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Novel method and device to minimize the high-order roundness error of large cylindrical rotors

Mikael Miettinen[1], Raine Viitala[1], Heikki Kettunen[2]

[1]*Aalto-University,* [2]*Valmet Technologies Oy*

mikael.miettinen@aalto.fi

Abstract

Large cylindrical rotors are used in continuous manufacturing processes to form sheet-like materials, such as steel, non-ferrous metals, cardboard and paper. Runout and roundness of these rotors directly affect the process reliability and quality of the end product. In reconditioning process the rotors are ground to remove wear and damage induced by the continuous manufacturing process. A periodic waviness error is a common wear pattern present in the roundness profile of a rotor. These undulations become problematic at few micrometer amplitude and lead to vibrations in the machinery.

A tool was developed to grind the rotor to a minimal roundness error, while removing minimal quantity of material from the rotor surface. The tool consists of a curved contact face that has equal radius to the rotor. The working principle of the tool is that the 300mm long contact face touches only at the undulation peaks of the runout profile, thus removing the material from the high spots. The large contact area additionally has elastic averaging effect, as the contact pressure is highest at the contact points on the undulation peaks.

A test rotor with 800mm diameter and 1800mm length was prepared by grinding an error profile at 33rd harmonic, meaning 33 undulations in the profile. The amplitude of the ground initial error was 10.6 µm. The rotor was ground using a free belt grinding tool and the developed grinding tool and the runout profile was measured periodically. The grinding was continued until the runout amplitudes did not reduce.

The results show that using the developed tool, the errors at 33rd harmonic amplitude can be removed almost completely. However, while using a free belt grinding, 1.4 µm amplitude undulation was left to the rotor surface. The developed tool had also a positive effect on improving the roundness at low harmonics, reducing the errors at 2nd harmonic significantly. The developed tool performed substantially better in reducing the roundness error than the free belt grinding method.

Grinding, roundness, runout, rotor, manufacturing

1. Introduction

Large cylindrical rotors are used in various manufacturing processes. For example, in paper and steel industry, the end product is formed using these large rotors. The product material is formed by compressing it between a pair of rotors. Thus the geometrical properties of these rotors have a substantial effect on the end product quality. However, it is challenging to manufacture the rotors to meet the required tolerances.

Manufacturing inaccuracies in the production of rotors, wear and damage during the operation results in geometrical errors, such as roundness errors. These geometrical errors lead to vibration in rotating machinery and cause undesired thickness variations in the produced goods. Thus, minimal runout is desirable as it improves the runnability of the manufacturing process and the quality of the end product.

In cylindrical rotor manufacturing process, the rotor surface is typically ground with a rotating wheel and finished with an abrasive belt grinding (superfinishing) to improve the surface finish. During operation, the rotors are periodically reground to remove surface defects and reduce runout errors resulting from operation. Changing and regrinding of the rotors are done on scheduled intervals or when the vibration levels in the machine increase over a critical threshold.

In the present study a novel method for grinding cylindrical rotors to minimal runout is experimentally investigated. The method targets the regrinding of polymer covered rotors as part of the maintenance process. The main purpose of the tool is to reduce the high-order periodic undulations present in the roundness profile, which is a common wear type in the rotors in question. Preferably, this grinding process should remove minimal amount of material to allow as many as possible regrounds.

The developed method uses a curved tool to contact the rotor cover on large surface area instead of line contact used in conventional methods where the rotating grinding wheel is used. This study compares the developed grinding tool against free-belt grinding, where also a large surface area contact is achieved. The methods were compared by measuring the residual runout profiles after grinding with each method.

2. Materials and Methods

2.1. Roundness and runout

Roundness is a measure of how close a measured cross section is to a mathematically perfect circle. Runout is the radial error in a cylindrical part (Figure 1). Runout is a sum of roundness error and movement of the rotation axis.

In present study the rotor is assumed rigid. For rigid rotors, runout is caused by the roundness error of the rotor surface and the error motion in the bearings. Assuming rigid rotation is valid as the diameter to length ratio for the rotor is high. Diameter of the rotor is 800 mm and the length of the rotor measured between bearing surfaces is 1800 mm. The rotor is rotating relatively slowly at 20 rpm, so dynamic runout can be assumed insignificant in the measurements.

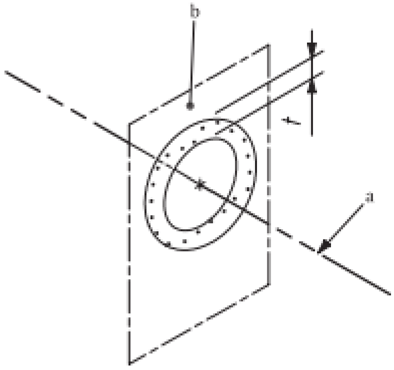

Figure 1. Runout measurement. Here the total indicated runout t is measured in cross-section plane b about the rotation axis a.[1]

2.2. Grinding tools

In grinding processes chips are removed by multiple abrasive grains, in comparison to machining tools where chip formation happens with clearly defined cutting edges. The abrasive degrades during use by releasing the dull abrasive grains from the binder and exposes fresh grains to continue the cutting action. The material removal by multiple cutting edges has an averaging effect that leaves good surface finish on the workpiece.[2]

Grinding and chip formation have been studied in depth by Denkena, Köhler and Kästner [3]. Brinksmeier et al. [4] present ultra-precision grinding methods used in various industries. Current systems in cylindrical rotor grinding include advanced measurement and control systems to determine the runout and roundness profiles of the rotor and compensate for the errors in the process allowing accurate grinding of flexible rotors [5].

