Arc Extraction Analysis for Circularity Measurement of Small Cylindrical Parts by the Segmenting-stitching Method

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Abstract: To reduce the stitching error of circularity measurement of small cylindrical workpieces (Diameter less than 3 mm) by the segmenting-stitching method, arc contour extraction is analyzed in this paper. The coordinates of cross-sectional circle of a small cylindrical part are segmented into several equal arcs to be obtained by a two-dimensional coordinate measuring machine. The circularity contour of the small cylindrical part can be formed by stitching a series of arc contours which are calculated by the obtained arc coordinate data. Due to the different measuring pressure angles of different measuring positions, the accuracy of obtained arc coordinate points is different. The bigger the pressure angle is, the accurate the obtained arc coordinate data are. The experiments show that the accuracy of two ends of the arc data is not as good as the central part. Therefore, the two ends of the obtained arc data are appropriately to be cut off, namely, only the central part of the arc data are extracted to be used for the stitching. As a result, the mean value of the matching coefficient is enhanced by 12%, the deviation between the overlap part of the neighbouring arc contour is reduced by 26%, and the average curvature of the arc contours is improved with the extraction method. Thus, the accuracy of the stitched circularity contour can be improved by this extraction procedure in the segmenting-stitching method for the circularity measurement of the small cylindrical parts.

Keywords: Circularity Measurement, Arc Extraction, Small Cylindrical Workpiece, Segmenting-stitching Method

1 Introduction

Precision reducers are widely used in various key precision machinery and equipment, such as RV reducers, in which needle roller bearings and some cylindrical parts are employed, are the main part of industrial robots' joint and precision NC machine tools' spindles [1]. Requirements of RV reducers' performance and life are increasing with the development of science and technology [2,3]. As shown in Fig.1(a), the accuracy of cylindrical parts employed by RV reducers has a crucial impact on the performance of the RV reducer, and the performance and life of the RV reducer affect the performance and life of the overall precision machinery and equipment [4–6]. Therefore, to ensure the performance and life of the precision machinery and equipment, it is necessary to enhance the precision and quality of the machining products. Precision metrology plays a significant role in precision machining and provides solid technical support for precision machining [7–13]. The parameters of diameter and circularity are very important for the cylindrical parts, which are increasingly required and crucial for the precision equipment used in industries. Therefore, surface metrology, such as precision circularity and diameter measurement for nano-micro fabrication, is necessary.

Conventionally, the two-point method, three-point method, multiple probe method, online-measurement method, and coordinate measuring method are used for the circularity measurement of cylindrical parts [14–20]. High-precision circularity measurement is carried out by a circularity measurement machine, such as the Talyrond 565H PRO, whose principle is the rotary-scan method with which the measured cylindrical part is aligned at the centre position of the rotation table and the cross-sectional circle of the measured cylindrical part is scanned by a stylus [21]. The axis of the cylindrical workpiece should be lined up with the rotational datum axis as much as possible it could be, or the measurement result is not accurate. The precision circularity measurement cannot be achieved by the rotary-scan method when the diameter of the measured workpiece is less than 3 mm (small cylindrical workpiece) since the eccentricity and inclination of the measured workpiece affect the measurement very much and cannot be ignored or compensated. Thus, the stitching-linear scan method, which can avoid the crucial alignment problem, is proposed for the circularity measurement of small cylindrical workpieces [22–25]. The cross-sectional circle of the small cylindrical workpiece is segmented into serval equal arcs to be measured and scanned linearly by a stylus of a profilometer. A series of arc contours and their radii can be calculated according to these measured arc data. The circularity and diameter of the measured small cylindrical workpiece can be obtained by stitching[26–28] these arc contours into an integral contour and averaging these diameters, respectively. However, the stitched circularity contour is not always accurate since the accuracy of some parts of arc data is not as good as the central part. Although the overlap parts of neighbouring arc contours, which are the same measured part on the small cylindrical workpiece but different measuring positions [29], should coincide theoretically, due to the measurement error [30], there are always some radial and circumferential deviations between neighbouring arc contours that can cause inaccurate stitching and affect the circularity contour, as well as value. To solve this problem, the analysis of the definition and computation methods for contour error and track error in polar coordinates platform will be made[35]. According to the analyses, a method of arc extraction is proposed to enhance the accuracy of the circularity measurement of small cylindrical workpieces. The results have important implications for the design, manufacture and measurement of workpieces[31]. Experiments and analyses are presented to demonstrate the arc extraction method.

