Improved Circularity Metrology of Small Cylindrical Workpieces by the Segmenting-stitching Technique

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Abstract: To address the alignment and measuring force problem in the segmenting-stitching technique for the circularity metrology of small cylindrical workpieces (diameter less than 1.5 mm and length less than 10 mm), a magnet combination jig method is proposed. A small round magnet is attached between the round magnetic jig and small cylinder, and the other end of the small cylindrical workpiece is attached to some cylindrical magnets. Thus, the smaller cylinder can be put in the V-groove and measured successfully with the magnet combination. For verifying the advantage of the magnet combination jig, four measurement quality evaluations are proposed: the circumferential deviation of neighbor arc contours, radial deviation of neighbor arc contours, angle of inclination between the V-groove and small cylinder, and curvature of the obtained arc. The results show that the matching coefficient is enhanced by 98%, the Euclidean distance of overlap parts of neighbor arc contours is reduced by 68%, the position error is reduced 27%, and the average curvature of the arc contours is improved. It can be concluded that the measuring quality can be enhanced prominently by this magnet combination method for the segmenting-stitching method.

Keywords: Circularity and Diameter Measurement, Magnets Combination Jig, Small Cylinder, Segmenting-stitching Method

1 Introduction

Fine cylindrical parts are widely used in precision machinery and machining, such as a pin gauge for machine tool positioning, chuck calibration, needle rollers for a bearing, and cylindrical rollers for an RV reducer[1–5]. Some of the fine cylindrical parts have a small dimension for the requirement of products. Large variation of the micro topography created by industrial machining processes tends to reduce impact of the usage of improved engineered surfaces on critical components[6]. Since the parameters of these small cylinders, such as circularity and diameter, greatly affect the performance and lifespan of the products, quality control of the small cylinders is necessary[7–10]. Measurement is essential for process and quality control in precision manufacturing, which can not only distinguish whether the manufactured part meets the assigned tolerances through inspection but also, in many cases, reduce the deviation of the manufactured part from the designed values through the improvement of the process or compensation manufacturing based on the measurement results[11–16].

Conventionally, simple circularity measurement, by which only the circularity value of cylindrical parts can be obtained, is carried out by the two-point method, three-point method, and coordinate measuring machine[17–18]. In recent years, an orthogonal mixed method using a pair of displacement and angle sensors has been proposed for error separation in circularity measurement, and based on this method, a non-contact error separation method with chromatic confocal sensors has been proposed[19–23]. High-accuracy circularity measurement, by which both the circularity contour and value can be obtained, is conducted by the rotary-scan method with a circularity-measuring instrument. The circularity measurement becomes difficult due to the crucial alignments of eccentricity and inclination between the measured cylinder and rotation center in the rotary-scan method when the dimension of the cylinder becomes small (diameter less than 3 mm)[24]. Thus, an alternative linear-scan method[25–27], in which the small cylinder is put in the V-groove and measured by a roughness measuring machine, has been proposed to solve the alignment problem. However, the segmenting-stitching method also has a bottleneck when measuring a small cylinder with a diameter of less than 1.5 mm and a length of less than 10 mm. The smaller cylinders are difficult to be placed in the V-groove and scanned successfully.

To solve the problems and break through the bottleneck, a magnets combination jig is tried and designed. One side of the small round magnetic jig is attached to a big round magnetic jig, and the other side is attached to the small cylindrical workpiece of whom the other end is attached to some cylindrical magnetic jig. The big round magnetic jig is marked on the surface to segment equally. This kind of combination not only can make the center of gravity of the small cylinder on the V-groove stably, but also increase the weight to stop the stylus from moving the small cylinder during the measurement. The coordinates of a cross-sectional circle of a small cylinder are segmented into serval equal arcs to be measured. The circularity (Including circularity contour and value) and diameter of the small cylinder can be obtained by a series of data processing. For verifying the proposed magnets combination jig, three kinds of experiments, no magnets combination, the first magnets combination, and the second magnets combination have been carried out under the same conditions. Since the circularity contour is obtained by stitching a series of arc contours accurately by matching the similar feature of overlap parts between neighbor arc contours, the circumferential deviation and radial deviation of neighbor arc contours can be used for evaluating the measurement quality. Besides, the angle of inclination between the measured small cylinder and V-groove can be calculated and used for evaluating the position error. The curvature of the obtained arc can also reflect the measurement quality to a certain extent. The analysis of the definition and computation methods for contour error and track error in polar coordinates platform will be made[28]. The physical principal and error model due to the splicing structure has been discussed and analyzed in detail[29]. Finally, the errors of test system were analyzed[30]. Experiments and results comparison are presented to demonstrate magnets' combination jig for the circularity and diameter measurement of small cylinders in the segmenting-stitching method.

