

Article

Improvement of a Stitching Operation in the Stitching Linear-Scan Method for Measurement of Cylinders in a Small Dimension

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Abstract: Attempts are made in this paper to improve the quality of the stitching between adjacent arc-profiles in the stitching linear-scan method for the roundness measurement of a cylinder in a small dimension. The data in the edge region of an arc-profile, which could be influenced by the pressure angle of the measurement probe of a linear-scan stylus profiler, are eliminated in the stitching process to improve the quality of stitching. The effectiveness of the elimination of the edge region of an arc-profile is evaluated by employing the cross-correlation coefficient of two adjacent arc-profiles as an evaluation index. Furthermore, a modification is made to the experimental setup to reduce the misalignment of a workpiece along its axial direction with respect to the scanning probe. Experiments are carried out by using the modified setup to demonstrate the feasibility of the stitching linear-scan method for the roundness measurement of a small cylinder, which is difficult to measure by the conventional rotary-scan method.

Keywords: improved stitching linear-scan method; small cylinders; precision measurement; roundness; diameter



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1. Introduction

A needle roller bearing is one of the bearings employed in a variety of industrial applications where long fatigue life is one of the most important criteria [1]. Figure 1 shows a schematic of the needle roller bearing, which is mainly composed of an outer ring, cage and needle rollers. The quality of a needle roller strongly affects the fatigue life of the bearing in which the needle roller is employed [2,3]. For the manufacturing of needle roller bearings having a long fatigue life, it is necessary to ensure the quality of needle rollers by evaluating their dimensional parameters, such as the diameter, out-of-roundness and so on [4,5].

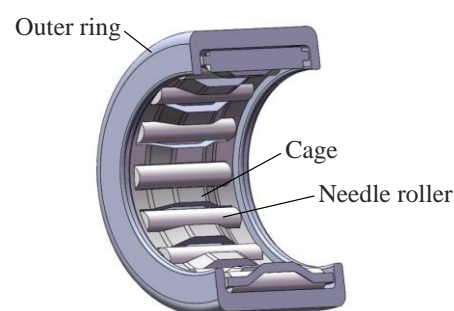


Figure 1. Needle roller bearing.

The out-of-roundness of a cylindrical workpiece can be measured by the conventional rotary-scan method [6–9]. For the precise evaluation of the out-of-roundness, error separation methods such as the multi-step method [10] and the multi-probe method [11,12] have often been employed. Moreover, the V-block method can be employed for the waviness and cylindricity measurement of a cylindrical workpiece [13]. Meanwhile, in the out-of-roundness measurement, precise alignment of a target workpiece with respect to the rotational datum is one of the necessary steps before measurement. The alignment of a small target workpiece is not an easy task, even for the state-of-the-art roundness measuring instruments with automatic alignment functions; for example, a decrease in the workpiece length could affect the accuracy of the workpiece tilt adjustment. A decrease in the workpiece diameter could also make it difficult to carry out centering alignment in a roundness measuring instrument. An optical method has also been developed for the measurement of a small cylinder [14]. Although the method is capable of measuring cylindricity and/or roundness while allowing fast measurement with easy workpiece alignment, the measurable diameter was reported to be no less than 3 mm [14].

In responding to the background described above, an alternative method referred to as the stitching linear-scan method has been proposed [15,16]. In the method, a series of arc-profiles of a small workpiece are obtained by a linear-scan surface form stylus profiler, which is often employed for surface form/roughness measurement [4]. For the positioning of a small workpiece, the unique workpiece-holding mechanism composed of a V-block and a round magnet jig having index marks has been developed [16]. Through the stitching process, the circumferential profile of a small workpiece can be reconstructed from the obtained series of arc-profiles for the evaluation of the workpiece cylindricity and/or roundness. The proposed method does not require a high-precision rotary table and is free from the influences of the workpiece eccentricity. Although the angular misalignments of the workpiece with respect to the scanning probe in the stylus profiler could degrade the accuracy of stitching operations, an experimental setup capable of compensating for the angular misalignments of a target workpiece has been developed to address the issue. Once the V-block is aligned with respect to the stylus of the commercial stylus profiler, only the circumferential misalignment of the workpiece will be the influence of the difference of user/operator on the measurement. On the other hand, the circumferential misalignment can be compensated through the circumferential stitching process—namely, a difference in the user/operator will not affect the results of the measurement. Experimental results have demonstrated that a workpiece having a diameter of 3 mm can successfully be evaluated by the proposed method [17]. The stitching linear-scan method is expected to have advantages with respect to the conventional rotary-scan method in the case where a workpiece diameter is smaller than 3 mm. Moreover, the stitching linear-scan method can realize high-precision measurement of a workpiece in the case where the workpiece length is not enough to be held stably by a mechanical chuck in the conventional rotary-scan method. Meanwhile, the improvement of the accuracy of the stitching between the neighboring arcs in the stitching linear-scan method remains an issue that needs to be addressed.

In this paper, an attempt is made to improve the stitching accuracy in the stitching linear-scan method. Investigation of the effect of eliminating the data at the edge regions of the arc-profiles in the circumferential stitching process is carried out. A modification is also made to the workpiece-holding mechanism, while paying attention to the reduction of the misalignment of the workpiece axis with respect to the V-groove in the V-block. The feasibility of the modified stitching operation, as well as that of the modified workpiece-holding mechanism, is verified by measuring a small workpiece having a diameter and a length of 1.5 mm and 5.8 mm, which is difficult to be measured by the conventional rotary-scan method.

2. Principle of the Stitching Linear-Scan Method

A schematic of the setup for the stitching linear-scan method is shown in Figure 2. As can be seen in the figure, the target workpiece is mounted on the V-groove in the

V-block, while a round magnet is attached to one end of the workpiece. It should be noted that the centering alignment of the workpiece with respect to the round magnet can automatically be carried out by the magnetic force between them. Since the round magnet has n indexing marks, the workpiece can coarsely be positioned in a step of $360/n$ degrees in the circumferential direction. By repeating the workpiece rotation and the linear scan of the arc-profile of the workpiece, a series of arc-profiles covering 360° of the circumferential profile of the workpiece can be obtained.

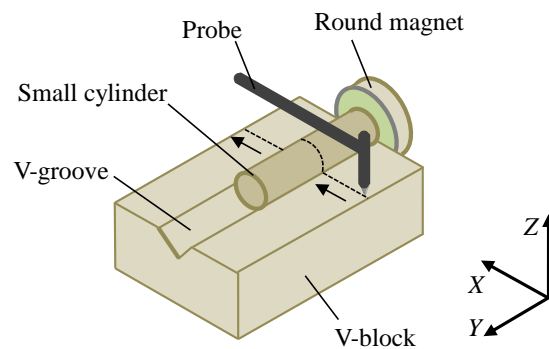


Figure 2. A schematic of the stitching linear-scan method.

The reconstruction of the circumferential profile of the workpiece can be carried out through the stitching process, which mainly consists of the radial stitching and the circumferential stitching. Figure 3 shows a schematic of the whole stitching process. Details of the stitching process can be found in [15–17].

