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# Experimental Study of Both-Sides Cylindrical Roller Machining Based on Ceramic Plate

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**Abstract:** In order to improve the accuracy and batch consistency of cylindrical roller machining, in this paper, a both-sides cylindrical roller machining method based on hard ceramic plate is proposed. Traditional cast iron and stainless-steel polishing plate were replaced by ceramic materials with high hardness and good wear resistance. After processing by centerless grinding, the cylindrical roller is processed by both-sides lapping and polishing using $Al_2O_3$ ceramic plates. The roundness, diameter and surface quality of the roller and the wear of the ceramic plate before and after machining were compared and analyzed in order to evaluate the feasibility and effectiveness of this method. After grinding for 1 h and polishing for 8 h, the average roundness of the cylindrical rollers decreased from the initial 2.3 µm to 0.32 µm, while the roundness of each roller tended to be the same. At the same time, the batch diameter deviation of cylindrical rollers was reduced from 3 µm to 1 µm, and the batch consistency was satisfactory. The machining marks produced by centerless grinding on the roller surface were completely removed, and the surface quality was significantly improved. The surface roughness after polishing reached Ra 16 nm. The upper and lower ceramic plate had certain wear, but the amount was small, having little impact on the machining results. The shape accuracy and batch consistency of the rollers after machining were satisfactory. The ceramic plate had high hardness, good wear resistance and small wear in the machining process. Additionally, it could maintain extremely high flatness for a long time. Using hard ceramic plates to process cylindrical rollers, high precision and high consistency cylindrical rollers can be obtained after machining.

**Keywords:** cylindrical roller; both-sides; ceramic plate; roundness; wear; consistency

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## 1. Introduction

Bearings are important precision components in the high-end equipment manufacturing industry, and are known as the "heart" of equipment manufacturing. The performance of bearings plays a vital role in the performance, life and reliability of equipment and related products [1–4]. As a key part of precision bearing, the machining accuracy and consistency of the rolling body will directly affect the performance and service life of bearings [5]. Cylindrical roller bearings are suitable for high speed and heavy load equipment—e.g., high-speed trains, wind turbines, machine tool spindles, etc.—because the rolling body and raceway are in contact with each other [6–8].

At present, centerless grinding and centerless superfinishing are the most important finishing methods for the mass production of cylindrical rollers [9]. Centerless grinding has the advantages of high production efficiency and easy automation. However, machining accuracy depends heavily on the relative position and speed error of the grinding wheel, guide wheel and workpiece. When the grinding wheel and other parts undergo wear, it is difficult to ensure the machining quality and accuracy, and batch consistency is poor [10,11]. Centerless superfinishing is sometimes performed after centerless grinding; it also has high production efficiency. Under the action of oilstone, cylindrical rollers can obtain better surface quality and shape accuracy. However, the oilstone is consumed quickly, the selection is cumbersome in machining and the front and rear guide rollers need to be trimmed to maintain high accuracy requirements. In summary, parts that wear easily affect machining accuracy and consistency [12,13].

Flat/both-sides polishing technology has been widely used in the ultra-precision machining of various materials. After machining, excellent shape accuracy and surface quality of a workpiece can be achieved [14–19]. For example, with silicon wafer, sapphire, quartz glass and other flat substrates, the machined flatness can be less than 0.2 µm and the surface roughness less than 1 nm [20,21]. In view of the aforementioned problems, combined with the characteristics of flat machining, some scholars have applied both-sides lapping and polishing technology to the precision machining of cylindrical rollers. By establishing a cylindrical surface machining system and analyzing the geometric kinematic model of the workpiece, it was found that the wear track of the polishing plate uniformly envelopes the cylindrical surface. Additionally, nano level removal of the material was realized in the form of multi-edge and multi-directional cutting with ultra-fine abrasive particles, thereby ensuring high shape accuracy, high surface quality and high batch consistency. After machining, the average roundness of a batch of cylindrical rollers reached 0.36 µm, the deviation reached 0.13 µm and the minimum roundness of a single workpiece was 0.295 µm [22–26].