2 Principle

The surface form of a small cylinder can be obtained by modeling with coordinates which can be measured by a coordinate measuring instrument. In this paper, as shown in Fig.1(a), the coordinates $(x_{i,j}, z_{i,j})$ of a cross-sectional circle of a small cylinder are segmented into 8 equal arcs to be measured where i is the i_{th} arc and j is the j_{th} coordinate. It should be noted that there are some overlap parts between neighbor arcs. As shown in Fig.1(b), the measured workpiece is attached to a round magnetic jig which is segmented into 8 equal parts, and put in the V-groove. The surface of the cylindrical workpiece is scanned linearly by a roughness measuring machine, then the first arc coordinates data can be obtained. The round magnetic jig is rotated manually by an equal part (45°) to make the small cylinder rotate by 45°, and the stylus is back to the initial position and scan again. Then the second arc coordinates data can be obtained. Repeat this procedure 7 times, then 8 arc coordinates data can be obtained as shown in Fig.1(c). The radius r_i and the center coordinate $(x_i, z_i)$of each arc can be fitted by the least square method. Meanwhile, the radius of each coordinate of each arc can be calculated by equation (1)

$$r_{i,j} = \sqrt{\left(x_i - x_{i,j}\right)^2 + \left(z_i - z_{i,j}\right)^2} \tag{1}$$

Therefore, the radius of the measured workpiece can be calculated by the mean of the radii of 8 arcs as shown in equation (2)

$$r^2 = \frac{1}{8}\left(r_1 + r_2 + \cdots r_8\right) \tag{2}$$

The arc contour of each arc can be characterized by equation (3)

$$\Delta r_{i,j} = r_{i,j} - r_i \tag{3}$$

Then 8 arc contours can be obtained as shown in Fig.1(d). The circularity contour can be formed by stitching these 8 arc contours as shown in Fig.1(e). The stitching procedure is that keep the i_{th} arc static and rotate the $(i+1)_{th}$ arc by 45° where $i = 1, 2, \cdots 7$ However, as shown in Fig.1(f), the stitched circularity contour is not accurate since the rotation angle of the small cylinder is not always 45° while the angular displacement for each arc contour is always 45° in the stitching process. Therefore, it’s necessary to make an angle compensation for the neighbor arc profiles.

As shown in Fig.2(a), the stitched arc contours in the X-Z coordinate system are converted into θ-Δr coordinate system as shown in Fig.2(d). An obvious mismatching can be seen at the overlap parts of neighbor arc contours after filter processing as shown in Fig.2(e). The matching of neighbor arc contours can be achieved by cross-correlation function according to the similar feature of overlap parts as shown in Fig.2(f). Keep the i_{th} arc contour static and move the $(i+1)_{th}$ arc contour by $\Delta\theta_{i\sim i+1}$ when the matching coefficient reaches the maximum value which can be calculated as shown in equation (4)