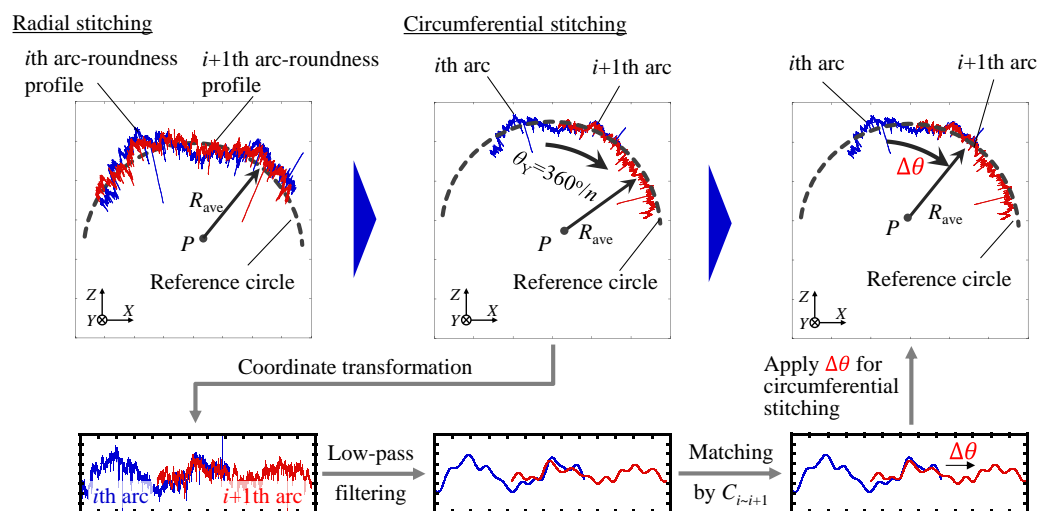


Figure 3. Stitching process.

After the radial stitching, the circumferential stitching is carried out. In the circumferential stitching, the arc-profiles in the Cartesian coordinates are at first transformed into polar coordinates. Then, the overlapped part of two adjacent arcs can be matched by referring to the following cross-correlation function [18–20]:

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

where C_{i-i+1} is the cross-correlation coefficient between the i th and $(i + 1)$ th arc-profiles $f_i(\theta)$ and $f_{i+1}(\theta + \Delta\theta)$, respectively, while $\Delta\theta$ is the adjusted angle of the $(i + 1)$ th arc-profile. When C_{i-i+1} is close to 1, this means that the two arcs match well. In the circumferential stitching process, the stitching of the adjacent arcs is performed in such a way that the

calculation based on Equation (1) is carried out by changing $\Delta\theta$ step by step to find out $\Delta\theta = \Delta\theta_{i \sim i+1}$ that can maximize $C_{i \sim i+1}$, since a higher cross-correlation coefficient means better stitching.

Meanwhile, in the stitching linear-scan method, there are two major issues that need to be addressed to improve the quality of stitching. The first issue is related to the geometric relationship between the stylus of a linear-scan surface form stylus profiler and the cylindrical form of a workpiece. As can be seen in Figure 4, the pressure angle of the stylus becomes different at each point on the surface of measurement target; namely, in the overlapped region between the i th and $(i + 1)$ th arc-profiles, the same point in the adjacent arc-profiles will be measured with different pressure angles. As a result, due to the influences of the shape of the probe tip and the local slope of the target surface, the profile of the overlapped region to be obtained in the i th arc-profile and that in the $(i + 1)$ th profile become slightly different from each other. The discrepancy between the two adjacent arc-profiles in the overlapped region could become significant at the edge of each arc-profile measured by the stylus with a large pressure angle.

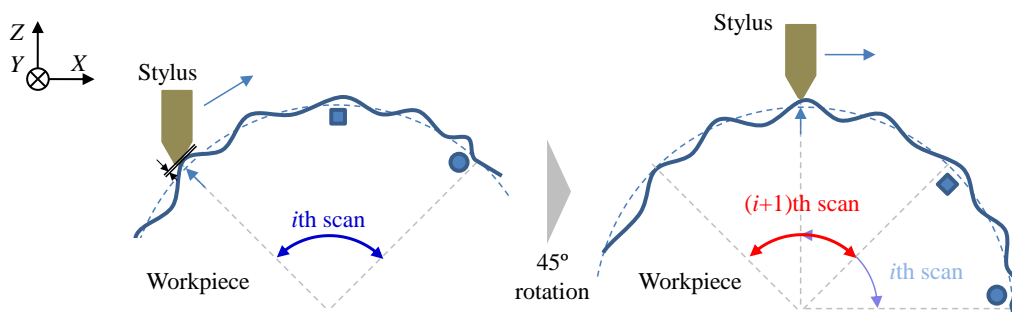


Figure 4. The influence of the pressure angle of a probe of the linear-scan stylus profiler.

According to the uncertainty analysis performed in the previous study by the authors [17], the reading of the X-coordinate in the stylus profiler is one of the main uncertainty sources. Uncertainty of the reading of the Z-coordinate in the stylus profiler, including the calibration uncertainty of the probe, could also be a major component of measurement uncertainty; it is not easy to reduce these components of measurement uncertainty. On the other hand, the influences of the workpiece misalignments can be suppressed by some efforts. The influence of the workpiece tilt was successfully suppressed by the tilt alignment technique [17]. Meanwhile, another issue that needs to be addressed is the misalignment of the workpiece along its axial direction. In the developed setup for the proposed stitching linear-scan method, the alignment of the workpiece along its axial direction is carried out with respect to the datum surface determined by the round magnet surface and the side face of the workpiece holder. Therefore, the out-of-flatness of these surfaces could induce the axial misalignment of the workpiece. In this case, as can be seen in Figure 5, different positions on the workpiece surface could be measured in the i th and $(i + 1)$ th arc-profiles at their overlapped region. Since a cylindrical workpiece tends to have a similar circular profile along its axial direction, a certain amount of the axial misalignment can be accepted. Meanwhile, the existence of a local profile error could generate a discrepancy between the obtained arc-profiles in the overlapped region, resulting in a decrease in the cross-correlation coefficient.

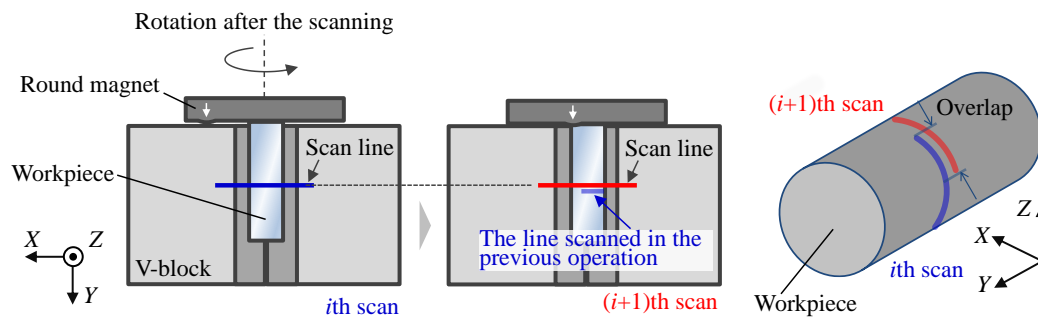


Figure 5. The influence of the workpiece misalignment along its axial direction.