## 2. Machining Principle

### *2.1. Characteristics of Ceramic Plate*

In this study, the polishing plates for both-sides cylindrical roller machining based on a hard ceramic plate, traditionally made of cast iron, stainless steel or bearing steel, were replaced by various ceramic materials (alumina, zirconia, silicon carbide and other materials). Ceramic materials have the characteristics of high hardness and good wear resistance [27,28]. Alumina ($Al_2O_3$), for example, has a Rockwell hardness of HRA80-90, which is second only to diamond and 10 times that of ball-milled cast iron [29]. The polishing plate has high hardness, which can ensure that the plate surface will not be deformed during machining. The cylindrical roller contour after machining reproduces the surface shape of the polishing plate, ensuring excellent roundness. The wear resistance of $Al_2O_3$ is 266 times that of manganese steel and 171 times that of high chromium cast iron [30]. With good wear resistance, the plate surface can maintain excellent flatness for a long time, thus ensuring that the cylindrical roller has high accuracy and consistency.

The surface of the ceramic plate that has not been polished into a mirror surface is covered with micro convex peaks. These hard peaks can be regarded as tiny blades which can replace abrasive particles to remove material from the cylindrical roller.

### *2.2. Both-Sides Machining Method*

The proposed both-sides machining device is shown in Figure 1. Figure 1a is structure diagram of machining device, which is mainly composed of upper and lower ceramic plates, a retainer and a squeeze head. The cylindrical rollers are placed in the retainer between the upper and lower ceramic plates. The lower ceramic plate is rotated by the motor, and the retainer is coaxial with the upper ceramic plate. The upper ceramic plate rotates with the friction force of the cylindrical roller, and the cylindrical roller performs a sliding and rolling motion during machining. The load is transmitted to the whole machining system by the squeeze head; the eccentric distance between the upper and lower plates can be changed by adjusting the position of the squeeze head. During machining, the ceramic plates must have an excellent flatness (i.e., less than 0.3 µm) to ensure that the machined cylindrical rollers have satisfactory roundness and consistency.

Figure 1b shows a schematic diagram of the both-sides machining principle, which can be divided into three stages. In the initial stage, the batch consistency is poor, with only cylindrical rollers with large diameter or high points coming into contact with the upper and lower plates, resulting in material removal. In the second stage, the cylindrical rollers with larger diameters or high points are gradually removed, the diameters of the rollers between the upper and lower ceramic plates tend to be the same, and all cylindrical rollers are in contact with the upper and lower ceramic plates. In the third stage, when the diameters of all cylindrical rollers are the same, the ceramic plates remove a small amount of material from the surface of the rollers, yielding a product with high precision and high consistency.