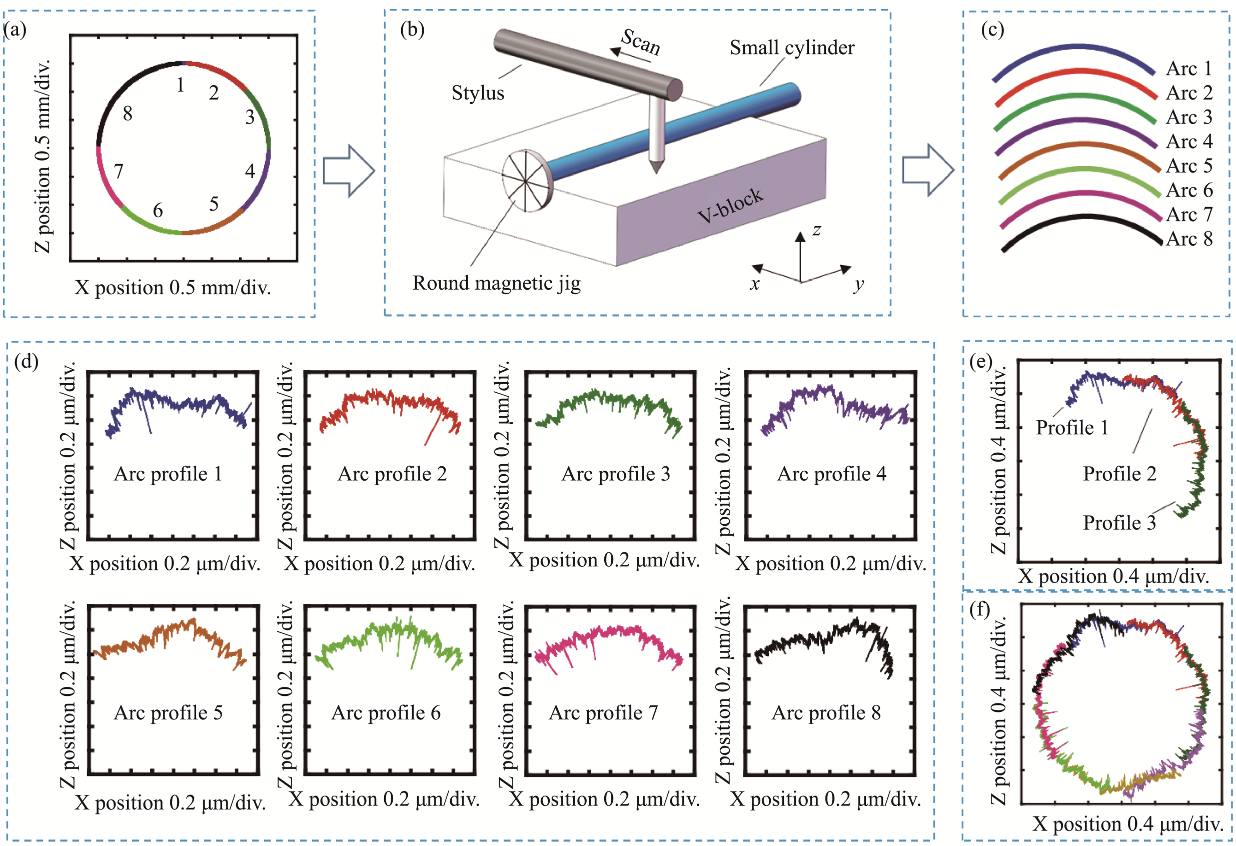

Fig.1 The Principle of Segmenting-stitching Method

(a) The Cross-sectional Circle of a Small Cylinder; (b) Linear Scan across the Surface of the Small Cylinder; (c) Obtained Arc Data; (d) Arc Contours; (e) Stitching Procedure; (f) Stitched Circularity Contour

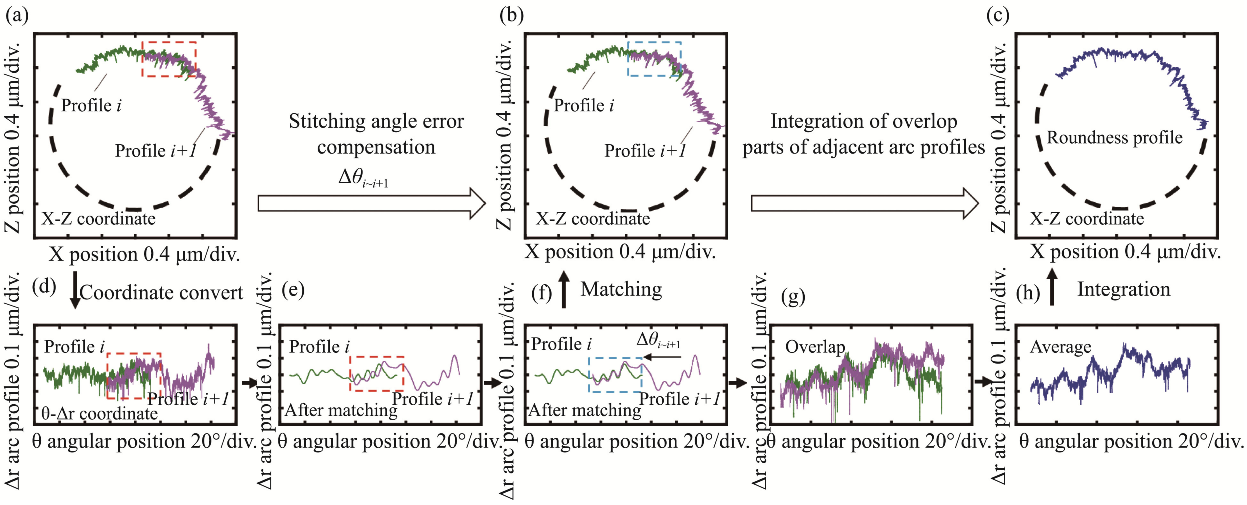

Fig.2 The Angle Error Compensation for the Stitching and Integration of Neighbor Arc Contours

(a) Stitched Contour in X-Z Coordinate System; (b) Stitched Contour after Stitching Angle Error Compensation; (c) Stitched Contour after Integration of Neighbor Arc Contour; (d) Stitched Contour in θ-Δr Coordinate; (e) Stitching Contour after Filtering; (f) Stitched Contour after Matching; (g) Overlap Parts of Neighbor Arc Contours; (h) Overlap Parts Averaging for Integration

$$C_{i\sim i+1} = \int_{-\infty}^{\infty} f_i(\theta) f_{i+1}(\theta + \Delta\theta_{i\sim i+1}) d_\theta \quad (4)$$

The stitching angle error compensation can be carried by rotating the $(i+1)_{th}$ arc contour by $\Delta\theta_{i\sim i+1}$ clockwise in X-Z coordinate system as shown in Fig.2(b). As shown in Fig.2(g), there are some overlap parts between the neighbor arc contours which can be integrated by averaging the overlap parts as shown in Fig.2(h). Then the integrated arc contour in the X-Z coordinate is obtained shown in Fig.2(c). The stitching angle error and integration of other neighbor arc contours can be conducted as the above procedure. Finally, an integrated, accurate, continuous, and smooth circularity contour can be obtained after filtering processing for the circularity contour shown in Fig.2(c).

