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Flatness and Thickness Measurements of Circular Plate Component Using Laser Distance Meter

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In this paper, we propose an innovative method for measuring the thickness, flatness, and Abbe angle of a disc. This innovative method includes three laser distance meters and one standard plate. In general, the three laser distance meters are used to determine the thickness and flatness of a disc. The Abbe angle is determined using the laser distance meter and reference plate. Our analytical results show that the proposed method can be used to obtain the precise thickness and flatness of a disc. The resolution of the measurement method is 1 μm. The flatness is measured by the least squares method. The front and back laser distance meters simultaneously measure the warp and wrinkle. The maximum deviation of the measured thickness of a disc is reduced by using two laser distance meters to determine the effects of warp and wrinkle. The thickness, flatness, warp, and wrinkle of a disc are measured quickly and conveniently.

1. Introduction

Flatness is an important property of the plate because poor flatness can cause the instability of a circular plate in a machine. A disc having a large flatness error has been reported to cause vibration and imprecise movement. Flatness and thickness can be measured by contact and noncontact methods.(1,2) In the contact method, a cantilever beam is used to measure the position of a workpiece. The noncontact method involves the use of a laser or an image to measure the position of a workpiece. In our study, we used the noncontact method to determine the position. This method can be applied to the measurement of variously shaped workpieces. According to the material test method and literature,(3) American Society for Testing and Materials (ASTM) F1530 is the standard test method for measuring flatness, thickness, and thickness variation on silicon wafers by automated noncontact scanning. In this method, the flatness is calculated by using the total indicator reading (TIR) and maximum focal plane deviation (FPD). ASTM F1530 is capable of four types of flatness measurement: global flatness, site flatness, TIR, and FPD. The global flatness is the measured value of a single side relative to a specified reference plate

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within the measured area. The site flatness is the measured value of the portion of the site that falls within the global area. TIR involves all values between the maximum and minimum. FPD is the largest of the absolute deviation values for the measurement plane from the reference plane. The most advanced sensors and computers are used to obtain the thickness and flatness of a plate quickly. Sheth and George[4] reviewed the techniques and sensors mainly used in the steelmaking industry to measure and quantify flatness defects in steel plates and shells. Most of these techniques and sensors can be used in other industries involving rolling mills or continuous production lines. To obtain the three-dimensional (3D) shape of a workpiece, many researchers use phase-to-height mapping.[5,6] Phase-to-height mapping is an indispensable part of a 3D shape measurement system based on phase analysis and guarantees the accuracy of 3D reconstruction. This mapping can reconstruct the full 3D shape of the workpiece. If the thickness of the workpiece is measured, phase analysis is not used to reconstruct the 3D shape. In this case, the laser distance meter is used to measure the flatness and thickness of the workpiece.

The flatness of a wafer is very important and requires high-precision measurement. The interferometric method[7,8] is widely used to determine the flatness of a wafer, but it cannot measure the thickness. The thickness measurement of a plate requires the use of the interferometric method and another probing sensor.[9] A laser distance sensor is a laser triangulation sensor. This sensor uses the triangulation measurement principle to measure the distance to targets accurately. To measure both the flatness and thickness of a plate, a laser distance or multibeam angle sensor must be used.[10,11] These methods determine the distance to a target from both sides of a plate at the same time.

The probing position is very important in flatness measurement.[12,13] From the literature, it is known that the probing position affects the precision of flatness measurement. The optimal number is defined by 81 (9 × 9) probing points. The probing area is rectangular or square. Ten probing point positions of the dimension of the piece are required.[14] If the flatness of an axisymmetric circular plate is to be determined, more than 40 probing point positions on the circumference of the circular plate are needed. Many researchers[15,16] also determine the thickness of a lens using optical path differences. Optical path differences are discerned by inserting a correction glass piece or lens into the measurement path, thus increasing the measurement optical path length. This method is not used to discern the thickness of a circular metal plate. Therefore, we use the laser distance meter to determine the thickness and flatness of a metal disc.