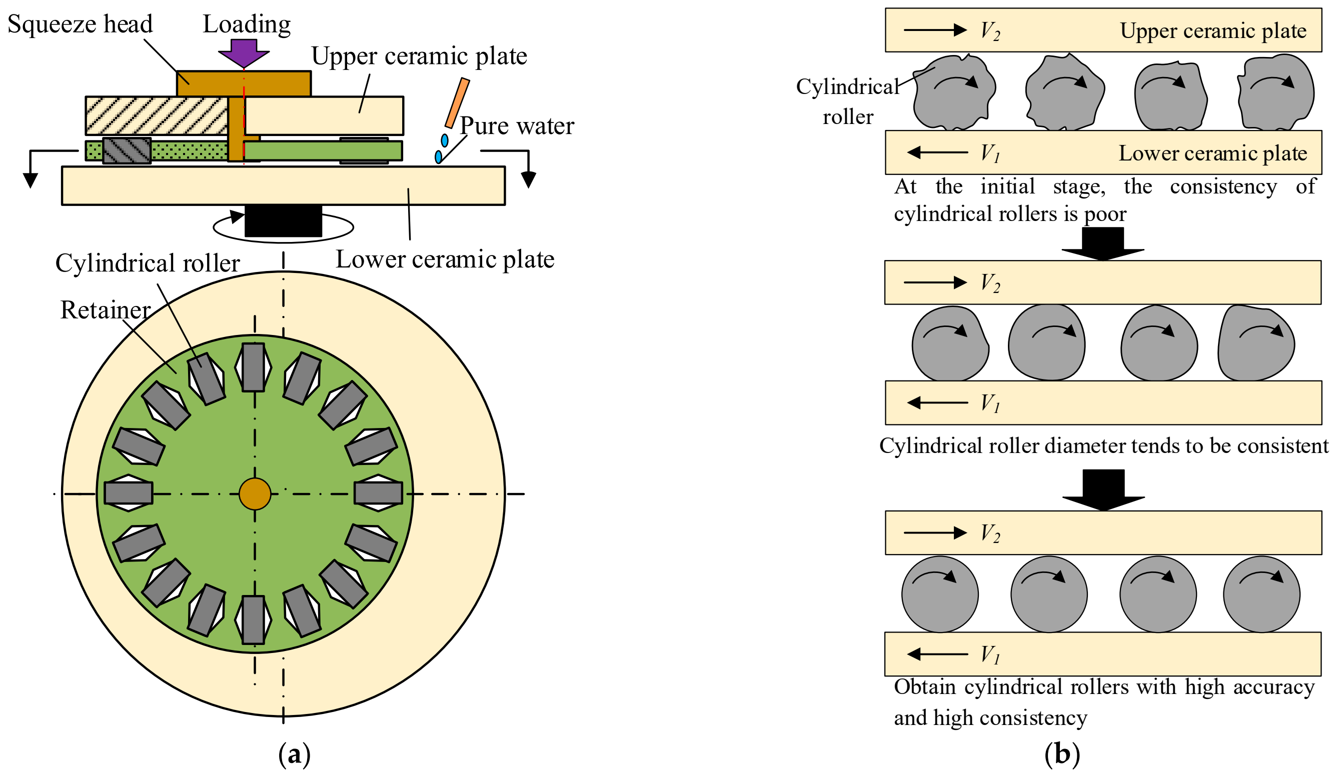



**Figure 1.** Both-sides cylindrical roller machining method based on hard ceramic plate: (**a**) Structure diagram of machining device; (**b**) Schematic diagram of machining principle.

## 3. Experiment

### *3.1. Experimental Device*

The machining equipment used in the experiment was a self-developed both-sides lapping and polishing machine, as shown in Figure 2. $Al_2O_3$ ceramics were used as the upper and lower polishing plates, and cylindrical rollers were placed between the upper and lower ceramic plates. Figure 3a,b show the initial surface shape of the upper and lower ceramic plates, respectively. The diameter of the upper ceramic plate was 180 mm and the flatness PV was 0.235 μm, while the diameter of the lower ceramic plate was 240 mm and the flatness PV was 0.261 μm. The surface roughness of the ceramic plate should not be too large or too small; if it is too large, the flatness of the plate does not meet the requirements, and if it is too small, the surface of the plate is too smooth, reducing the friction and exerting a cutting effect on the roller and reducing the material removal rate. When the surface roughness was between Ra 20–50 nm, the surface of the ceramic plate was relatively smooth but was nonetheless covered with micro convex peaks. When the cylindrical rollers roll and slide on the surface of these micro convex peaks, the micro convex peaks can be regarded as hard, micro blades which remove the material from the roller surface.