2 Principles and Experiment

A coordinate segmenting-stitching method is used for the circularity measurement of the small cylindrical workpieces with a diameter of 1.5 mm and a length of 5.8 mm. The coordinates of the cross-sectional circle of the small cylindrical workpiece are segmented into eight equal arcs to be measured. The circularity contour of the small cylindrical workpiece can be obtained by stitching these eight arc contours into an integral contour. Fig.1(a) shows that the small cylindrical workpiece is attached to the round magnetic jig, which is segmented into eight equal parts. This kind of combination is mounted on the V-groove. A profilometer is employed to measure the arc coordinates of the cross-sectional circle of the small cylindrical workpiece. The stylus of the profilometer is brought to scan on the surface of the small cylindrical workpiece linearly. Fig.1(b) shows that a series of arc coordinate data can be obtained after the scanning. Rotate the magnetic jig by an equal angle (θ=45°), and the small cylindrical workpiece is brought to rotate by an equal angle on a new measuring position. The stylus returns to the initial position and scans again, and another arc coordinates data can be obtained. Due to the measuring range of the stylus, the maximum angle of the obtained arc data is 90°. Repeat the rotation-scan procedure seven times; 8 arc coordinate data can be obtained, as shown in Fig.1(c). Then eight related arc contours can be calculated according to the arc data. An integral circularity contour can be obtained by stitching these eight arc contours together. It should be noticed that there are some overlapped parts and stitching angle errors between neighbouring arcs. Therefore, accurate continue circularity contours can be obtained after stitching angle error compensation and integration of neighbouring arc contours. The final circularity contour can be obtained after a low-pass filter (50UPR).

Fig.2 shows the stitching detail of neighbouring arc contours. As shown in Fig.2(a), since the small cylindrical workpiece is scanned at the same position each time, all the arc data are on the same initial position as shown in Fig.2(b). Since the small cylindrical workpiece is rotated by an equal angle (45°) each time, for the reconstruction of the circularity contour of the small cylindrical workpiece, arc contour 2 should be rotated by an equal angle (45°) from arc contour 1 which is kept on the initial position as shown in Fig.2(c).

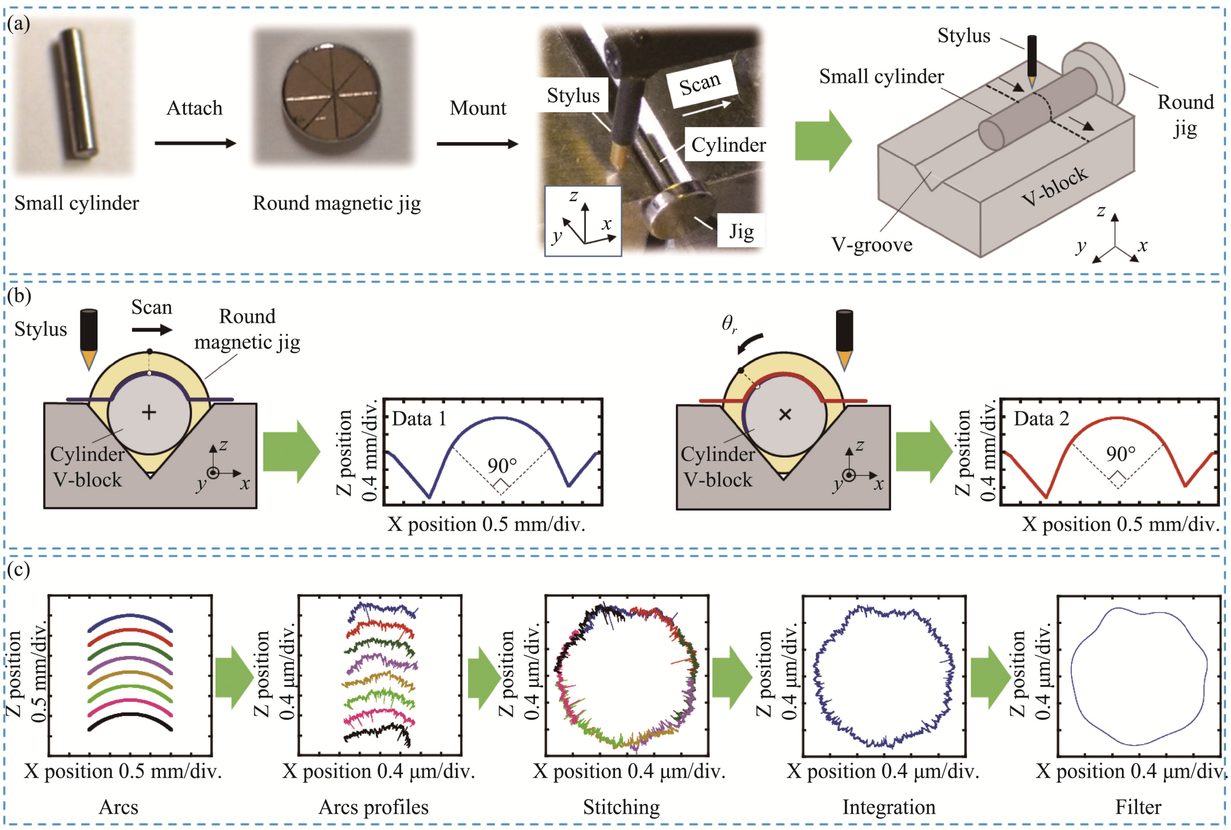

Fig.1 The Principle of the Dividing-extracting- stitching Method for Circularity Measurement of Small Cylindrical Workpieces: (a) a Small Cylindrical Workpiece Segmented by a round Jig and Mounted on a V-block; (b) Linear Scan on the Surface of a Small Cylindrical Workpiece for Arc Data; (c) Arc Contour Stitching for Circularity Contour.