3 Experiment

As shown in Fig.3(a), the small cylinder with a diameter of 1.5 mm and length of 5.8 mm attached to the round magnet with a diameter of 8 mm and thickness of 1 mm is difficult to be placed in the V-groove successfully since there are always some position errors which are caused by the unstable center of gravity of the small cylinders as shown in Fig.3(b). Although the round magnet can be replaced with a smaller round magnet for balance, the dividing of the smaller round magnet is difficult to be carried out. Therefore, a magnets combination method is proposed to solve the above problems as shown in Fig.3(c). As shown in Fig.3(d) which is the schematic of the combination of the magnets, a small round magnet with a diameter of 4 mm and thickness of 1.5 mm is attached between the round magnet and a small cylinder whose other end is attached to three cylindrical magnets with the dimension smaller than the measured workpiece. There are four advantages in the magnets combination method: the dividing of the smaller round magnet is not necessary; the ruction of the contact area between the small round magnet and the small cylinder can reduce the position error which is caused by the surface roughness of the small magnet; the small cylinder can be focused on the center of the round jig more easily; the small cylinder can be placed in the V-groove successfully with the magnet combination since the entire weight is increased and the center of gravity is on the V-groove.

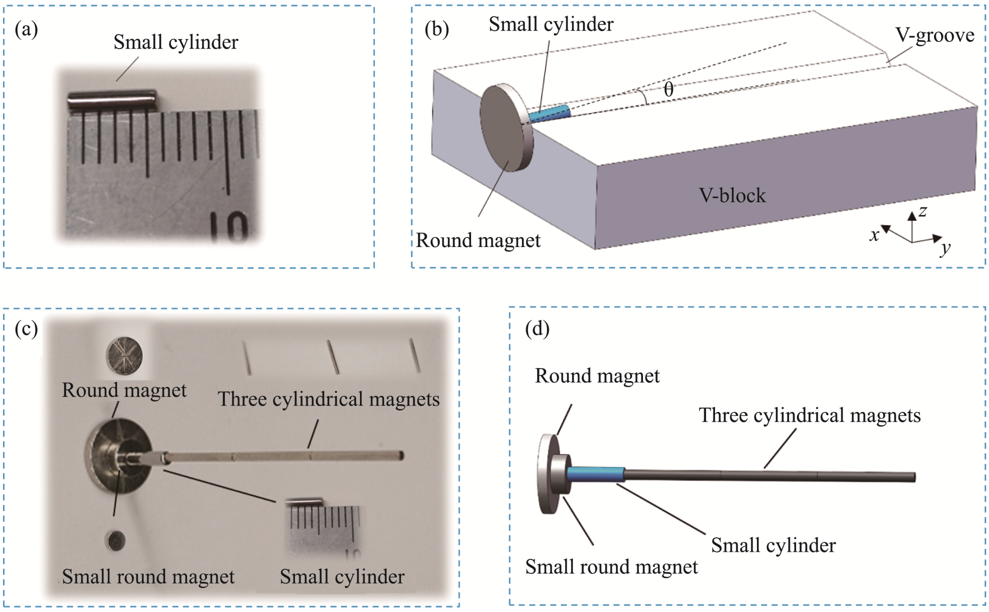

Fig.3 (a) Small Cylinder; (b) Small Cylinder Mounted on the V-block with a Position Error; (c) The Photo of Magnet Combination; (d) The Diagram of Magnet Combination

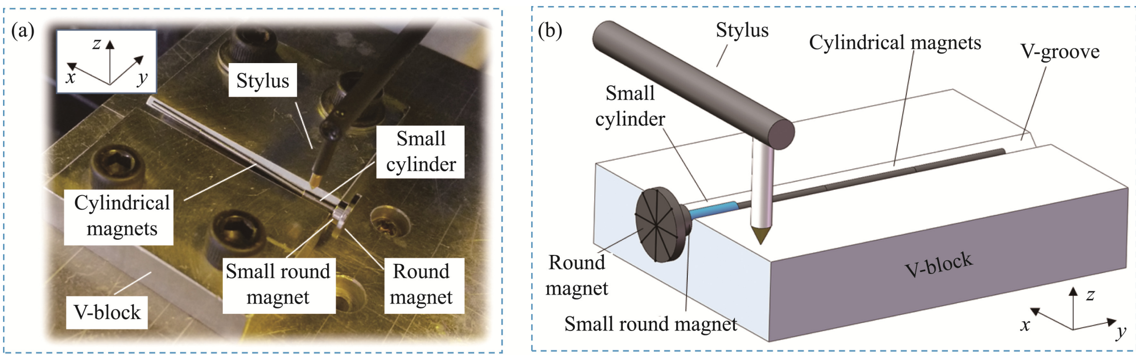

Fig.4 The small cylinder attached to the combination of the magnets and mounted on the V-block

(a) The Photo of the Measured Workpiece Attached with the Magnet Combination Placed in the V-groove;

(b) The Diagram of the Measured Workpiece Attached with the Magnet Combination Placed in the V-groove

As shown in Fig.4, the experiments with the magnet combination jig and without magnets combination jig are performed respectively on the same experimental conditions. The matching results and circularity contours are shown in Fig.5 and Fig.6 respectively.

