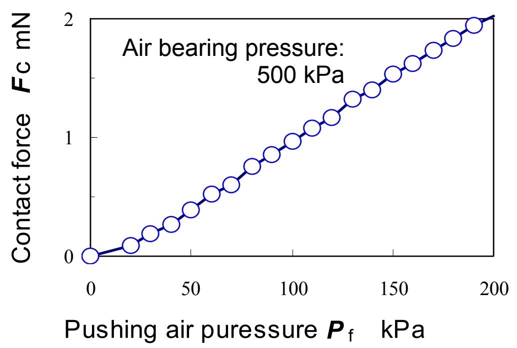


Figure 5: Relationship between supplied air pressure and generated contact force.

4.2 Structure of measuring unit and on-machine measurement system

Figure 6 shows a schematic diagram of the measurement unit. A small glass linear scale is attached to the rear end of the air slider made of SIALON. The amount of the slider movement is measured with the detector of the linear glass scale. The resolution of the linear glass scale is 0.14 nm.

The measurement unit is installed to the ultra precision machine and is set to be inclined at 45 degrees to the Z-axis on the X-Z plane, as shown in Figure 7. The machine is a 4-axis (*X*,*Y*,*Z*,*C*) control grinding machine with 1 nm resolution driven by linear motors. The machine is controlled by the NC program generated within the PC. The measured deviation data (*dZ*) are taken step by step onto the PC and the base workpiece profile (*X*,*Y*,*Z*) is added to obtain the real profile.

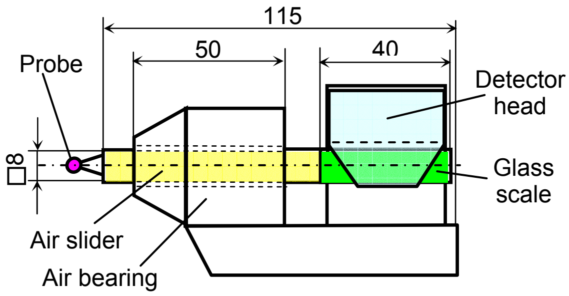


Figure 6: Measurement unit.

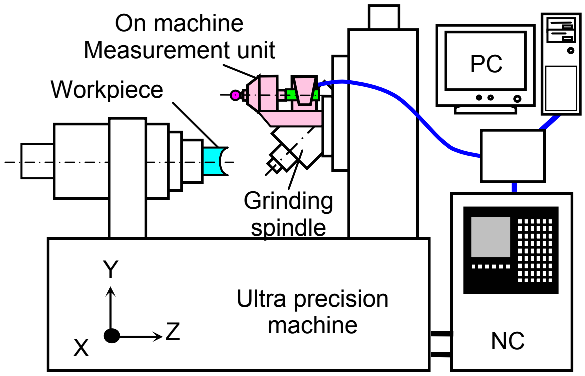


Figure 7: Schematic diagram of developed on-machine measurement system.

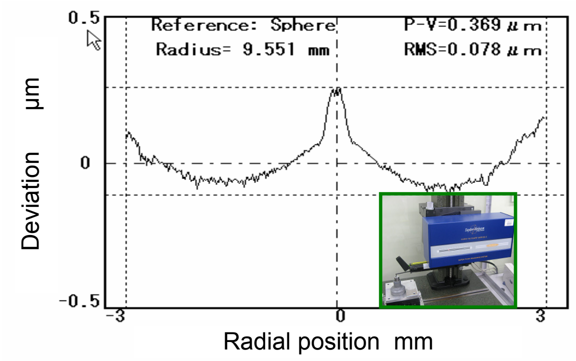
5 ON-MACHINE MEASUREMENT EXPERIMENTS

5.1 Evaluation of developed measurement unit

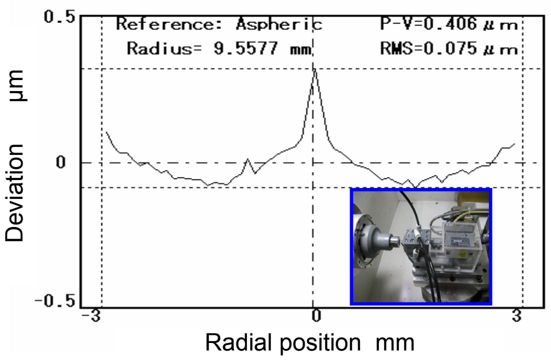
A ground concave mold made of tungsten carbide was measured to evaluate the accuracy of measurement unit developed. Experimental conditions are shown in Table 2. A ruby probe of about 0.5 mm radius was used and the contact force was 0.3 mN. The measurement unit was not tilted and the measured results were compared with those of a conventional contact type aspherical measurement instrument. Figure 8 shows a comparison of the measured results. Figure 8(a) shows the form deviation profile measured with Form Talysurf, and (b)

Ball probe Radius	Ruby r_n = 0.5009 mm
Measured workpiece Sphere radius	Tungsten carbide mold *R*=9.55 mm (Concave)
Contact force	F_p = 0.3 mN
Scanning speed	0.2 mm/min

Table 2: Experimental conditions.