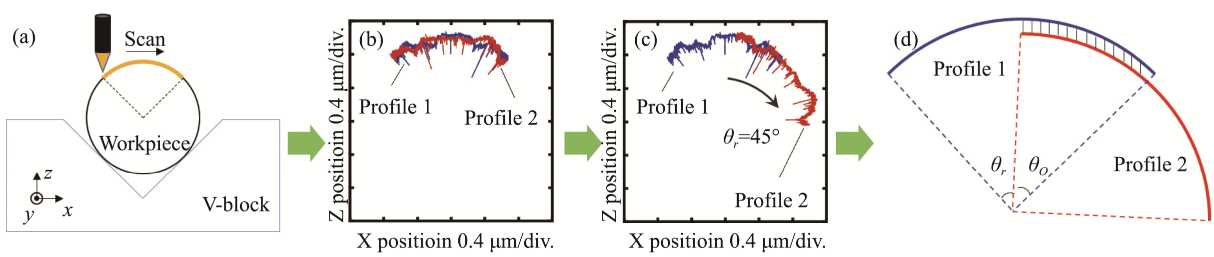

Fig.2 The Stitching of Neighbouring Arc Contours: (a) Stylus Scanning for Arc Data; (b) the Initial Position of Each Arc Contour; (c) the Stitching of Contours 1 and 2; (d) the Schematic of Stitching of Neighbouring Arcs.

There is an overlap part between neighbouring arc contours, as shown in Fig.2(d), which can be calculated by Equation (1) where θ_o is the overlap angle of neighbouring arc contours, θ_e is the extraction angle concerning the measured data, and θ_r is the equal angle.

$$\theta_o = \theta_e - \theta_r \tag{1}$$

Then the rest of the arc contours should be rotated by an equal angle of 45° from their former arc contours. The rotation angle is not always 45° at each time in the measuring procedure. Therefore, stitching angle error is necessary. Fig.3(a) shows that the stitching between Contour 1 and Contour 2 is mismatched in the X-Z coordinate system. As shown in Fig.3(b), the coordinates of contours 1 and 2 are converted into θ–ΔR ordinate system. Fig.3(c) shows that the mismatching between contours 1 and 2 can be seen clearly after filter processing. The cross-correlation function is used to find the correct matching between contours 1 and 2 according to the similar feature of the overlap part. As shown in Fig.3(d), contour 1 is kept static, and contour 2 is moved to the correct matching position by $\Delta\theta_{1\sim2}$ hen the matching coefficient of the cross-correlation function reaches the maximum value shown in Equation (2)

$$C_{1\sim2} = \int_{-\infty}^{\infty} f_1(\theta) f_2(\theta + \Delta\theta_{1\sim2}) d_\theta \tag{2}$$

Then the stitching angle error compensation can be achieved by rotating contour 2 counter-clockwise by $\Delta\theta_{1\sim2}$ n the X-Z coordinate system shown in Fig.3(e). The stitching angle error compensation of the rest of the neighbouring arc contours can be completed in this manner.

3 Analysis and Solution

Although an accurate and continuous circularity contour can be obtained by stitching these contours together and stitching angle error compensation of neighbouring arc contours, there are some circumferential and radial deviations between neighbouring arc contours. These deviations can affect the stitching accuracy, stitched circularity contour, and circularity value. As shown in Fig.4 (a), the stitching of contours 7&8 and contours 8&1 after filtering but before matching, it's difficult to match the neighbouring contours at the correct position due to the inaccurate data, which can cause circumferential deviations and