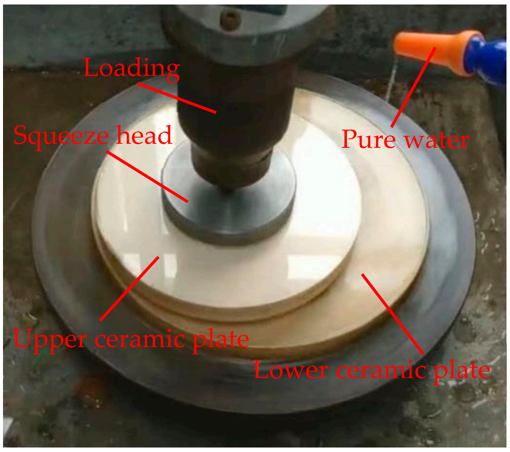



**Figure 2.** Image of both-sides cylindrical roller machining setup.

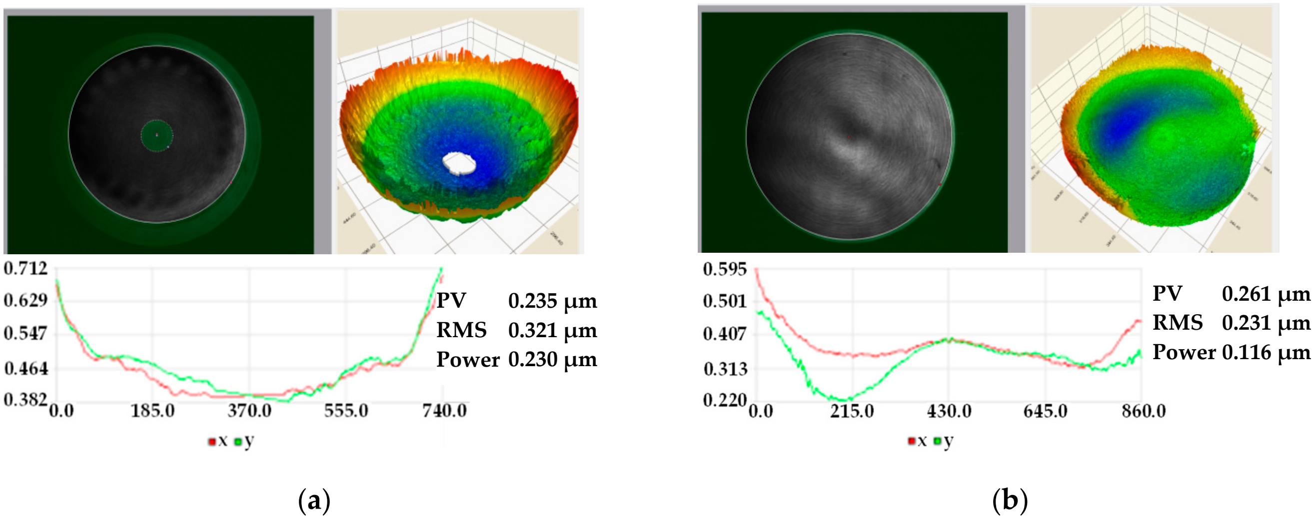



**Figure 3.** Initial shape of ceramic plates: (**a**) Initial shape of upper ceramic plate; (**b**) Initial shape of lower ceramic plate.

*3.2. Experimental Scheme*

To verify the feasibility and effectiveness of the proposed machining method, a bearing steel cylindrical roller (ϕ6.5 × 10 mm), finished by centerless grinding, was taken as the experimental machining object. The roundness was measured using a Taylor Hopson 565 roundness meter, the surface roughness was measured with a Mitutoyo SJ410 roughness meter and the diameter was measured with a micrometer. Twenty-seven cylindrical rollers from the same batch were randomly selected for measurement. Three different roller surfaces were measured and the average value was taken as the surface roughness. The roundness and diameter were measured at both ends and the middle of each roller, and the average value were taken as the roundness and diameter. The initial average surface roughness was about Ra 50 nm and the initial average roundness was 2.3 µm. The roundness of the 27 cylindrical rollers varied greatly; values of 4–5 µm were considered poor, while 0.3 µm indicated good roundness. Combinations of these values indicated that the roundness consistency of the same batch machining by centerless grinding was poor; the data are shown in Figure 4. Figure 5 shows the diameter measurements of 27 cylindrical rollers; the measured diameter range was 6.497–6.5 mm, and the deviation of diameter reached 3 µm. The consistency was also poor.