For thickness, ASTM F657 is the standard method of measurement. The thickness of a plate is the distance between corresponding points on the front and back surfaces. In a traditional method of disc thickness measurement, the distance between the front and back surfaces of a disc is measured. Traditional contact methods involve the use of a probe and a dial indicator. However, contact methods cannot measure large differences in thickness. This can cause the measurement failure of the sensor. Traditional noncontact methods make use of laser distance meters and capacitive displacement sensors, and have the capability to measure any shape of a workpiece within the measuring range. Many researchers use two laser distance meters to measure the thickness of a plate with high precision. If the measuring system is not placed coaxially (in line) with the line along which displacement is to be measured on the workpiece, Abbe error arises. To reduce the Abbe error, we introduce a third laser distance meter. This ensures that the measuring system is placed coaxially with the line of displacement. Our method is used to measure the thickness, flatness, warp, wrinkle, and Abbe error quickly and conveniently.

2. Design Modeling

Our measurement model includes three laser distance meters. Two of these meters are used to determine the distance from the front surface to the back surface of a plate. The third laser distance meter measures the position on the back surface of the standing plate. This measured value can be used as reference data. This model is shown in Fig. 1. Laser distance meters A and B are used to measure the thickness without Abbe error. When the distance between laser distance meters A and B is L, the distance is constant. The thickness of a plate can be calculated as

$$Tw = L - LA - LB. \tag{1}$$

In general, the laser distance meter has a reset option where the thickness of the standard disc is used to reset the distance of the laser distance meter. The true thickness of a disc can then be obtained.

If the measuring system is not placed coaxially (in line) with the line of displacement (giving length), the measuring data includes angular error. This is the Abbe error. With the measurement model, the Abbe error is reduced by using the third laser distance meter. This is shown in Fig. 2

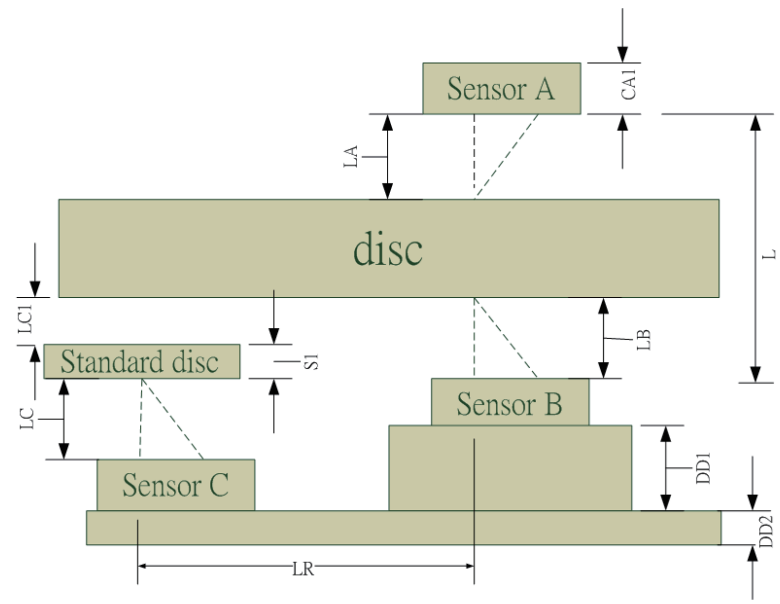

Fig. 1. (Color online) Diagram of analysis model.

From Fig. 2, we can see that the distance between the front and back surfaces is unequal to the thickness of the plate because it includes angular error. If the angular error can be eliminated, the modified thickness will be

$$Twm = \left(L - LA - LB\right) \times \cos\theta. \tag{2}$$

The angle θ is the Abbe angle, which can be determined using the laser distance meters. LR is the horizontal distance between laser distance meters A and B. From Fig. 2, the Abbe angle is

$$tan\theta = \frac{LBB - LCC}{LR}, \tag{3}$$

where $LBB = DD1 + CA1 + LB$ and $LCC = CA1 + LC + S1 + LC1$. From Fig. 1, it is known that the parameters $DD1$, $CA1$, $S1$, and $LC1$ are constant. Then the Abbe angle can be obtained by using the three laser distance meters, and simultaneously, the dynamic measurement error can be reduced.

To obtain high-precision measurement data, we chose the laser distance meter Panasonic HL-G103-S-J-C5. The measurement center distance of this laser distance meter is 30 mm, the depth of field (minimum to maximum measurable distance) is ±4 mm, and the resolution is 0.5 μm.

3. Measurement Results

3.1 Thickness measurement

To understand the measurement result, we consider the measurement of the brake disc shown in Fig. 3.