Some attempts are thus made in this paper to address the aforementioned issues. An attempt is made to eliminate the data at the edge regions of the arc-profiles in the circumferential stitching process based on Equation (1). A modification is also made to the experimental setup in such a way that a small round magnet is added between the round magnet and workpiece; this modification is expected to reduce the influences of out-of-flatness of the round magnet surface and the side face of the workpiece holder by reducing the contact area between them.

3. Improvement in the Implementation of Stitching Linear-Scan Method

3.1. Improvement of the Cross-Correlation Coefficient in the Circumferential Stitching Process by the Elimination of the Data in the Edge Region of an Arc

The feasibility of eliminating the edge part of an arc in the stitching process for the improvement of a cross-correlation coefficient was at first verified in experiments. Figure 6 shows a schematic of the setup employed in the following experiments. A workpiece-holding mechanism with a V-groove having a depth of 2.5 mm and an angle of 90° was mounted on a two-axis manual rotary stage so that the fine adjustment of the three-axis tilt of a workpiece could be carried out. As reported in the previous work [17], angular misalignments of a workpiece about the X- and Z-axes can be reduced to less than 0.1 arc-seconds by using a stylus profiler [17]. A commercial stylus profiler (Form Talysurf PGI-420, Taylor-Hobson) was employed as the linear-scan stylus profiler for the stitching linear-scan method. A cylindrical workpiece with a radius of 3.0 mm and a length of 50 mm was employed as the specimen for measurement. The circumferential profile of the workpiece was obtained as the eight-divided arc-profiles. After the linear scan of each arc, the workpiece was rotated 45 degrees manually by referring to the index mark on the round magnet. Measurement conditions are summarized in Table 1. The scanning speed was set to be 0.1 mm/s; this is the lowest speed allowed in the employed stylus profiler.

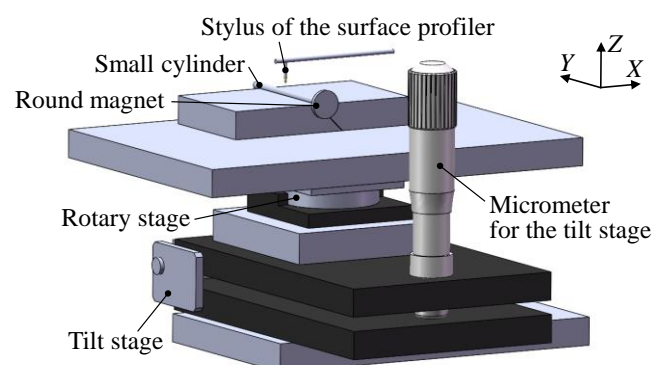


Figure 6. Schematic of the setup employed in experiments.

Table 1. Measurement conditions.

Item	Value	Unit
Straightness	≤ 0.5	μm
Measurement range	0.1–120	mm
Resolution	0.125	μm
Tip angle of the stylus	60	degree
Tip radius of the stylus	2	μm
Scanning speed	0.1	mm/s

Figure 7a,b show the profiles of Arc1 and Arc2, respectively, after the low-pass filtering and the radial stitching [15,16]. Figure 7c shows the variation in the cross-correlation coefficient due to the change in $\Delta\theta$ calculated based on Equation (1) with the employment of the profile data in the highlighted region in Arc2. From the obtained plot in Figure 7c, $\Delta\theta$ ($=\Delta\theta_{1-2}$), providing the maximum cross-correlation coefficient, was subtracted. By using the obtained $\Delta\theta_{1-2}$, Arc1 was stitched with Arc2 as shown in Figure 7d. It should be noted that the difference between Arc1 and Arc2 in the overlapped region is also plotted in Figure 7d. The maximum cross-correlation coefficient C_{1-2} was evaluated to be 0.64.

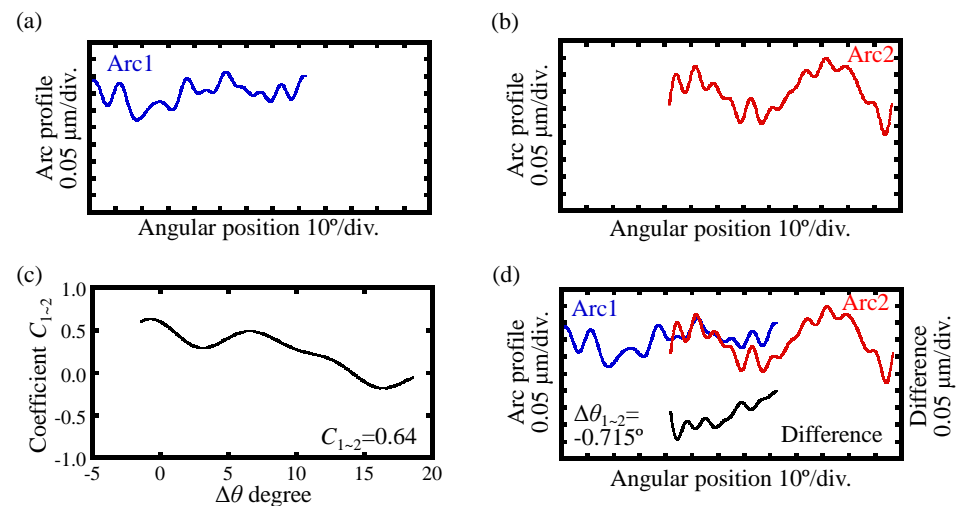


Figure 7. The stitching of the Arc2 with respect to Arc1 by employing all data in the overlapped region: (a) Arc1; (b) Arc2; (c) Variation in the cross-correlation coefficient C_{1-2} due to the change in $\Delta\theta$; (d) The stitched Arc1 and Arc2 at $\Delta\theta = \Delta\theta_{1-2}$.

Experiments were extended to carry out the stitching process with the limited data in the overlapped region in an arc-profile to be stitched with the neighboring arc. Figure 8 shows a schematic of the exclusion of the edge data in the arc-profiles for the circumferential stitching. In the circumferential stitching process, arc-profile data in the angular range of ϕ_e is excluded from the neighboring i th and $(i + 1)$ th arc-profiles for the calculation of the cross-correlation coefficient $C_{i \sim i+1}$ based on Equation (1). In the $(i + 1)$ th arc-profile, the profile data in the angular range of ϕ_u next to the excluded region is employed for the calculation of $C_{i \sim i+1}$. In the calculation process, the angular position of the i th arc-profile is fixed, while the $(i + 1)$ th arc-profile is shifted along the circumferential direction to maximize $C_{i \sim i+1}$.