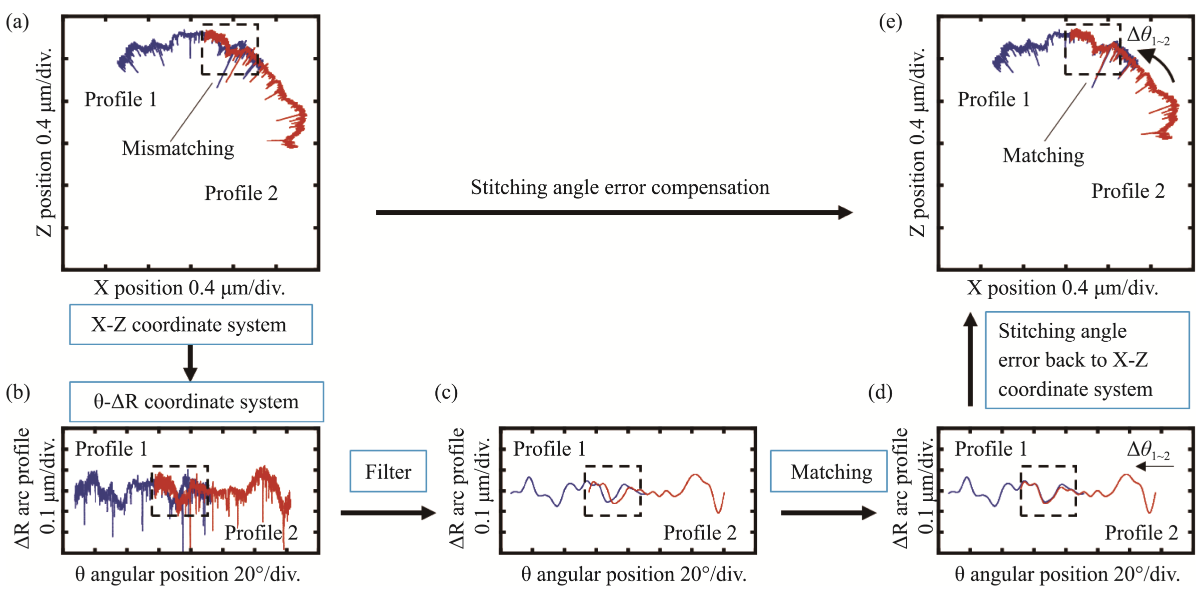

Fig.3 Stitching Angle Error Compensation of Neighbouring Arc Contours: (a) The Stitching of Contours 1 and 2 in the X-Z Coordinate System; (b) The Stitching of Contours 1 and 2 in θ-ΔR Coordinate System; (c) The Stitching of Contours 1 and 2 in θ-ΔR Coordinate System after Filter Processing; (d) The Stitching Angle Error Δθ Calculation after Matching; (e) The Stitching Angle Error Compensation.

radial deviations at both ends of overlap parts of neighbouring arc contours. These deviations can cause ambiguous matchings between neighbouring arc contours. Thus, two different matchings among contours 7&8&1 are presented as shown in Fig.4(b)&(c). Finally, two different circularity contours and values are obtained, as shown in Fig.4(b)&(c).

To address this problem, the measurement mechanism by the profilometer and its stylus is analyzed as shown in Fig.5(a), which is the scanning trajectory on the surface of the small cylindrical workpiece. As shown in Fig.5(b), α_1 is the pressure angle between the stylus tip and the measured cylinder when the stylus scans across A point of the measured cylinder. As shown in Fig.5(c), α_2 is the pressure angle when scanning across A' point of the measured cylinder, which is rotated by θ_r concerning the former position. Points A and A' are the same points on the measured cylinder but in different measuring positions. From the matching graph shown in Fig.4, as can be seen, the central overlap part of the neighbouring arc contours is better than the end overlap part; namely, the larger the measuring pressure angle is, the better the overlap part is. Therefore, for accurate stitching, two ends of each arc contour should be cut off as much as possible, as shown in Fig.5(d)&(e).

Although extracting the accurate arc contours can enhance the stitching accuracy, incorrect matching between neighbouring arc contours can be caused due to the less overlap part when cutting off too much. As shown in Fig.6(a)&(b), the overlap part of neighbouring arc contours is only 20° and 25°, respectively, while both of the stitching angle error are nearly 10° which is incorrect. As shown in Fig.6(c)&(d), the overlap parts of neighbouring arc contours are only 30° and 35°, respectively, and both of the stitching angle error are less than 0.5° which mean correct matchings. Therefore, it can be inferred that enough overlap part of neighbouring arc contours can ensure the accuracy of the matching results. According to the above analyses, it can be known that not only the extraction of accurate arc contours is necessary, but also enough overlap part of the neighbouring arc contours should be ensured. The experiment is carried out to verify