In the measurement of the thickness of a disc, the thickness of the whole disc is measured. In general, the thickness measurement requires the use of two laser distance meters. If the distance

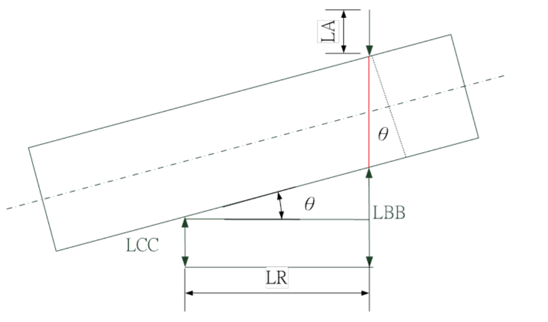

Fig. 2. (Color online) Simplified diagram of Abbe error.

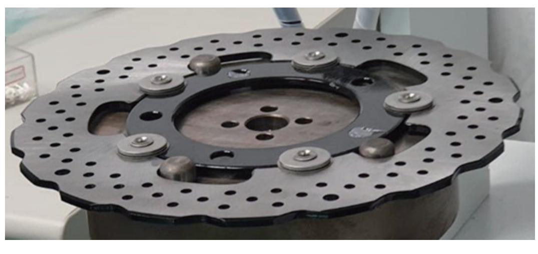

Fig. 3. (Color online) Measured disc.

between the positions of laser distance meters A and B is constant (L = constant), the difference in the measured value between laser distance meters A and B is the thickness of the disc without taking into account the Abbe angle. The distance (L) is constant at 60 mm. The actual thickness of the disc is 4 mm. The measurement results are shown in Table 1. From Table 1, the measuring resolution is determined to be 1 μm. The thickness values were obtained at various rotation angles.

To consider the Abbe error in the measurement system, the Abbe angle is determined by using three laser distance meters and the horizontal distance between laser distance meters A and B (L = 60 mm). The results are shown in Table 2. From Table 2, we can see that the maximum Abbe angle is 0.047006 rad. This is equivalent to a measurement error of about 4 μm. Large Abbe angle causes large measurement error.

Table 1
Measured thicknesses of the brake disc (h = 4 mm).

Rotation angle (degree)	Measured value with laser distance meter C (mm)	Measured value with laser distance meter A (mm)	Measured value with laser distance meter B (mm)	Thickness without Abbe angle (mm)
0	−0.011	−0.019	0.007	4.012
30	−0.014	−0.040	0.031	4.009
60	−0.024	−0.059	0.056	4.004
90	−0.025	−0.069	0.068	4.001
120	−0.031	−0.066	0.068	3.998
150	−0.028	−0.069	0.066	4.003
180	−0.013	−0.062	0.063	3.999
210	−0.022	−0.044	0.050	3.994
240	−0.028	−0.010	0.019	3.990
270	−0.009	0.013	−0.011	3.998
300	−0.011	0.016	−0.018	4.002
330	−0.009	0.006	−0.008	4.002

Table 2
Measured thicknesses and Abbe angles.

Rotation angle (degree)	Measured value with laser distance meter C (mm)	Measured value with laser distance meter A (mm)	Measured value with laser distance meter B (mm)	Thickness without Abbe angle (mm)	Abbe angle (rad)	Thickness with Abbe angle (mm)
0	−0.011	−0.019	0.007	4.012	−0.007261	4.012
30	−0.014	−0.040	0.031	4.009	−0.02465	4.008
60	−0.024	−0.059	0.056	4.004	−0.033630	4.002
90	−0.025	−0.069	0.068	4.001	−0.04223	3.999
120	−0.031	−0.066	0.068	3.998	−0.032866	3.996
150	−0.028	−0.069	0.066	4.003	−0.039554	4.001
180	−0.013	−0.062	0.063	3.999	−0.047006	3.995
210	−0.022	−0.044	0.050	3.994	−0.021401	3.993
240	−0.028	−0.010	0.019	3.990	0.017389	3.990
270	−0.009	0.013	−0.011	3.998	0.020828	3.997
300	−0.011	0.016	−0.018	4.002	0.025414	4.001
330	−0.009	0.006	−0.008	4.002	0.013758	4.002

To determine the measurement reliability, data of five measurements are shown in Fig. 4. When the rotation angle is 330 degrees, there is a large measurement error caused by the vibration of the brakes.