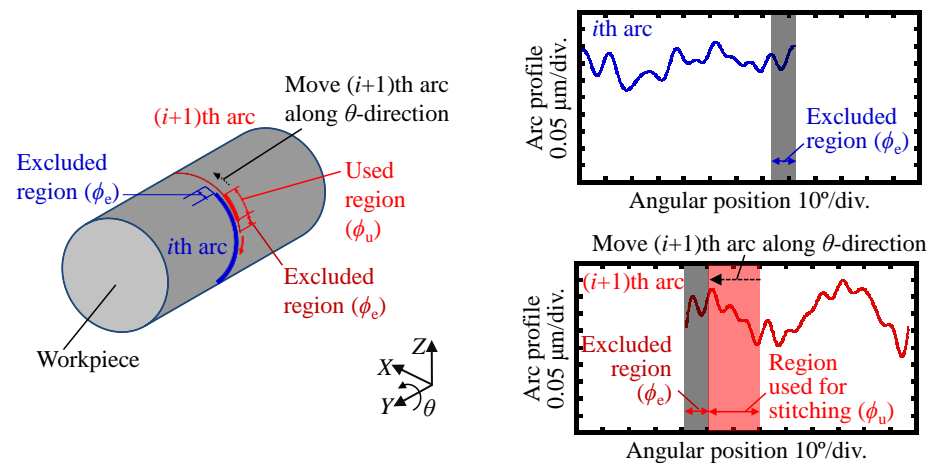


Figure 8. Exclusion of the edge data in the arc-profiles for the circumferential stitching.

Figure 9a,b show the profiles of Arc1 and Arc2, respectively, which are the same as those in Figure 7a,b. The stitching process was carried out in the same manner as described above, while excluding the data in the edge region of Arc2. The parameters ϕ_e and ϕ_u were set to be 10° and 20° , respectively. Figure 9c shows the variation of the cross-correlation coefficient due to the change in $\Delta\theta$, and Figure 9d shows the stitched Arc1 and Arc2 with $\Delta\theta_{1-2}$ obtained from the plot shown in Figure 9c. In Figure 9d, the region in Arc2 employed in the stitching process, in which the data corresponding to 10° from the edge of Arc2 is excluded, is highlighted. The maximum cross-correlation coefficient C_{1-2} was evaluated to be 0.89; this value is larger than that obtained by the stitching with the data in Arc2 shown in Figure 7b.

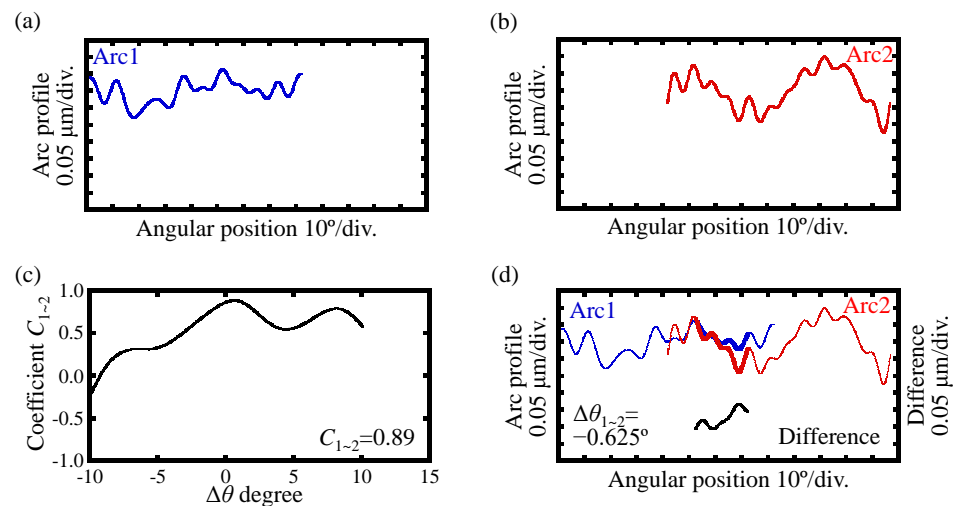


Figure 9. The stitching of the Arc2 with respect to Arc1 by employing the profile data excepting the edge region in Arc2 in the overlapped region: (a) Arc1; (b) Arc2; (c) Variation of the cross-correlation coefficient C_{1-2} due to the change in $\Delta\theta$; (d) The stitched Arc1 and Arc2 at $\Delta\theta = \Delta\theta_{1-2}$.

To further verify the effect of eliminating the data in the edge region of an arc on the improvement of the cross-correlation coefficient in the stitching process, stitching operations of two neighboring arcs in the eight arc-profiles were carried out. Figure 10 shows the results.