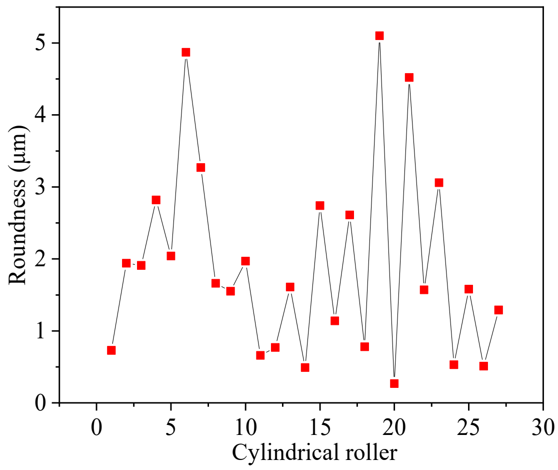



**Figure 4.** Initial roundness of cylindrical roller.

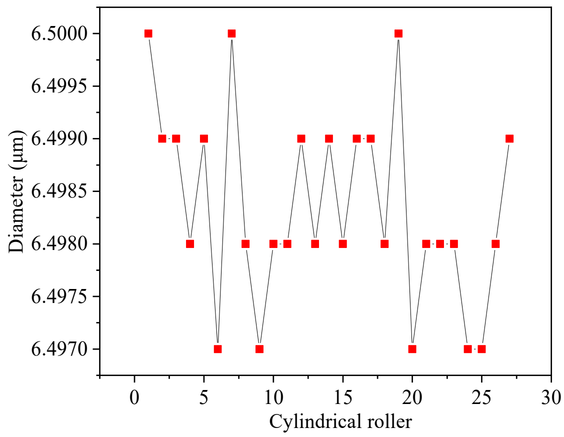



**Figure 5.** Initial diameter of cylindrical roller.

In the machining process, the eccentricity of the axis of the upper and lower ceramic plates was set to 3 cm, the rotation speed of the lower ceramic plate was set to 60 rpm and the machining load was the weight of the upper ceramic plate. Since the initial roundness and diameter of the cylindrical roller varied greatly, in order to make the roundness and diameter of the cylindrical roller converge quickly, diamond was first used as an abrasive for 1 h. Then, the ceramic plates were cleaned and polished. The purpose of lapping was to quickly trim the shape and dimensional accuracy of the cylindrical rollers, while the purpose of polishing was to improve the shape accuracy and surface quality. The cylindrical rollers were reversed every 30 min. The experimental conditions are shown in Table 1.

**Table 1.** Experimental condition.

| Parameter | Parameter Data |
|---|---|
| Workpiece material | GCr15 Bearing Steel |
| Workpiece size | Φ6.5 mm × 10 mm |
| Lapping abrasive | W2.5 diamond (wt.10%) |
| Polishing slurry | Pure water |
| Eccentricity | 3 cm |
| Polishing plate speed | 60 rpm |
| Machining load | Weight of ceramic plate |

## 4. Results and Discussion

### *4.1. Shape and Dimensional Accuracy*

Figure 6 shows the variation of the average roundness of the cylindrical roller with machining time, while Figure 7 shows the variation of the roundness of each cylindrical roller. After lapping for 1 h, the high points on the cylindrical roller surface were gradually removed, and the average roundness was reduced to 1.45 μm. After polishing with pure water for 0.5 h and 4 h, the average roundness was reduced to 1.05 μm and 0.39 μm, respectively. In the latter case, the roundness of the cylindrical rollers tended to be almost the same. Therefore, the material removal rate of polishing became small and the convergence speed of roundness was reduced. After polishing for 8 h, the average roundness only decreased to 0.32 μm. It can be seen from the figure that after machining, the initial irregularities in terms of the roundness of the cylindrical roller gradually diminished in scale. The machining accuracy was greatly improved and the consistency was excellent. The diameter of the machined cylindrical roller was found to be 6.486–6.487 mm, and the diameter deviation was reduced to 1 μm. The consistency was also greatly improved. Roundness measurements are shown in Figure 8.