(a) Measured with conventional instrument



(b) Measured with developed measurement unit

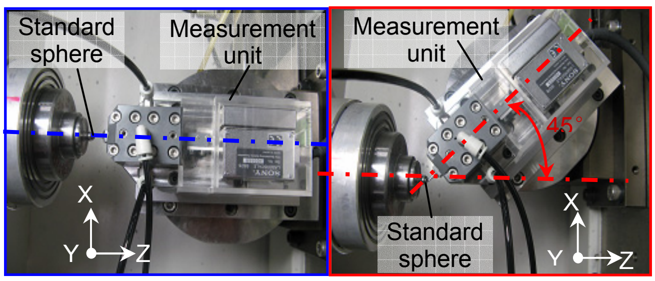
Figure 8: Comparison of measurement results.

shows the one measured with the developed measurement system. The form deviation profile measured with the developed unit is close to that of conventional one, and it is proved that the developed unit has sufficient accuracy.

5.2 Evaluation of 45 degrees tilted measurement system

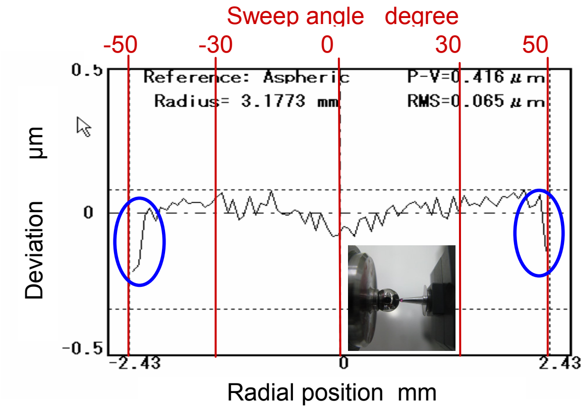
A standard convex steel sphere of 3.17 mm radius was measured using the proposed 45 degrees tilted method and the conventional method to compare the measuring performances. Figure 9(a) shows a view of measuring the standard sphere by the conventional method where the probe axis is pararell to the workpiece axis. On the other hand, Figure 9(b) shows a view of measuring the standard sphere by the proposed method where the probe axis is tilted at 45 degrees to the workpiece axis.

Figure 10(a) shows the form deviation profile measured by the conventional method, and Figure 10(b) the one by the developed measurement method. In the case of the conventional method, the measurement error increases at a high sweep angle of 50 degrees because of the changes in the contact force angle of the probe. On the other hand the form deviation profile is measured correctly with the proposed method.

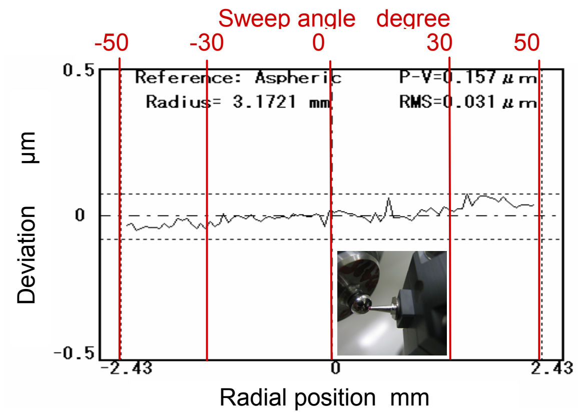


(a) Conventional method (b) Proposed 45 degrees tilted method

Figure 9: Views of measureing standard sphere.



(a) Conventional scanning method



(b) Proposed 45 degrees tilted method

Figure 10: Measured form deviation profiles.

6 SUMMARY

A new contact type on-machine measuring system was developed in order to measure aspherical optical parts with steep surface angles for high numerical aperture (NA). A ceramic air slider was fabricated, which is made of SIALON having a low thermal expansion coefficient, high rigidity and light weight. A high accuracy glass scale was employed to reduce the thermal drift of the displacement gauge. The measuring air slider was tilted at 45 degrees against the aspherical workpiece axis, and the probe was scanned over the workpiece surface, so as to keep the probe contact angle constant. The experimental results proved that the measuring accuracy was much improved as compared to the conventional method.

7 REFERENCES

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