Defining feature of the developed grinding tool was arc shaped contact area matching the curvature of the rotor surface. The tool was manufactured from PE 1000 plastic. The contact face on the developed tool is 300 mm long. Conventionally used methods have line contact between the abrasive wheel and the rotor surface. The only degree of freedom of the developed tool is in the radial direction of the rotor, and it is pressed into contact with constant pressure by a pneumatic actuator. The tool will only contact the rotor cover at the highest undulation peaks in the rotor surface (Figure 2). This leads to grinding of the cover material at the current peak areas and to averaging of the rotor surface towards minimal runout situation.

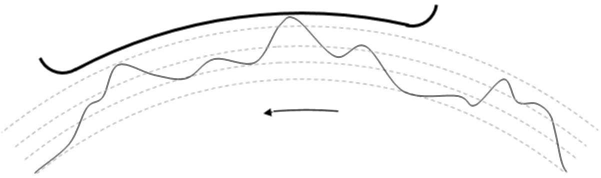

Figure 2. The grinding tool contacts only on the highest peak under its contact face. This averages down the highest runout peaks until uniform runout is reached at the point of lowest runout point.

In free belt grinding the developed tool was removed from the machine and only the guide rolls were used to support the abrasive film backed with a processing belt (Figure 3). Habasit HAB-12E –processing belt was used. The belt was used to support the abrasive film and prevent it from stretching or tearing during the grinding process. The Contact length between the abrasive and rotor was 270 mm in free belt grinding.

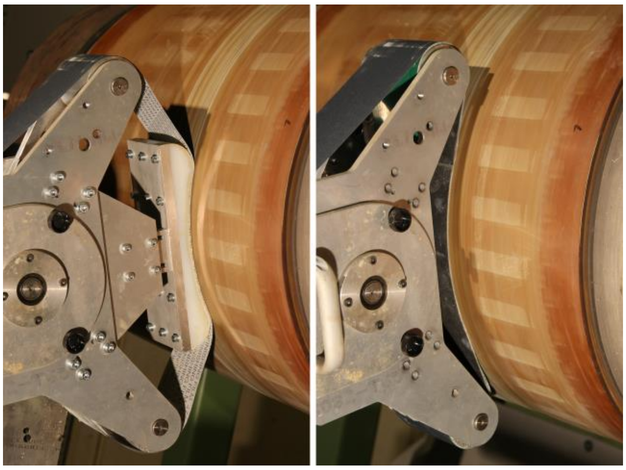

Figure 3. Developed grinding tool (left) and free belt grinding (right). On the test rotor surface there are marks left from grinding the initial runout error.

2.3. Measurement setup

The experimental measurement setup consisted of a large cylindrical rotor supported on roller bearings (Figure 4). The test rotor was made out of steel and was covered with polymer coating. The tool stand for the interchangeable grinding tools was mounted on a servo axis allowing linear motion along the rotor length. The tools can be pressed against the rotor surface with a pneumatic actuator. The developed tool was aligned to the rotor by pressing it against the rotor cover while the attaching fasteners were tightened. The contact face was ground to equivalent radius of the rotor surface before use.

The measurement setup includes a Heidenhain MT-12 incremental length gauge with 0.2 µm measurement uncertainty to measure the runout of the rotor. The length gauge was rigidly attached to the frame of the rotor support by using a magnetic indicator stand. Stegmann DG60 rotational encoder attached to the end of the rotor was used to trigger the measurements. The encoder has resolution of 2500 pulses per revolution. The measurement data was collected by using Heidenhain EIB700 evaluation device and a pc.

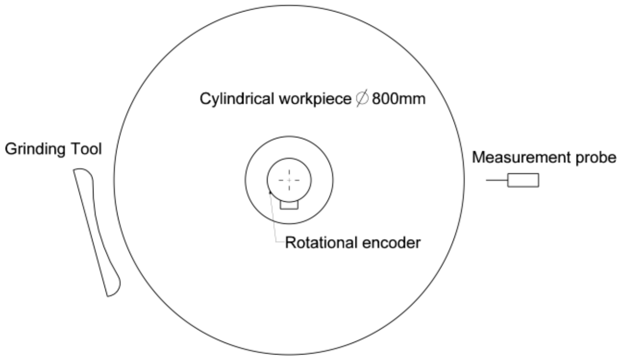

Figure 4. Grinding and measurement setup. Grinding tool is pressed against the cylinder with constant force from a pneumatic actuator.