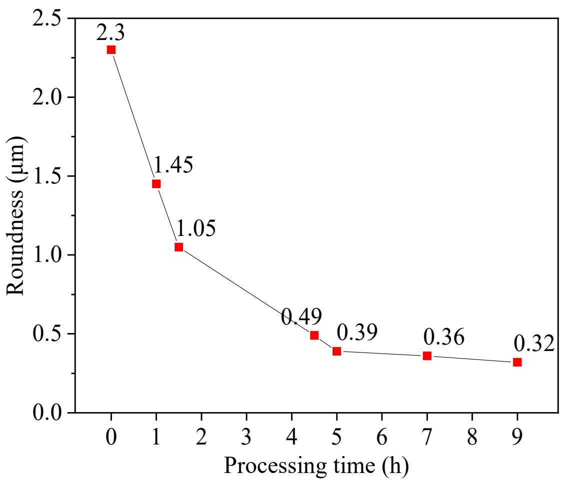



**Figure 6.** Variation of average roundness with machining time.

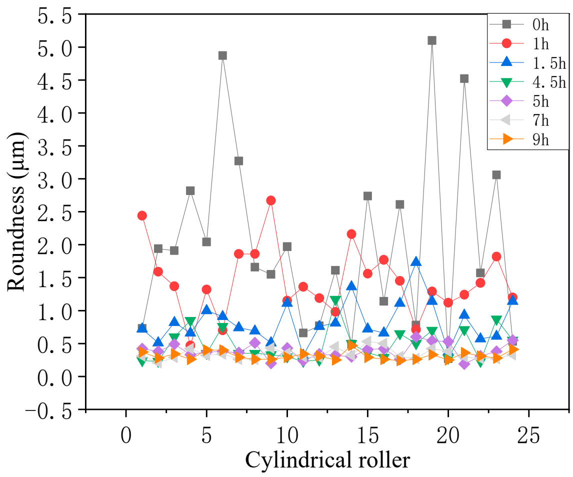



**Figure 7.** Variation of roundness of each roller with machining time.

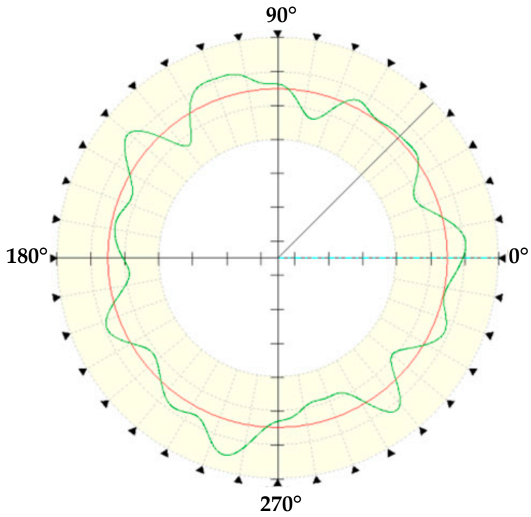



**Figure 8.** Cylindrical roller roundness measurements (0.18 μm).

### *4.2. Surface Quality*

Figure 9 comprises micrographs of a cylindrical roller surface before and after machining. The comparison shows that the surface quality before machining was poor, e.g., longitudinal machining marks generated by centerless grinding are very obvious. In the polishing process, the material on the roller surface was removed by the multi-directional micro blades on the surface of the ceramic plate. As a result, the machining marks were completely removed, and only some pits generated by the materials forming of the roller were left on the surface. As such, the surface quality was significantly improved, with the surface roughness after polishing reaching Ra 16 nm; see Figure 10.