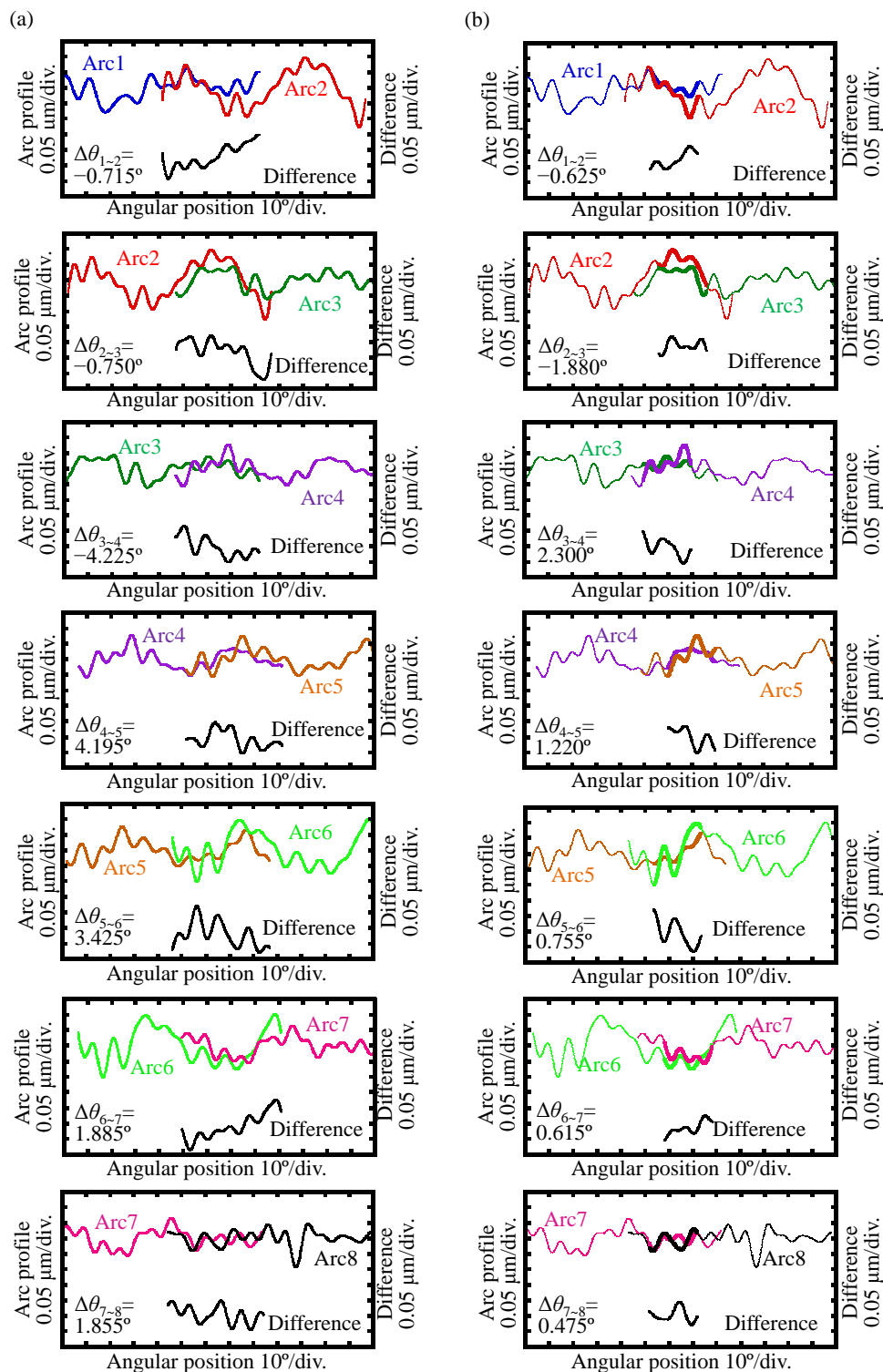


Figure 10. Stitched neighboring arc-profiles from the eight arc-profiles: (a) Stitching by employing all data in the overlapped region; (b) Stitching by employing the profile data in the overlapped region except the edge region in an arc to be stitched.

Cross-correlation coefficients obtained in the stitching operations are also summarized in Figure 11. As can be seen in the figures, the elimination of the data in the edge region of an arc was found to be effective in improving the cross-correlation coefficient in each stitching operation.

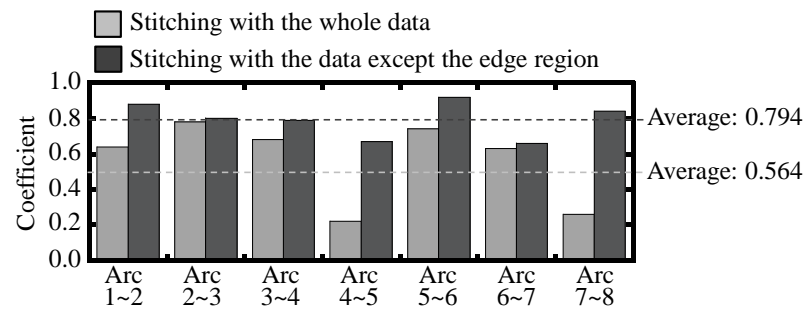


Figure 11. Cross-correlation coefficients observed in the stitching operation.

Figure 12 shows the relationship between Arc8 and Arc1 after the stitching operations. It should be noted that the angular position of Arc8 is determined by the sum of $\Delta\theta_{i \sim i+1}$ ($i = 1 \sim 7$), and the cross-correlation coefficient between Arc8 and Arc1 (C_{8-1}) could be a parameter indicating the quality of circumferential stitching operations. In the case of the stitching operations employing the full data in the overlapped region between the two neighboring arcs, C_{8-1} was evaluated to be 0.44. Meanwhile, in the case of the stitching operations with the data eliminating the edge region of an arc to be stitched, C_{8-1} was evaluated to be 0.66; these results indicate that the quality of the stitching was improved by eliminating the data in the edge region of an arc to be stitched.

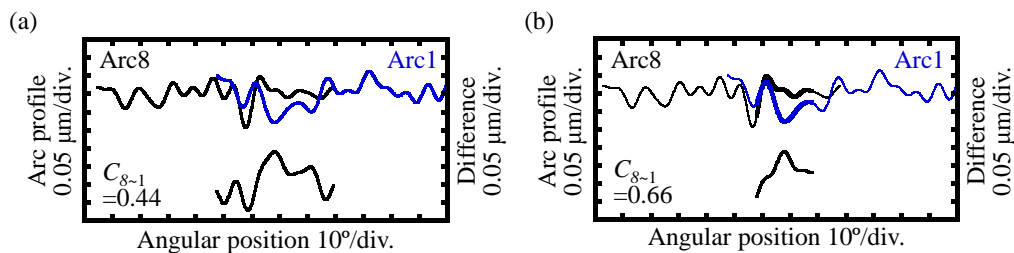


Figure 12. The relationship between Arc8 and Arc1 after the stitching operations: (a) Stitching by employing all data in the overlapped region; (b) Stitching by employing the profile data in the overlapped region except the edge region in an arc to be stitched.

3.2. A Hardware Modification for the Improvement of the Cross-Correlation Coefficient in the Circumferential Stitching Process

A hardware modification was also made to the experimental setup for the improvement of the quality of the stitching of arc-profiles. Figure 13 shows a schematic of the setup before and after the modification. In the modified setup, a small round magnet was sandwiched between the round magnet and workpiece as shown in Figure 13b; this modification was expected to reduce the influences of out-of-flatness of the round magnet surface and the side face of the workpiece holder by reducing the contact area between them.

Experiments were carried out to verify the feasibility of the modified workpiece-holding mechanism. Figure 14 shows a photograph of the modified setup. A small magnet with a diameter and a thickness of 1.5 mm and 4.0 mm, respectively, was placed between the round magnet and workpiece. The workpiece having a diameter and a length of 3.0 mm and 50 mm, respectively, evaluated in the previous section was also employed. Moreover, the experimental conditions except the modified workpiece-holding mechanism were set to be the same as those in the previous experiments described in Section 3.1.

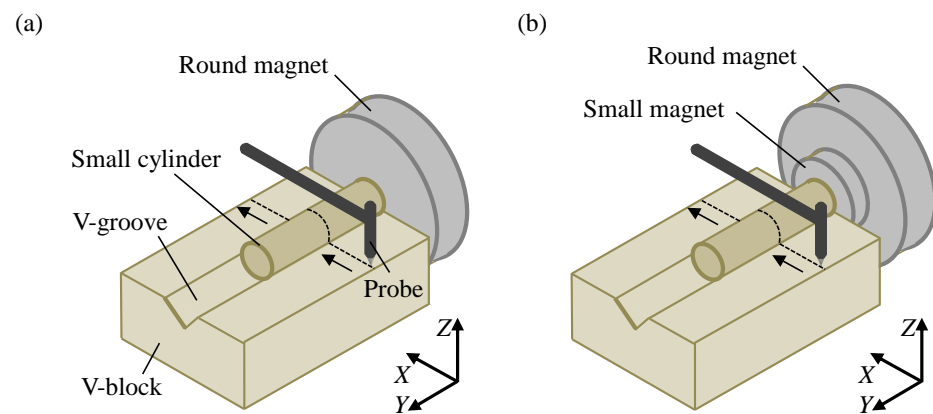


Figure 13. A schematic of the workpiece-holding mechanism: (a) Before modification; (b) After modification.