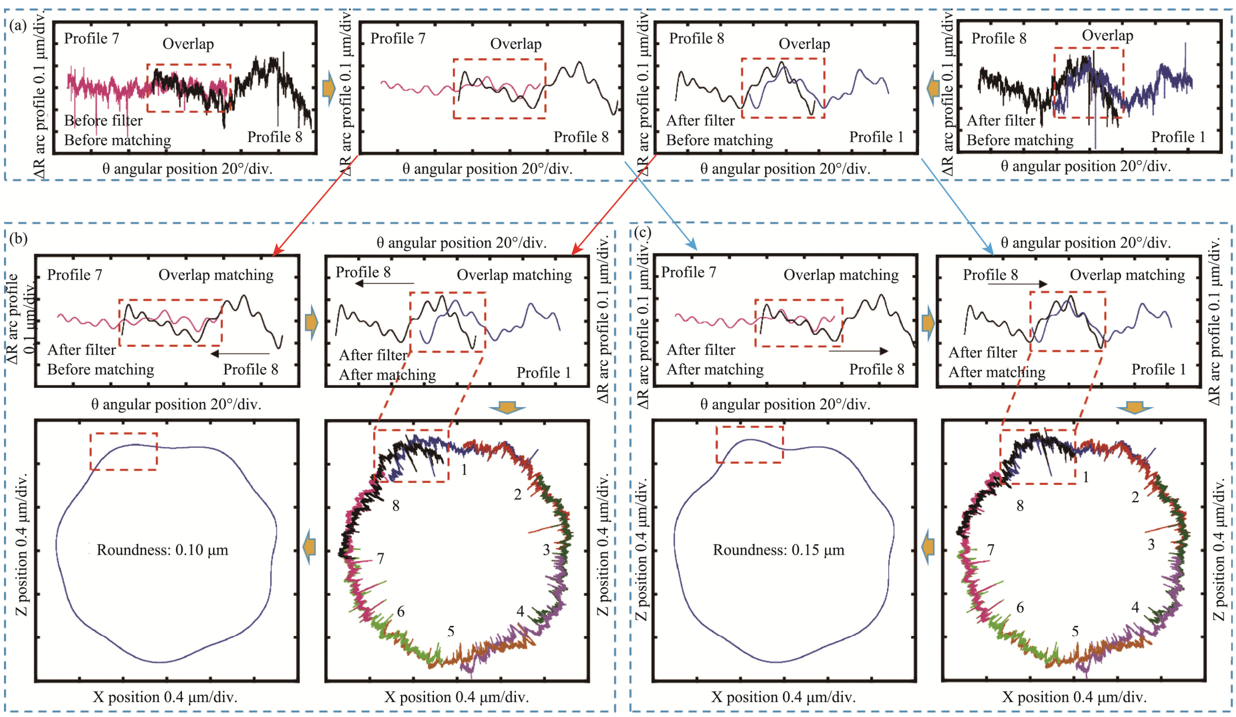

Fig.4 The Ambiguous Matching Caused by the Incorrect Arc Data of the Tail End: (a) before Matching; (b) Result 1 after Matching; (c) Result 2 after Matching

this conclusion, and three kinds of extraction are conducted, as shown in Fig.7. The maximum measurable range is 90°, and the extraction of 85°, 80° and 75° are designed for the circularity contour stitching. Due to the limited space, some of the selected matching results of neighbouring arc contours concerning the extractions are shown in Fig.8. The stitched circularity contours after stitching angle error compensation are shown in Fig.9.

Three indicators, the circumferential deviation of the overlap part of neighbouring arc contours, the radial deviation of the overlap part of neighbouring arc contours, and the average curvature of the obtained arcs, which are shown in Fig.10, are employed to evaluate the results of the three kinds of arc contour extractions. As shown in Fig.10(a), the circumferential deviation can be evaluated by the matching coefficient of Equation (2). As shown in Fig.10(c), the radial deviation can be evaluated by the Euclidean distance of the overlap part of neighbouring arc contours, which can be calculated by Equation (3) where i is the i_{th} arc contour, j is the i_{th} point of an arc contour, θ is the angular position, and Δr is the difference between the radius of an arc and the radius concerning a point on the arc.

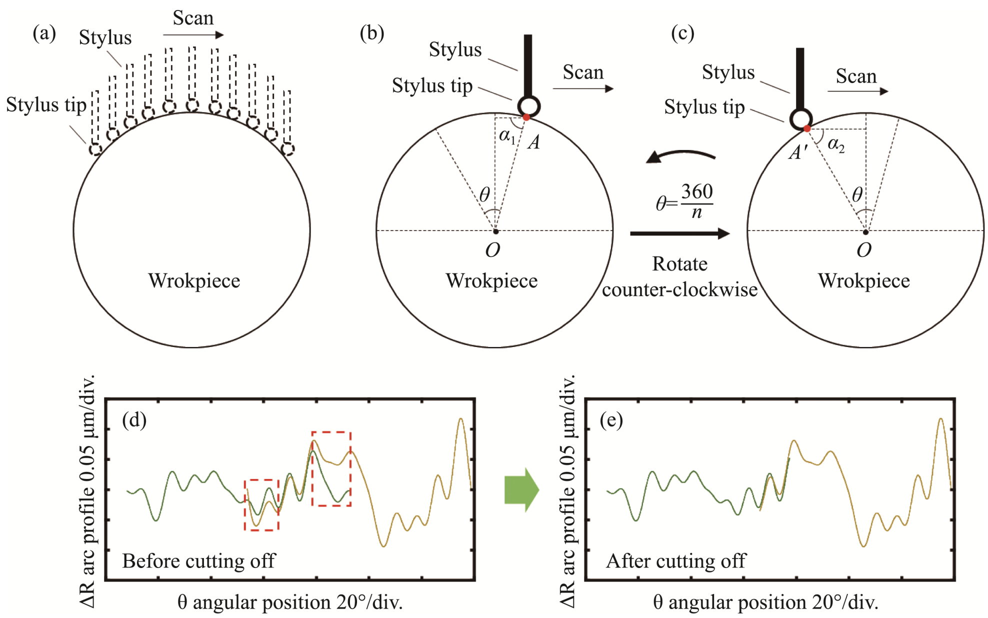

Fig. 5 The Measurement Mechanism by a Profilometer and Its Stylus: (a) The Scanning Trajectory of the Stylus on the Cylinder; (b) The Pressure Angle α_1 on Point A; (c) The Pressure Angle α_2 on Point A'; (d) The Stitching of Neighbouring Arc Contours; (e) The Stitching of Neighbouring Arc Contours after End Part Cutting Off.