The results of the above analysis confirm that our measurement system measures the Abbe angle and precise thickness of a disc. The reliability of the analysis result is high.

3.2 Flatness measurement

In the standard ASTM F1530 measurement method, the global flatness is the measured value of a single side relative to a specified reference plate within the front surface of a disc. This is expressed as TIR or the maximum FPD. The measuring angle of the TIR is 1 degree. The measurement result is shown in Fig. 5. From Fig. 5, it is found that the maximum deviation is 0.075 mm. The results were obtained at four measurement points with rotation angles of 1, 91, 181, and 271 degrees. The average of these measurement values of the four measurements points is 0.062 mm.

Next, we consider the standard reference plane using the least squares method. The plane equation is $h = 0.0002\theta + 0.0249$. The result is shown in Fig. 6. The dashed line is the reference line.

To determine the deviation, the reference value is subtracted from the measured value at the same angle. The difference is the deviation between the measured value and the value for the reference plate. The results are shown in Fig. 7. From Fig. 7, the maximum deviation is found to

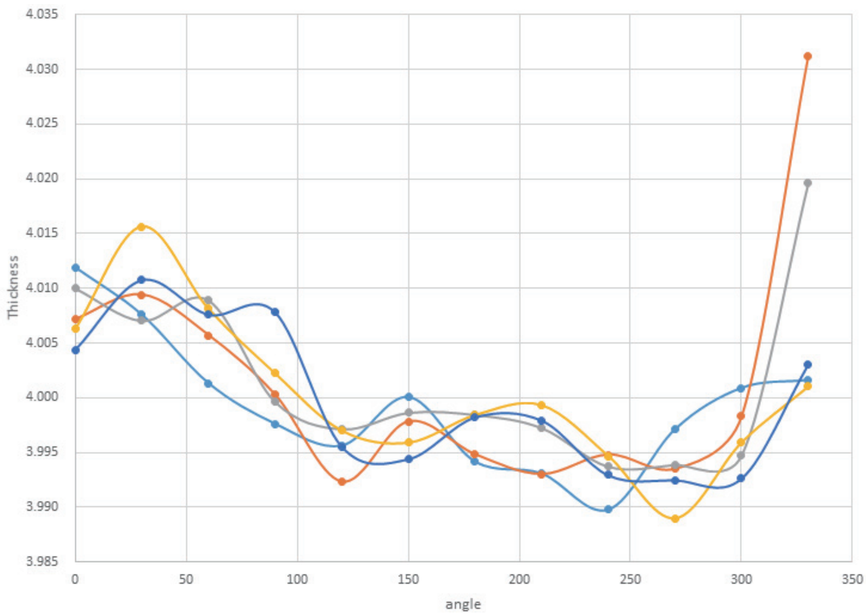

Fig. 4. (Color online) Thicknesses (mm) of five measurements vs rotation angle (degree).

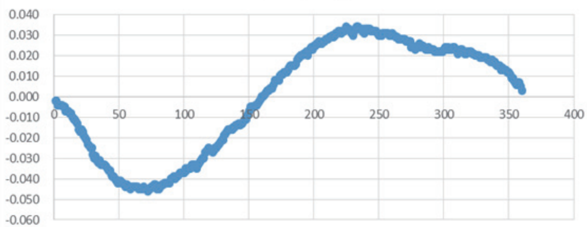

Fig. 5. (Color online) TIR (mm) with rotation angle of 360 degrees on the front surface of a disc.

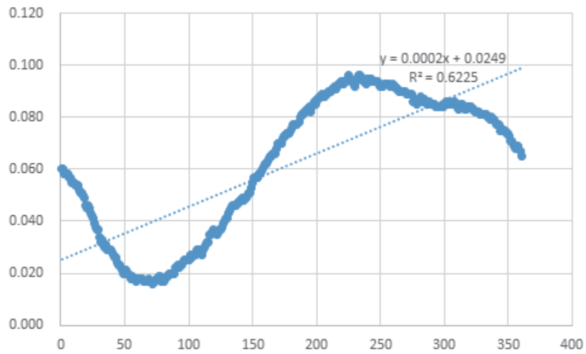

Fig. 6. (Color online) Reference line obtained by least squares method.