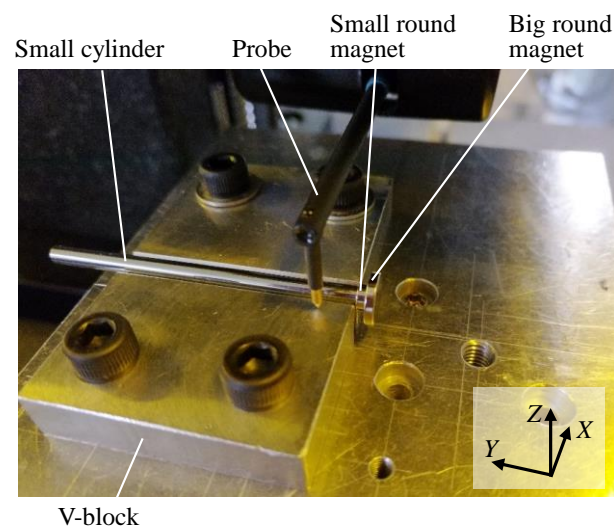


Figure 14. A photograph of the modified setup.

Stitching operations of the neighboring arc-profiles were carried out by eliminating the data in the edge region of an arc. Figure 15 shows the results of the stitching operations, and Figure 16 compares the cross-correlation coefficients obtained in the stitching operations of the arcs obtained by the conventional setup and the modified setup. As can be seen in the figure, cross-correlation coefficients were found to be further improved by the employment of the modified workpiece-holding mechanism.

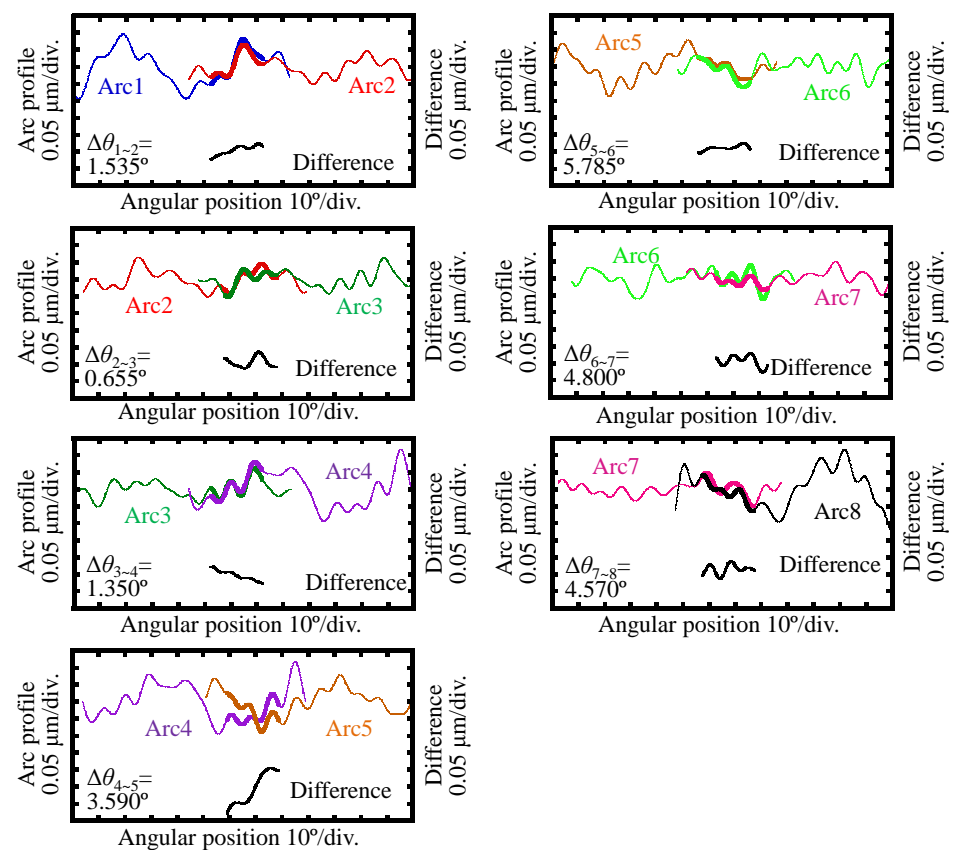


Figure 15. Stitched neighboring arc-profiles from the eight arc-profiles.

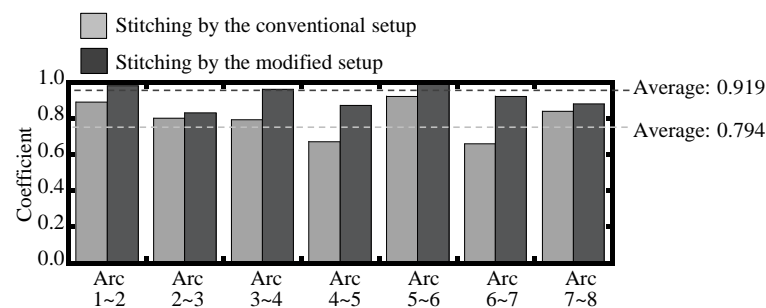


Figure 16. Cross-correlation coefficients observed in the stitching operations.

Figure 17a,b show the degree of agreement between Arc8 and Arc1 obtained through the stitching operations of the arc data measured by the conventional and modified setups, respectively. It should be noted that the angular positions of Arc8 with respect to Arc1 in the figure were determined by the sequential stitching operations of i th and $(i + 1)$ th arcs ($i = 1 \sim 7$). As can be seen in the figures, a better cross-correlation coefficient was obtained in the case with the modified workpiece-holding mechanism. These results demonstrated the feasibility of the modified workpiece-holding mechanism.

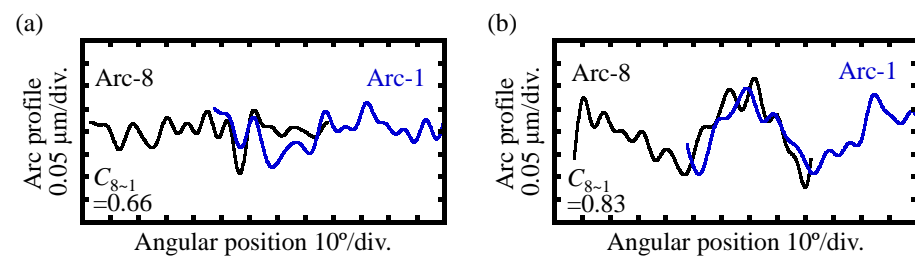


Figure 17. The relationship between Arc8 and Arc1 after the stitching operations: (a) Stitching of the arc-profiles obtained by the conventional setup; (b) Stitching of the arc-profiles obtained by the modified setup.