There are four indicators for the evaluation of measurement quality with the magnet combination jig and without the magnet combination jig. It should be noted that the overlap parts of neighbor arc contours should coincide completely, while they can't coincide actually because of all kinds of measurement errors. The more the coincidence is the better the measurement quality is. As shown in Fig.7(a), the circumferential and radial deviations of overlapped parts of neighbor arc contours can be evaluated by the mean value of matching coefficient and Euclidean distance respectively[31,32], which can be calculated as shown in equation (4) & (5)

$$D_{i\sim i+1}=\frac{1}{n}\sum_{i,j=1}^{n}\sqrt{\left(\theta_{i,j}-\theta_{i+1,j}\right)^{2}+\left(\Delta r_{i,j}-\Delta r_{i+1,j}\right)^{2}} \quad (5)$$

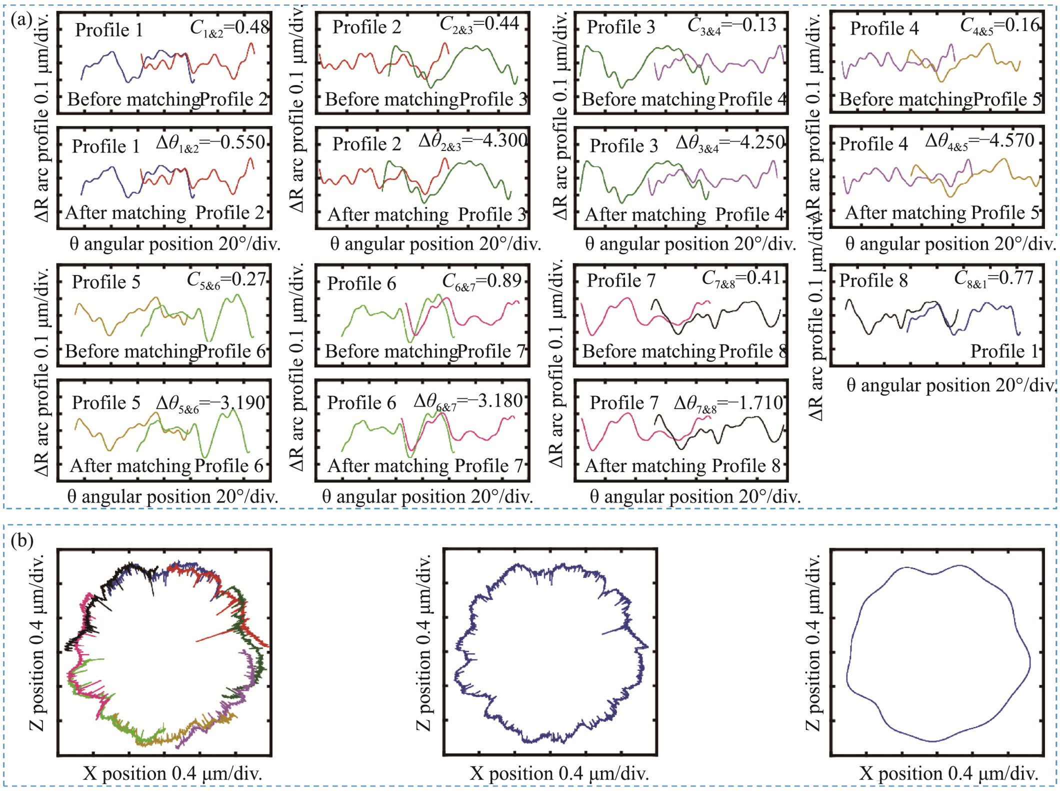

Fig.5 The Results of the Normal Jig without Magnets Combination

(a) The Matching Results of Neighbor Arc Contours; (b) The Circularity Contours

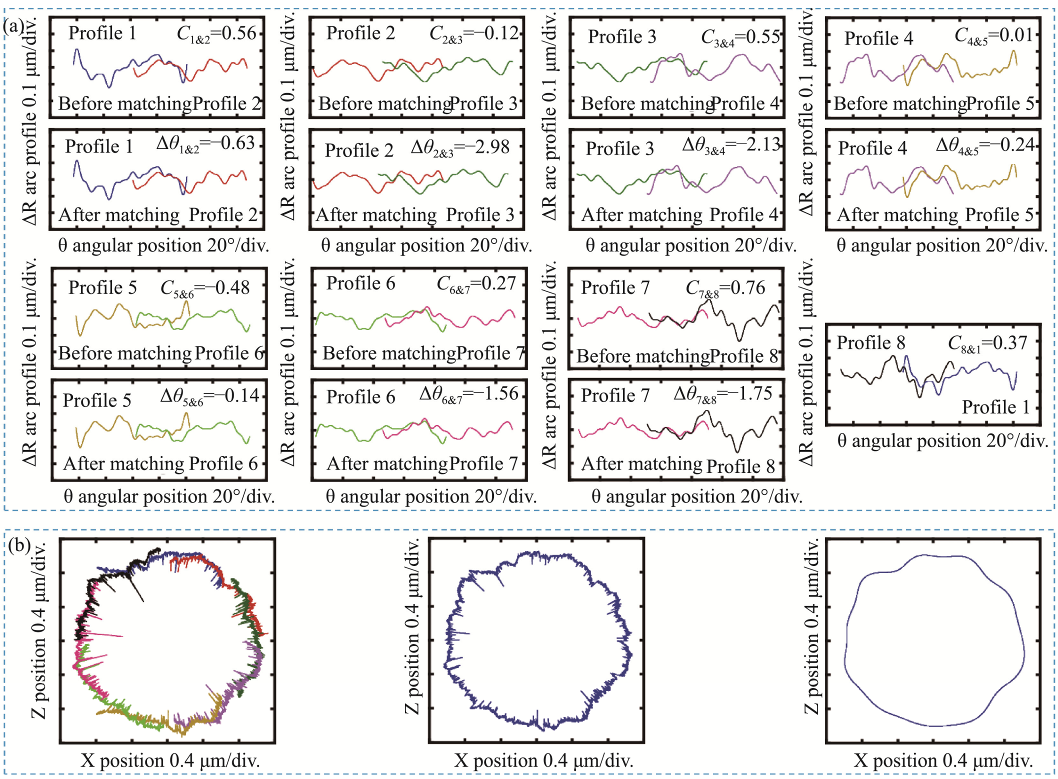

Fig.6 The Results of the First Magnets Combination Jig

(a) The Matching Results of Neighbor Arc Contours; (b) The Circularity Contours

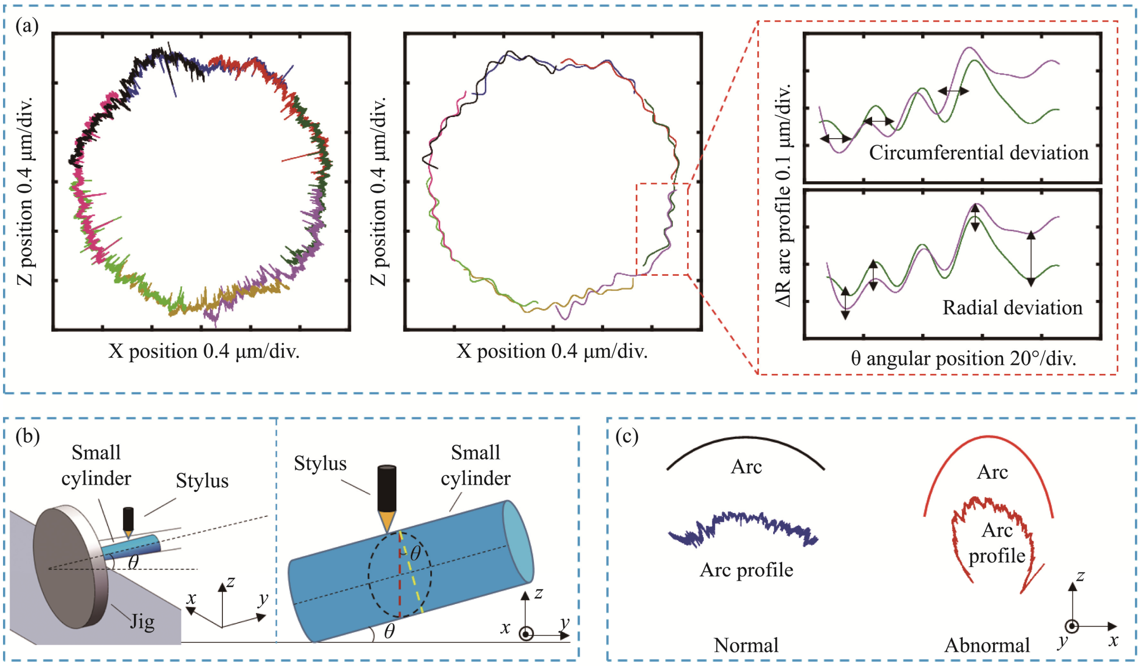

Fig.7 Measuring Quality Analysis

(a) Circumferential Deviation and Radial Deviation of Overlap Parts of Neighbor Arc Contours;
(b) Position Error of the Small Cylinder; (c) Curvature of a Measured Arc

As shown in Fig.7(b), the position error, which is the inclination between the Y axis and the axis of the small cylinder, can be calculated as shown in equation (6) where D_{mean} and D_{max} are the mean value and maximum value of the obtained 8 arc's radii.

$$\theta = \frac{D_{mean}}{D_{max}} \tag{6}$$

The curvature of obtained arcs, which should be equal or close to the nominal value, is influenced by the alignment. As shown in Fig.7(c), a normal arc contour can be obtained according to the arc data with a good alignment and an abnormal arc contour can be caused by the arc data with a bad alignment. Therefore, the average curvature of the obtained arcs, which is obtained by equation (7), can be also used to reflect the measurement quality.

$$K = \frac{1}{n}\left(\frac{1}{r_1} + \frac{1}{r_2} + \cdots \frac{1}{r_n}\right) \tag{7}$$

The evaluation results of these four indicators for the measurement with the magnets combination method and without the magnets combination method are shown in Table 1. The results show that the Euclidean distance, position error, and curvature by the magnets combination method are better than the previous method. However, the average matching coefficient is not good. Therefore, it's necessary to develop another magnets combination jig for the measurement.