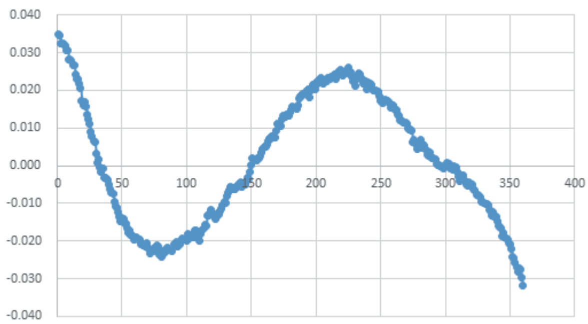

Fig. 7. (Color online) Deviation (mm) of the measured data from the reference line data vs rotation angle (degree).

be 0.035 mm. This is smaller than the average of these measurement values (0.062 mm) of the four measurements points.

To determine the flatness of the underside plane of a disc, the laser distance meter for the underside plane of the disc is used to obtain the deviation of the TIR with the rotation angle of 360 degrees. The results are shown in Fig. 8. From Figs. 5 and 8, it is found that the measured data present the reverse behavior. At the rotation angle of 88 degrees, the maximum measured value on the underside of the disc and the minimum measured value on the top side are obtained using the laser distance meter. Figure 1 shows that laser distance meters A and B are vertically aligned on opposite sides of disc laser distance meter A that measures a positive value and laser distance meter B that measures a negative value, indicating disc warping.

The sum of the values measured using laser distance meters A and B is shown in Fig. 9.

From Fig. 9, the maximum deviation between laser distance meters A and B is found to be 0.015 mm. The trend line method of linear regression between the sum values combines these measured values and the rotation angle. The trend line is close to a horizontal line. The average deviation is 0.0064 mm. This indicates reduced effects of warp and bow displacement.

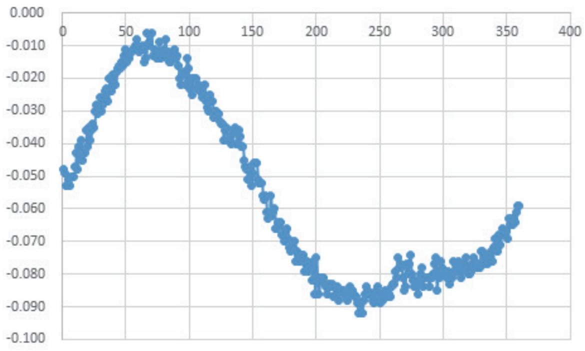

Fig. 8. (Color online) TIR (mm) with rotation angle of 360 degrees on the underside of disc.

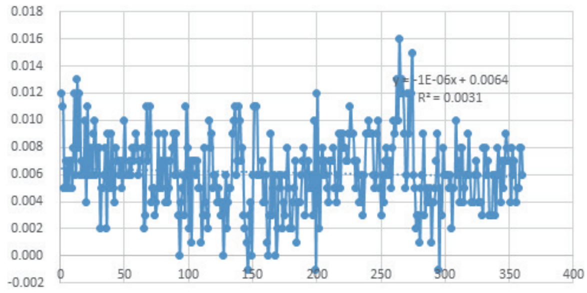

Fig. 9. (Color online) Sum of values (mm) measured by laser distance meters A and B vs rotation angle (degree).

Subtracting the deviation of 0.0064 from the measured value of the front surface of the disc gives the maximum deviation between laser distance meters A and B as 0.016 to 0.0096 mm. The results of the above analysis confirm the high precision of our measuring system.

4. Conclusions

We measured the thickness and flatness of a circular component using three laser distance meters, as well as the Abbe angle. From the analysis of the results, the following conclusions were drawn:

1. In general, the method with two laser distance meters yields measurements of the front and back surface planes on a circular component, but do not reveal the Abbe error. We used three laser distance meters to measure the Abbe error.
2. Our method provides the thickness of a disc with the Abbe angle taken into account.
3. The flatness of a disc was calculated by the least squares method.
4. The use of two laser distance meters reduces the effect of warping.
5. The maximum deviation between the front and back surfaces of a disc without warping can be obtained.

Our measurement system was able to measure the thickness, flatness, warp, and Abbe angle of a circular component, making it a very powerful measurement system.

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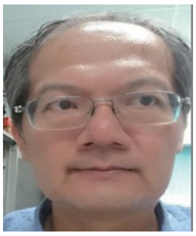

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