3.3. Implementation of the Stitching Linear-Scan Method for a Workpiece with a Small Dimension

Experiments with the modified setup were then extended to evaluate a workpiece in a smaller dimension, which is difficult to evaluate by the conventional rotary-scan method. In the following, a small workpiece with a diameter and a length of 1.5 mm and 5.8 mm, respectively, was employed as the measurement specimen. A V-groove having a depth of 1 mm and an angle of 90° was employed. With decreases in the diameter and the length of a workpiece, the holding of a workpiece on the workpiece-holding mechanism in the stitching linear-scan method becomes difficult. To achieve the stable holding of the workpiece in a small dimension, a counter-mass was employed in this paper. Figure 18 shows a photograph of the setup. As can be seen in the figure, a long cylindrical magnet having a diameter slightly smaller than that of the workpiece was attached to another end of the workpiece. The added long cylindrical magnet acted as a counter-mass for stable mounting of the workpiece. It should be noted that the long cylindrical magnet can be centered due to the magnetic force.

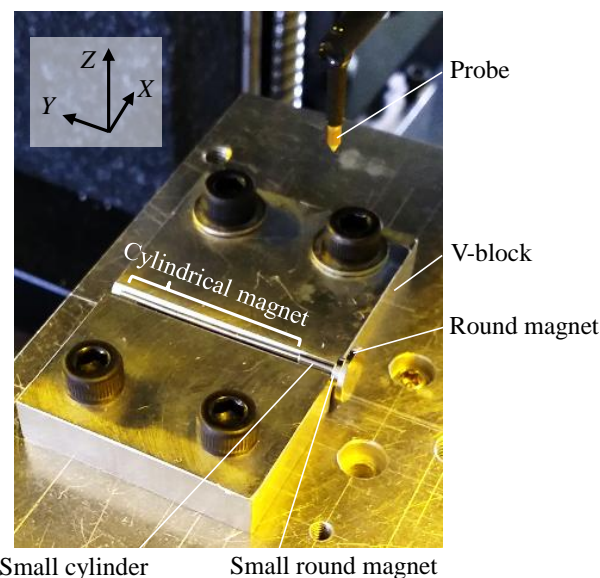


Figure 18. A photograph of the setup with a small magnet.

Figure 19 shows the results of the stitching operation of the neighboring two arcs, and the cross-correlation coefficients obtained in the series of stitching operations are summarized in Figure 20. The relationship between Arc8 and Arc1 after the stitching operations is also indicated in Figure 21. The mean value of the obtained cross-correlation coefficients was evaluated to be 0.81; this value is much higher than the maximum value (0.58) observed in the previous study by the authors' group [16]. Figure 22a shows the circumferential profile of the workpiece obtained through the stitching operations. Figure 22b shows the circumferential profile shown in Figure 22a after the simple filtration by a low-pass filter

with a cut-off frequency expressed in terms of undulations per revolution (upr) of 50. The diameter and out-of-roundness of the workpiece evaluated from the obtained circumferential profile are summarized in Table 2. The evaluated values of the diameter and out-of-roundness were found to be almost identical to those indicated in the specification sheet of the workpiece (diameter: 1.50 mm, out-of-roundness: <0.15 μm).

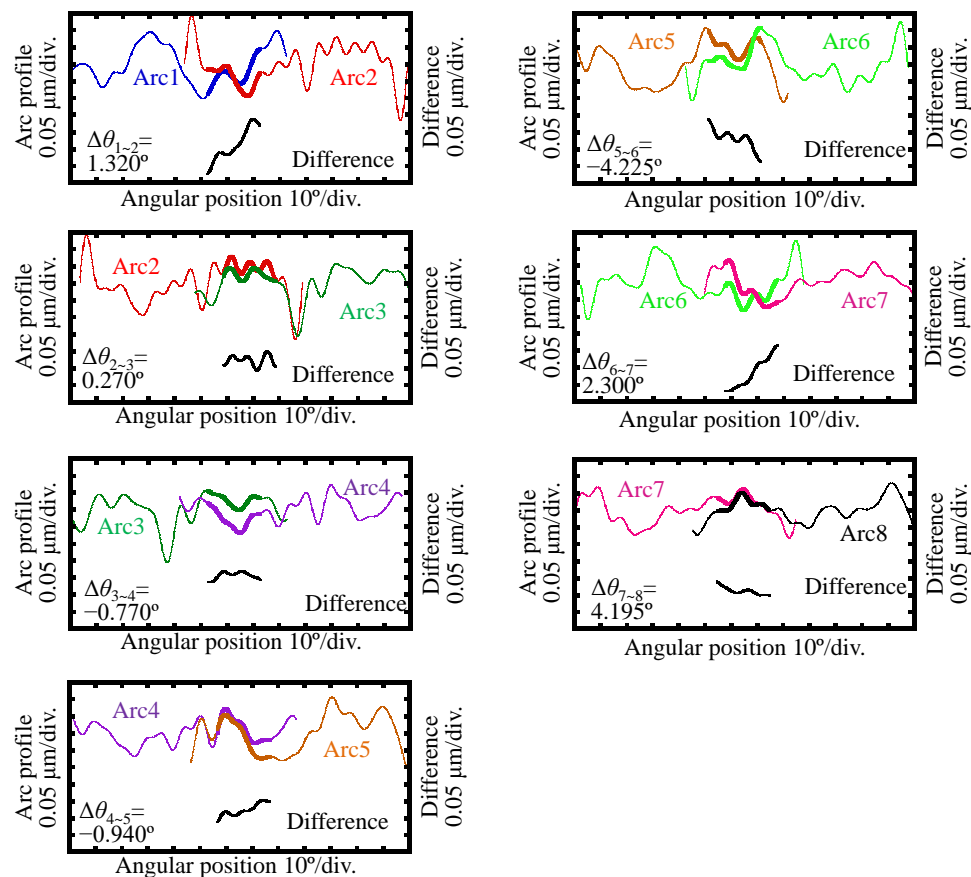


Figure 19. Stitched neighboring arc-profiles from the eight arc-profiles obtained by measuring the workpiece with a diameter of 1.5 mm.

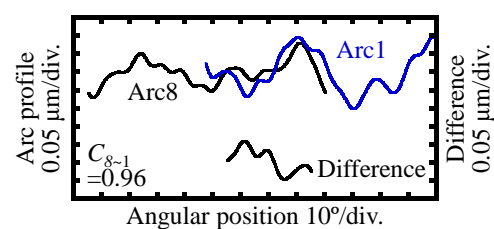


Figure 20. Relationship between Arc8 and Arc1 after the stitching operations.

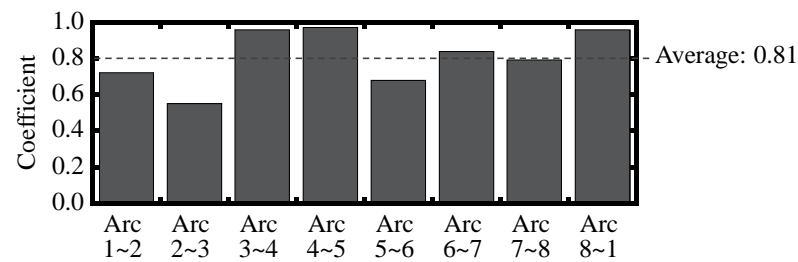


Figure 21. Cross-correlation coefficients observed in the stitching operations of the arc-profiles obtained by measuring the workpiece with a diameter of 1.5 mm.