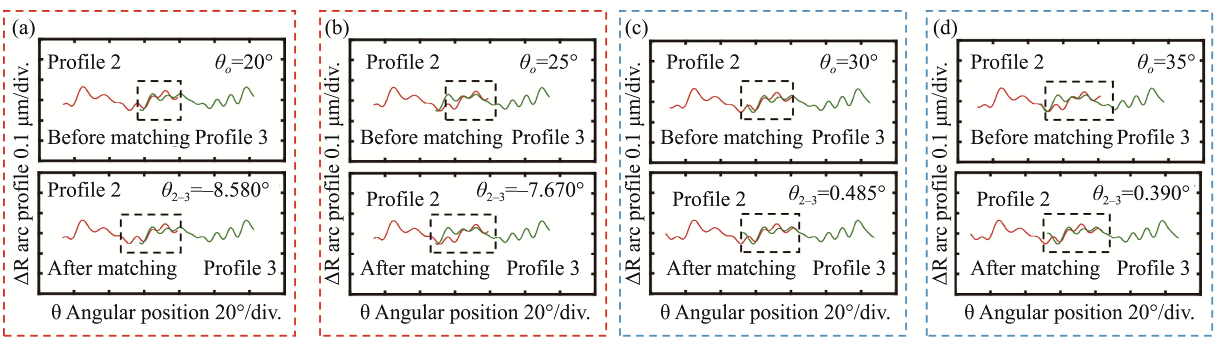

Fig.6 Different Overlap Angles for Matching of Neighbouring Arc Contours: (a) The Matching of Overlap Angle θ_o=20°; (b) The Matching of Overlap Angle θ_o=25°; (c) The Matching of Overlap Angle θ_o=30°; (d) The Matching of Overlap Angle θ_o=35°.

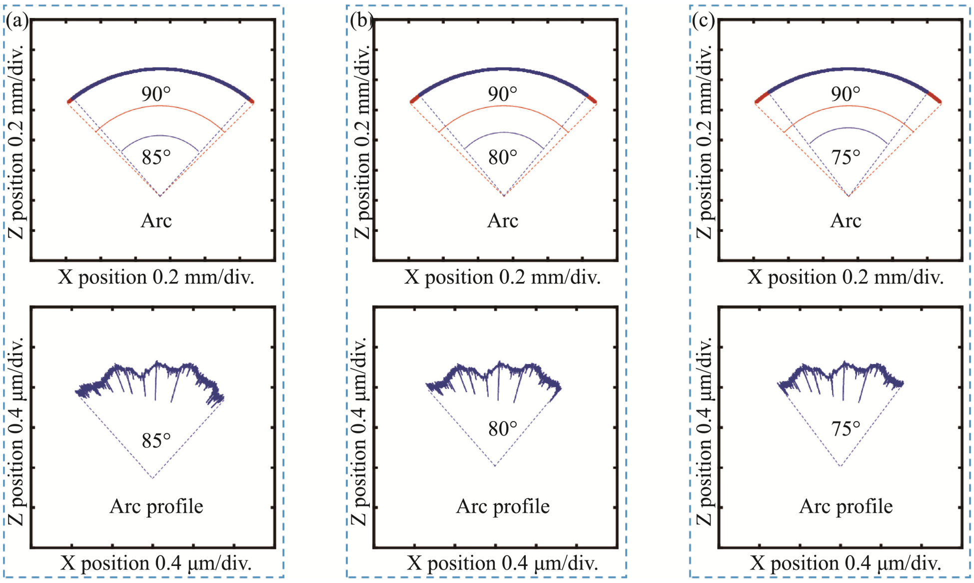

Fig.7 The Extraction of Arc Data and Its Contour: (a) The 85° Extraction; (b) The 80° Extraction; (c) The 75° Extraction.