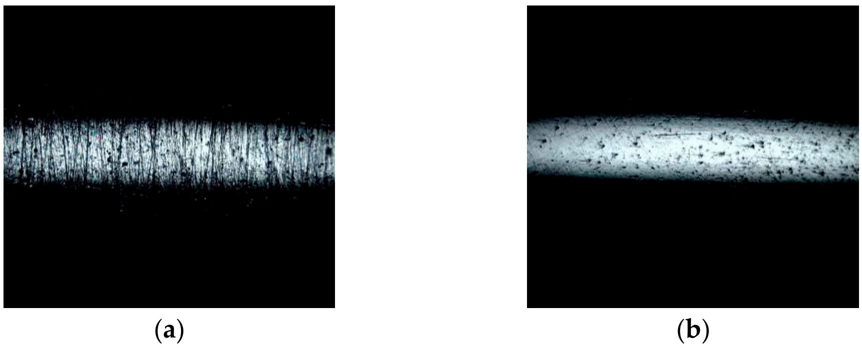



**Figure 9.** Micrograph of workpiece surface before (**a**) and after (**b**) machining.

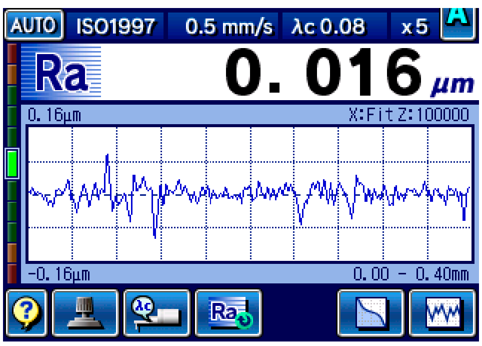
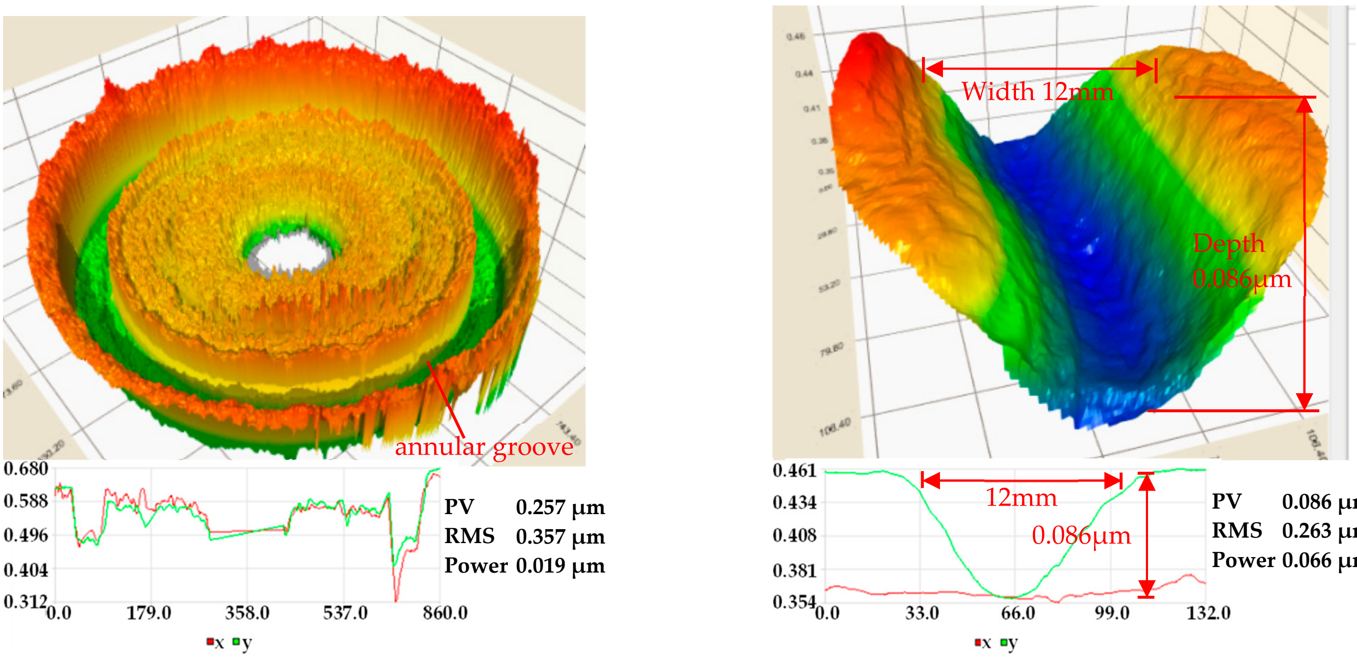