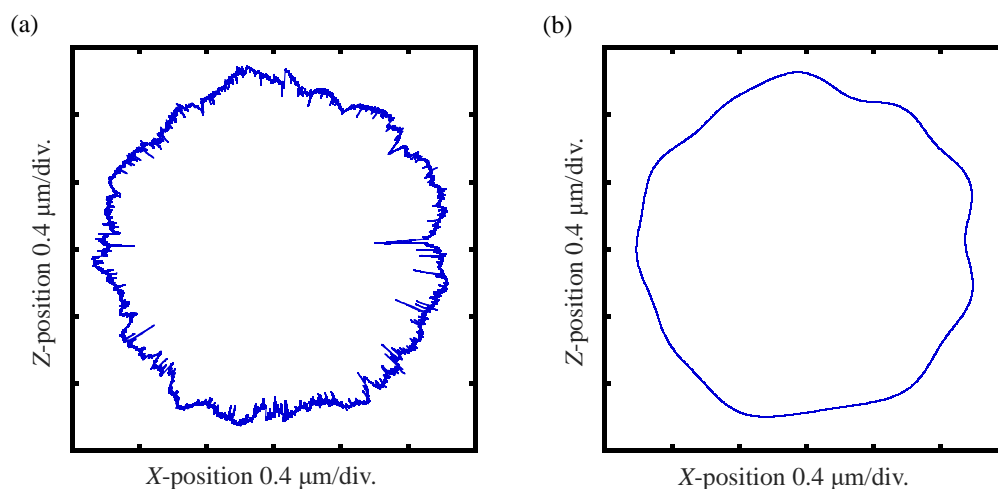


Figure 22. The circumferential profile of the workpiece obtained through the stitching operation: (a) Before the filtering process; (b) After the filtering process.

Table 2. The diameter and out-of-roundness of the workpiece evaluated from the circumferential profile obtained by the stitching linear-scan method.

	Diameter	Out-of-Roundness
Nominal value	1.500 mm	<0.15 μm
Measured value	1.497 mm	0.12 μm

4. Discussion

The experimental results described above demonstrate the feasibility of the elimination of the edge part of an arc in the stitching process for the improvement of a cross-correlation coefficient. The modified workpiece-holding mechanism was also found to be effective in improving the quality of stitching between two neighboring arcs in the stitching linear-scan method. Meanwhile, cross-correlation coefficients were found to become smaller with the decrease in the workpiece diameter. The increase in the pressure angle of the stylus in the linear-scan surface profiler due to the decrease in the workpiece diameter is one of the main root causes of the degradation of the cross-correlation coefficients. The pressure angle α of the stylus can be represented by the following equation:

$$\alpha = \arcsin \sqrt{1 - \left(\frac{x}{r}\right)^2} \quad (2)$$

where r is the workpiece radius. As can be seen in the above equation, the decrease in the workpiece diameter increases the pressure angle of the stylus even though the same X-directional position on a workpiece surface is measured. Figure 23a,b summarize

the differences in two neighboring arc-profiles in the overlapping regions obtained by measuring workpieces with diameters of 3.0 mm and 1.5 mm, respectively (shown in Figures 10 and 19). As can be seen in the figures, the well-matched region was found to become narrower with the decrease in the workpiece diameter. Although the increase in the eliminating region of the edge part of an arc-profile in the stitching process is expected to improve the cross-correlation coefficient, too much data elimination in an arc-profile could result in the degradation of the accuracy of stitching. It is, therefore, necessary to optimize the measurement conditions by the measurement uncertainty analysis based on GUM [21], while considering the number of arcs to reconstruct a whole circumferential profile, the eliminating region of the edge part of an arc-profile in the stitching process, as well as the measurement throughput.

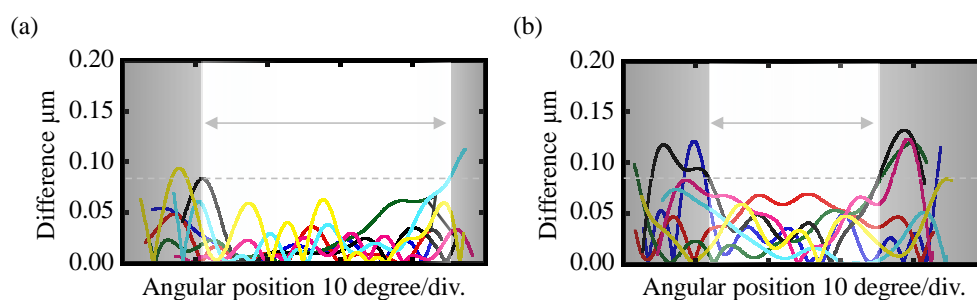


Figure 23. Differences of two neighboring arc-profiles in the overlapped regions obtained by measuring workpieces: (a) With a diameter of 3.0 mm; (b) With a diameter of 1.5 mm.

5. Conclusions

For the accuracy improvement of the circumferential stitching in the stitching linear-scan method, an attempt has been made to eliminate the data at the edge regions of the arc-profiles in the circumferential stitching process. With a small cylindrical workpiece having a diameter of 3.0 mm, experiments based on the stitching linear-scan method have been carried out. Experimental results have demonstrated that the elimination of the edge part in an arc-profile, where the influence of the pressure angle of the measurement probe in the linear-scan stylus profiler on the measured profile becomes significant, is effective in improving the cross-correlation coefficient of the stitched arc-profiles in the stitching operation. A hardware modification has also been made to the workpiece-holding mechanism in the setup for the stitching linear-scan method. A small round magnet has newly been inserted between the round magnet with the index mark and the workpiece to reduce the influences of the out-of-roundness of the round magnet surface and the side face of the workpiece holder by reducing the contact area between them. Experimental results have demonstrated that the hardware modification is effective in further improving the cross-correlation coefficient in the stitching operation. Experiments have also been extended to evaluate the workpiece having a diameter and a length of 1.5 mm and 5.8 mm, respectively, that cannot have been evaluated by the conventional rotary-scan method. From the whole circumferential profile of the workpiece obtained based on the stitching linear-scan method with improved stitching quality, the diameter and out-of-roundness of the workpiece have successfully been evaluated quantitatively.

It should be noted that, in this paper, attention has been paid to improving the quality of stitching in the stitching linear-scan method. The comparative tests involving the measurement of roundness deviations of a series of cylinders with the reference method, as well as the harmonic analysis of the profile of a workpiece obtained by the stitching linear-scan method, remain to be addressed, and will be investigated in future work. A comprehensive comparison between the stitching linear-scan method and the conventional rotary-scan method for the clarification of the upper limit of the advantageous workpiece diameter will also be carried out in future work.

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