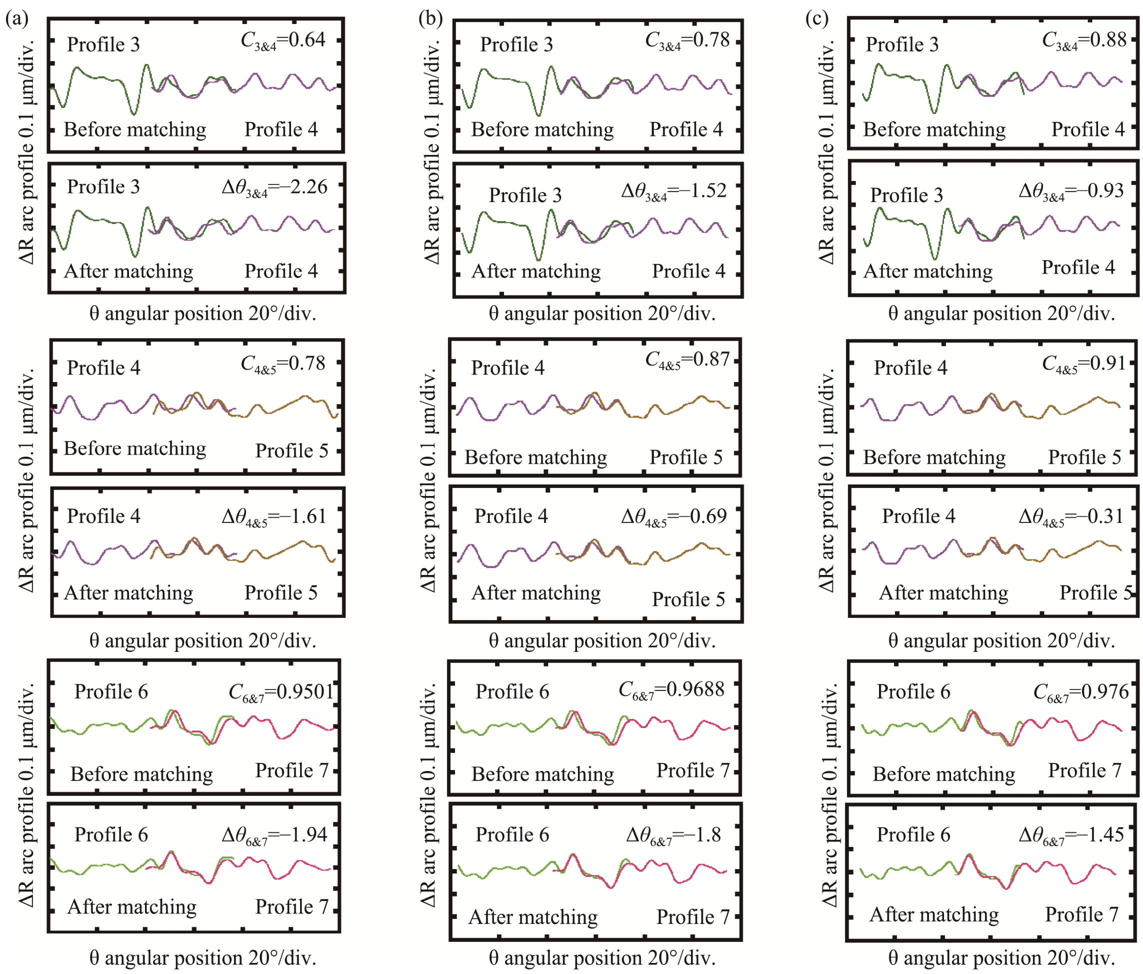

Fig.8 The Selected Matching Results of Neighbouring Arc Contours of Three Kinds of Arc Extraction: (a) the Matching Results of 85° Extraction; (b) the Matching Results of 80° Extraction; (c) the Results of 75° Extraction

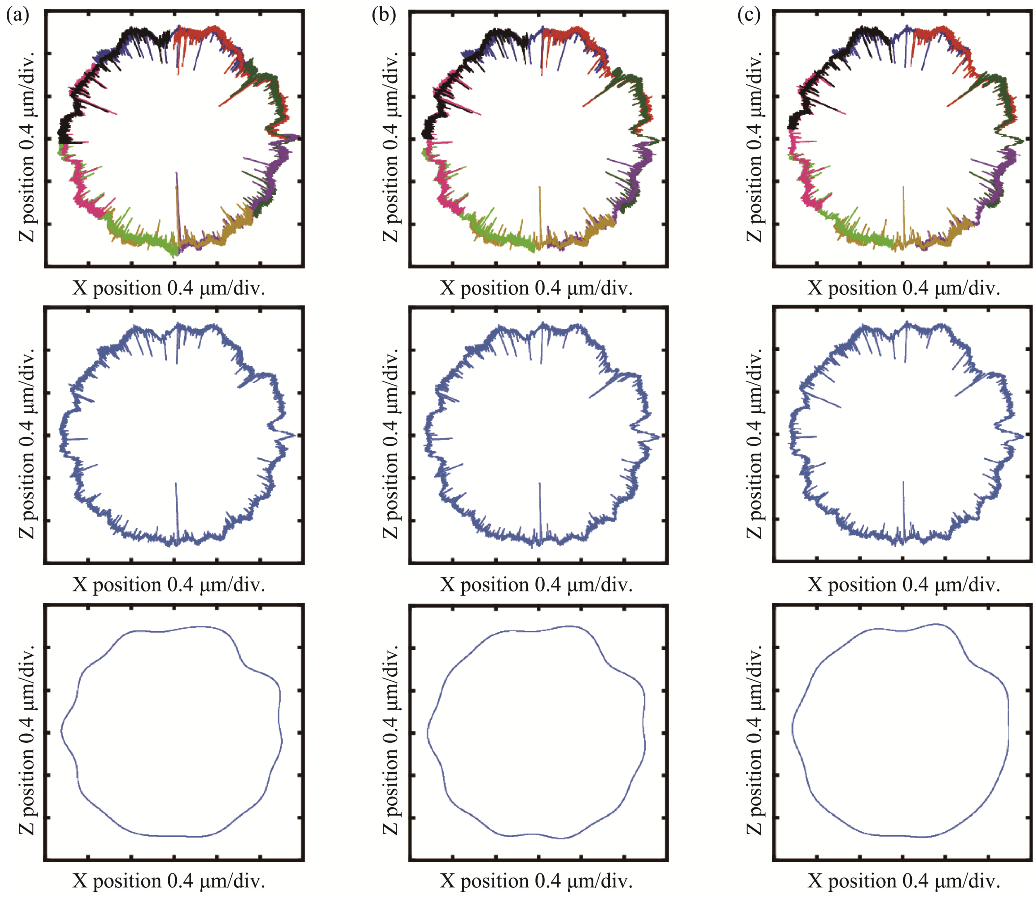

Fig.9 The Circularity Contours of Three Kinds of Arc Extraction: (a) the Circularity Contours of 85° Extraction; (b) the Circularity Contours of 80° Extraction; (c) the Circularity Contours of 75° Extraction