Table 1 The Results of the Magnets Combination Method and the Previous Method Respectively

	Average Matching Coefficient	Average Euclidean Distance	Position Error	Average Curvature	Diameter	Circularity
Magnets Combination Method	0.24	0.043 μm	2.8°	1.336	1.496 mm	0.15 μm
Previous Method	0.41	0.053 μm	3.0°	1.338	1.494 mm	0.16 μm

A new magnets combination is developed instead of the first magnet combination as shown in Fig.8 in which the round magnet with a diameter of 8 mm and thickness of 1 mm is replaced by the magnet with a diameter of 7 mm and thickness of 1 mm, and the previous small round magnet is replaced by a new magnet with smaller dimensions. The experiment with the second magnets combination jig is carried out, and the results with these three kinds of jigs are presented in Table 2. According to the evaluation results of four indicators, it can be seen that the measurement equality has been improved prominently by the second magnets combination method. Furthermore, the magnets combination method is not only proper for the measured small cylinder in this paper but also for the small cylinder with various dimensions.

4 Summary

For the circularity measurement of small cylindrical workpiece, a segmenting-stitching technique, with which the cross-sectional circle of a small cylinder is placed in the V-groove and segmented into several equal parts to be scanned, has been proposed to replace the traditional rotary-scan method by which the cylindrical workpiece with the diameter less than 3 mm cannot be measured precisely. However, the segmenting-stitching method also has a bottleneck in the case of measuring smaller cylindrical workpiece. The small cylinders with a diameter of less than 1.5 mm and a length of less than 10 mm can hardly be placed in the V-groove to be measured successfully since the center of gravity is not on the V-groove. Thus, some round magnets are employed to develop a combination jig for the measurement of smaller cylinders.

A round magnetic jig with a small dimension is employed to attach between the round magnet and small cylinder, meanwhile, three cylindrical magnets are attached to the other end of the small cylinder. The measurement of the smaller cylinder can be carried out with the magnet combination technique since the center of gravity of the small cylinder is properly placed in the V-groove. Furthermore, there are four advantages with this magnet combination method: the segmenting of the small round magnetic jig is not necessary, the contact area between the V-block and round magnetic jig become smaller, the rotation center of the measured cylindrical workpiece can be focused on the center easily, and the entire weight of the combination is increased.

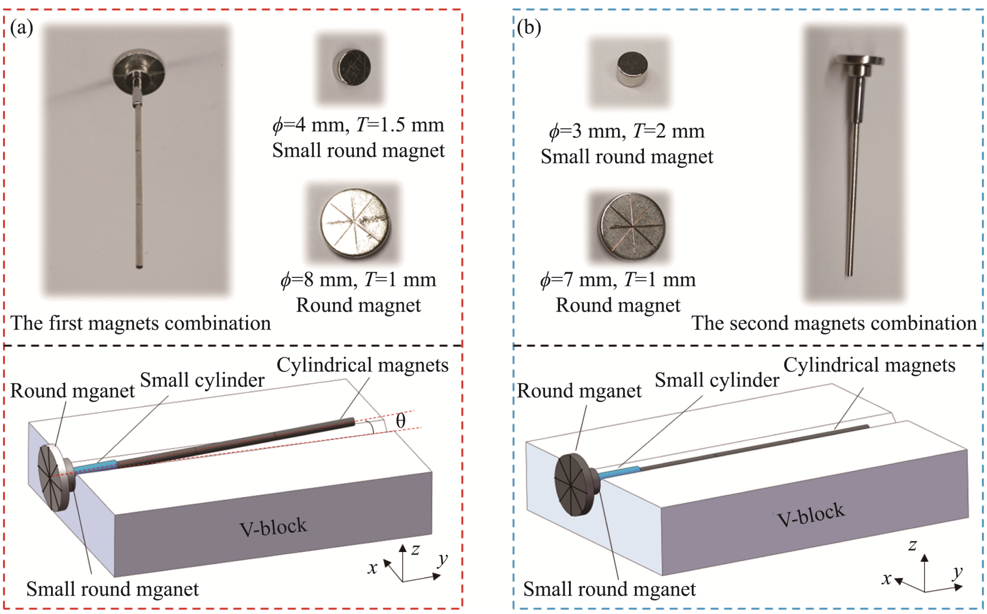

Fig.8 Magnets Combination Jigs for the Alignment of a Small Cylindrical Workpiece