**Figure 10.** Surface roughness measurements.

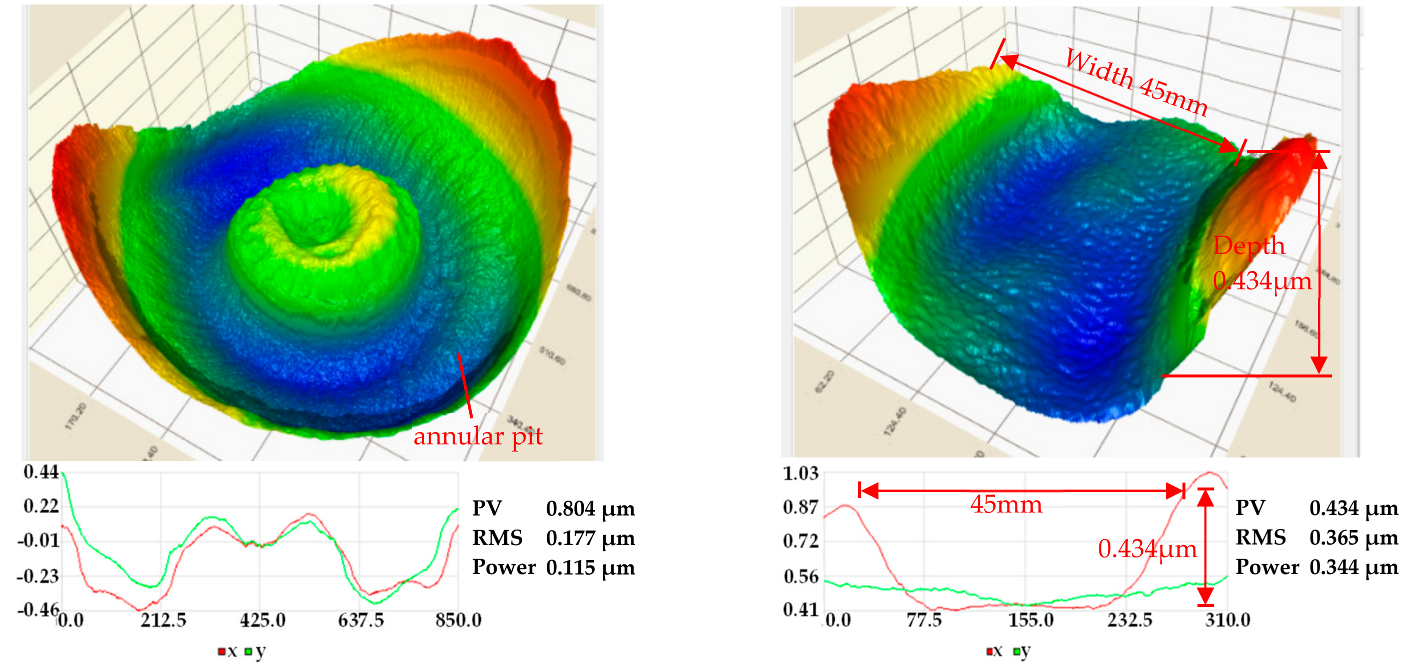
### 4.3. Wear of Ceramic Plate

Figure 11 shows the surface morphology and flatness of the upper ceramic plate. After machining for 9 h, a ring band groove was ground, changing the flatness PV from 0.235 µm to 0.257 µm. According to our measurement of the annular groove, as shown in Figure 11b, the wear depth was about 0.086 µm and the width was about 12 mm. The wear width was slightly larger than the length of the roller. This was attributed to the gap between the retainer and the rollers. The two ends of the roller had small arc chamfers. It was found that the morphology of the grooves produced by wear on the ceramic plate was deep in the middle and shallow at both ends, coinciding with the generatrix of the roller. Figure 12 shows the surface morphology and flatness of the lower ceramic plate. A ring band pit was formed, and the flatness PV ranged from 0.261 µm to 0.804 µm. By measuring the pits, it was found that, as shown in Figure 12b, the pit (wear) depth was about 0.434 µm, which was significantly larger than that of the upper ceramic plate. This was because the cylindrical roller experienced both rolling and sliding friction with the lower ceramic plate, but only rolling friction with the upper plate. The pit width was about 45 mm, due to the 30-mm eccentricity between the upper and lower ceramic plates. The amount of wear on the upper and lower plates was largely negligible. By analyzing the morphology of the wear area, it could be seen that the wear surface was very smooth, i.e., flatness was maintained. The height difference between the highest and lowest points of the wear area on the lower ceramic plate was only about 0.1 µm, and as such, this had little impact on the machining results. It was therefore concluded that excellent shape accuracy and batch consistency could be obtained, even when the cylindrical roller came into contact with wear areas.




(**a**) (**b**)

**Figure 11.** Surface morphology and flatness of upper ceramic plate: (**a**) Morphology and flatness of the whole plate (wear condition); (**b**) Morphology and flatness of annular groove (wear condition).




(**a**) (**b**)

**Figure 12.** Surface morphology and flatness of lower ceramic plate: (**a**) Morphology and flatness of the whole plate (wear condition); (**b**) Morphology and flatness of annular pit (wear condition).

## 5. Conclusions

A both-sides cylindrical roller machining method using a hard ceramic plate was developed and experiments were carried out. The experimental results showed that the batch average roundness and diameter of cylindrical rollers reached 0.32 um and 1 µm, respectively. As such, the machining accuracy and consistency were greatly improved. Meanwhile, the machining marks generated by centerless grinding were removed, the surface quality of the cylindrical roller was improved, and the surface roughness after polishing reached Ra 16 nm. On the other hand, the ceramic plate showed good wear resistance, and it is expected that it would maintain excellent flatness for a long time. Therefore, consistently high quality cylindrical rollers could be obtained by the proposed both-sides machining technique.

**Author Contributions:** Conceptualization, T.Z. and K.F.; methodology, J.Y.; validation, B.L., X.H. and X.L.; investigation and data curation, J.D.; writing—original draft preparation, and writing—review and editing, T.Z.; supervision, X.L.; project administration, J.Y. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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