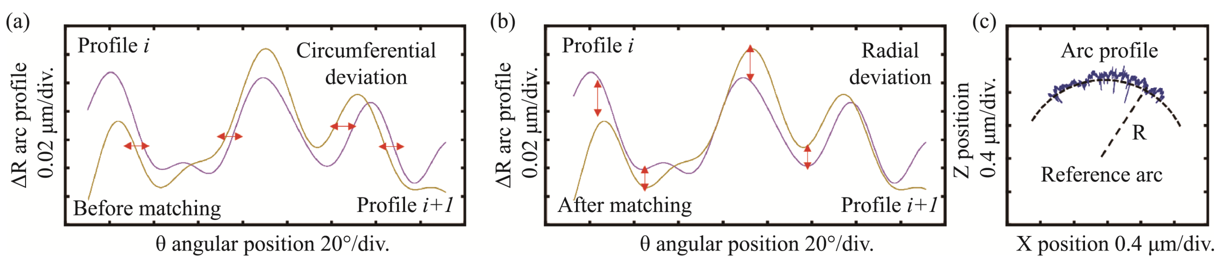

Fig.10 Three Indicators for the Evaluation of Arc Contours Stitching: (a) Circumferential Deviation between Neighbouring Arc Contours; (b) Radial Deviation between Neighbouring Arc Contours; (c) Curvature of an Arc Contour

Table 1 The Evaluation Results of the Three Kinds of Arc Data Extraction.

	Average Matching Coefficient	Average Euclidean Distance(μm)	Average Curvature	Diameter (mm)	Circularity (μm)
θ_e=85°	0.80	0.019	1.335887	1.49713	0.15
θ_e=80°	0.85	0.017	1.335829	1.49720	0.14
θ_e=75°	0.91	0.014	1.335737	1.49730	0.16

$$D_{i\sim i+1}=\frac{1}{n}\sum_{i,j=1}^{n}\sqrt{\left(\theta_{i,j}-\theta_{i+1,j}\right)^2+\left(\Delta r_{i,j}-\Delta r_{i+1,j}\right)^2} \quad (3)$$

As shown in Fig.10(c), the average curvature K of the obtained arcs can be calculated by Equation (4), where n is the number of the obtained arcs.

$$K=\frac{1}{n}\left(\frac{1}{r_1}+\frac{1}{r_2}+\cdots\frac{1}{r_n}\right) \quad (4)$$

The evaluation results of the three kinds of arc data extraction are summarized in Table 1. The average matching coefficient increases with the extraction angle decreasing. The larger the matching coefficient is, the smaller the circumferential deviation is. The average Euclidean distance decreases with the extraction angle decreasing. The smaller the Euclidean distance is, the smaller the radial deviation is. With the extraction decreasing, the average curvature is closer to the curvature of the arc with a nominal diameter of 1.5 mm. The curvature of the arc can reflect the quality of the measured arc data to some extent.

4 Summary

This paper analyzes and performs the arc extraction for the accuracy of circularity measurement of small cylindrical workpieces by the stitching linear-scan method. The coordinates of the cross-sectional circle of the small cylindrical workpiece with a diameter of 1.5 mm and length of 5.8 mm are segmented into several equal arcs to be measured by a profilometer with its stylus. The circularity contour of the small cylindrical workpiece can be obtained by stitching the arc contours together. Due to the changing pressure angle of the stylus scanning on the surface of the small cylindrical workpiece, the accuracy of the obtained arc coordinates is not the same, which can cause some circumferential and radial deviations at the overlap part of the neighbouring arc contours in the stitching procedure. To address this issue, the two ends of the arc data are considered cutting off. However, when the arc data are cut off too much, there needs to be more overlap between neighbouring arc contours for correct matching, which is carried out by the cross-correlation function according to the similar feature of the overlap part, namely, incorrect matching can be caused. Therefore, not only the accurate arc data should be extracted, but also enough overlap should be ensured for the correct matching. To verify the analyses, the extraction of 85°, 80°, and 75° are conducted from the same experiment result whose maximum range is 90°. Three indicators, circumferential deviation, which can be evaluated by the matching coefficient of cross-correlation functions; radial deviation, which can be evaluated by Euclidean distance; and curvature of the arc data, which can be evaluated concerning the nominal arc, are employed to evaluate the results by the three kinds of arc extraction. The results show that the average circumferential and radial deviation at the overlap part of neighbouring arc contours, as well as the average curvature of the arc data, can be improved by valid arc data extraction. Therefore, the accuracy of the circularity measurement of small cylindrical workpieces by the stitching linear-scan method can be improved by the proposed arc data extraction method.

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Author Declarations

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zhao Jiali: Conceptualization (lead); Formal analysis (lead); Writing - original draft (lead); Methodology (equal); Resources(lead); Writing – review & editing (lead). Wu Dan: Investigation (equal); Data curation(equal); Writing – review & editing (equal). Zhang Liang: Writing – review & editing (supporting). Shen Bobo: Investigation (equal); Writing – review & editing (supporting). Li Qiaolin: Writing – review & editing (supporting).

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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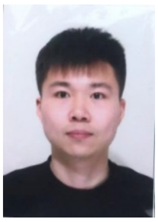

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