(a) The Previous Magnets Combination; (b) The Present Magnets Combination

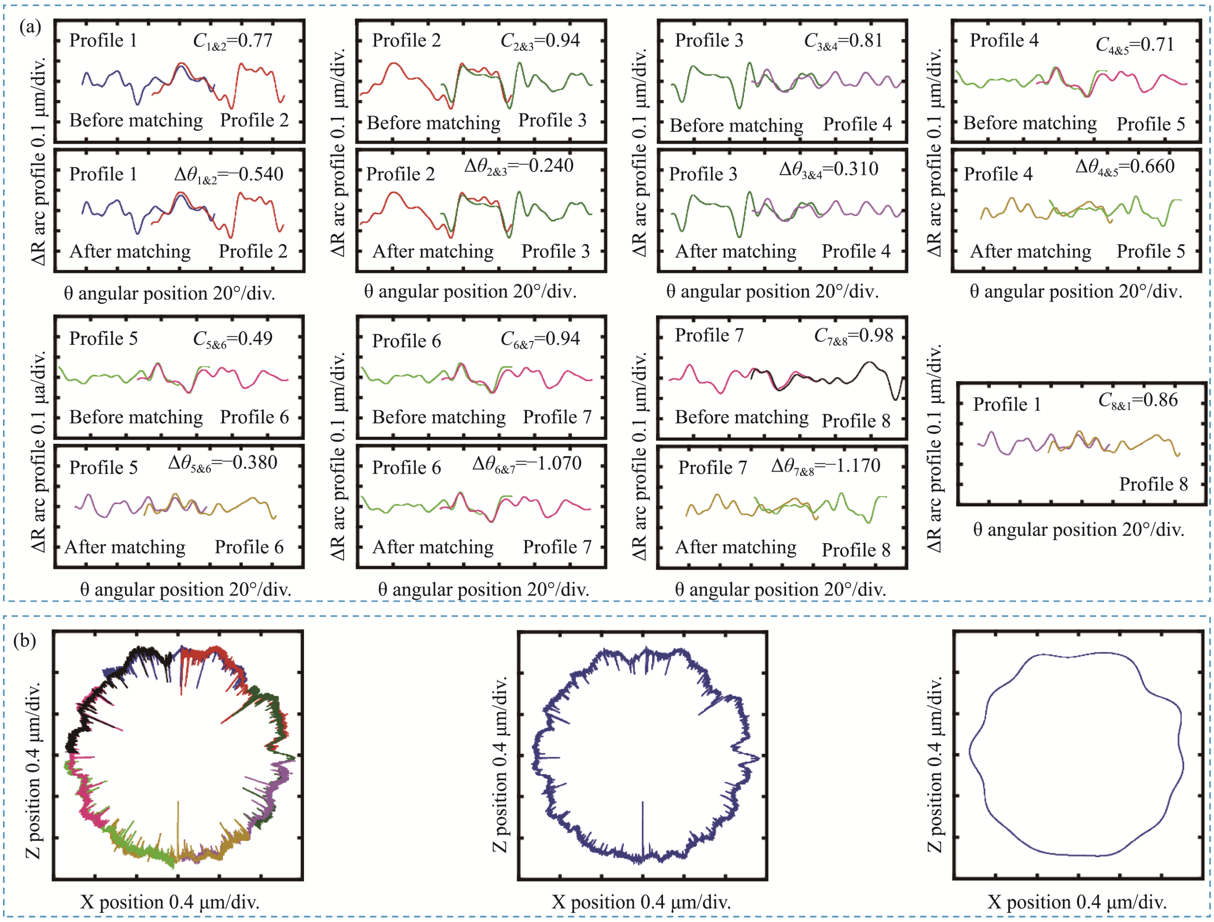

Fig.9 The Results of the Second Magnets Combination Jig

(a) The Matching Results of Neighbor Arc Contours; (b) The Circularity Contours

Table 2 Results by the Second Magnets Combination Method, First Magnets Combination Method, and Precious Jig Respectively

Jig	Average Matching Coefficient	Average Euclidean Distance	Position Error	Average Curvature	Diameter	Circularity
Second Magnets Combination Method	0.81	0.017 μm	2.2°	1.335	1.497 mm	0.16 μm
First Magnets Combination Method	0.24	0.043 μm	2.8°	1.336	1.496 mm	0.15 μm
Previous Method	0.41	0.053 μm	3.0°	1.338	1.494 mm	0.16 μm

Experiments with the magnet combination and without the magnet combination have been conducted respectively on the same conditions. Four indicators, circumferential deviation, radial deviation, position error, and curvature of the measured arc, have been proposed to evaluate the measurement equality of the small cylinder. Through the comparison of the results, it can be seen that measurement equality is prominently improved by the magnet combination method. Furthermore, different magnets combinations can be applied to measurements of small cylindrical workpieces with different sizes. Therefore, it can be thought that the bottleneck problem of measurement of small cylinders by the segmenting-stitching method has been solved.

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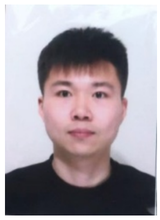

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