2.4. Measurement procedure

Measurements were conducted by following procedure:

1. Initial error was ground to the rotor using a voice coil controlled grinding head at 11 µm amplitude repeating at 33rd harmonic.
2. Grinding setup was changed to a free belt.
3. Free belt grinding.
4. Runout measurement.
5. Steps 3 and 4 were repeated until there was no decrease in runout amplitudes.
6. Grinding setup was changed to developed tool.
7. Grinding with the developed tool.
8. Runout measurement.
9. Steps 7 and 8 were repeated until there was no decrease in the runout amplitudes.

In all grinding operations 3M 472L -abrasive film with 40 Micron abrasive size was used. Each runout measurement consisted of 5 measured revolutions of the rotor.

2.5. Analysis methods

Time synchronous averaging (TSA) is a popular method in vibration analysis of rotation components and machinery. TSA requires a periodic and steady state system. The system is measured over multiple revolution periods using a trigger signal which is phase locked to the rotation of the rotor. The measured data is averaged over the periods into single representative period. By using TSA, random noise is attenuated while the periodic components of the signal stay unchanged.[6, 7]

In the present study rotational encoder with 2500 pulses per revolution was used to trigger the runout measurement. With phase locked measurement points, the effects of rotation speed fluctuations can be negated and TSA assumptions are valid. For each measurements, 5 measured revolutions of the rotor were used for the TSA calculation.

Fourier analysis allows the separation of individual frequency components from a time domain signal. It is based on representing time domain signals as infinite sum of sinusoidal waves in frequency domain. Each sinusoidal component represents a frequency present in the signal with some amplitude and phase shift. Fast Fourier Transform (FFT) is algorithm to calculate the Discrete Fourier Transform (DFT) originally presented by Cooley and Tukey [8].

Matlab FFT-function based on the improvements of Frigo and Johnson [9] was used to calculate the FFT for measurement data. Frequency domain runout data is normalized with respect to the rotation frequency of the rotor. Normalization transforms the runout data into harmonic domain. Harmonic domain components represent the amplitude of undulations repeating 1, 2, 3… N times in each revolution of the rotor. Harmonic domain representation is an intuitive way to show the results. Harmonic low pass filtering was used, terms higher than 400th harmonic were set to 0.

3. Results

The runout profiles are presented in polar coordinate systems showing the exaggerated profile of the rotor in various stages of the grinding. Harmonic domain figures show the amplitude of each component. The phase information is omitted because it has no significance in the present study. The Nth harmonic component represent runout variations occurring N times during the revolution of the rotor. Therefore, the angular period for Nth component is 360°/N.

The runout profile of the rotor in initial state and after grindings is presented in Figure 5. The initial state had a waviness error of 33 undulations with 10.6 µm amplitude and was also slightly oval 20.7 µm amplitude at the 2nd harmonic (Figure 6). After free belt grinding the runout amplitude was reduced to 1.4 µm while the 2nd harmonic was still at 11.3 µm (Figure 7). After grinding with the developed tool the initial error at 33rd harmonic had disappeared, and while 2nd harmonic was at 3.9 µm amplitude (Figure 8).

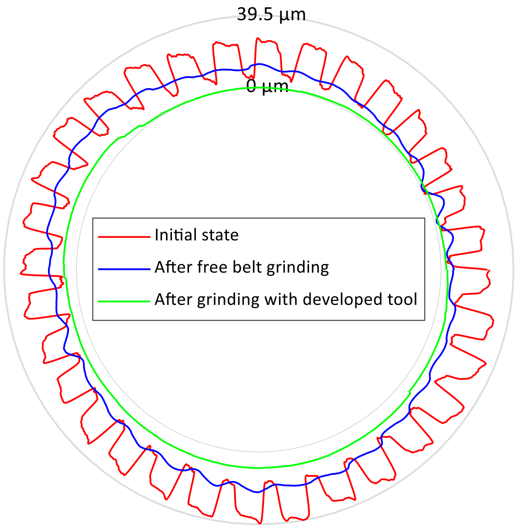

Figure 5. Runout profile during different phases of the study.

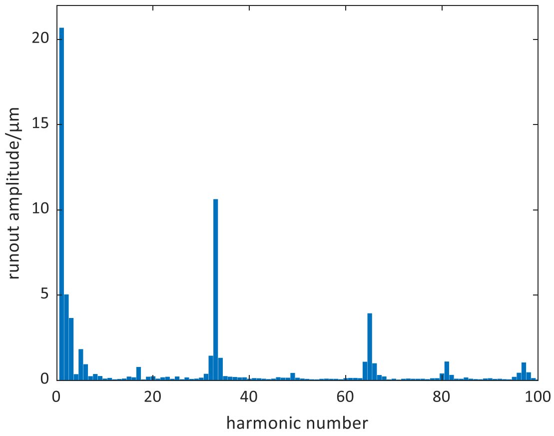

Figure 6. Initial state before grinding. Error was ground to the cylinder with 10.6 µm amplitude at 33rd harmonic. There was initial errors below 10th harmonic with 2nd harmonic being the largest at 20.7 µm amplitude.

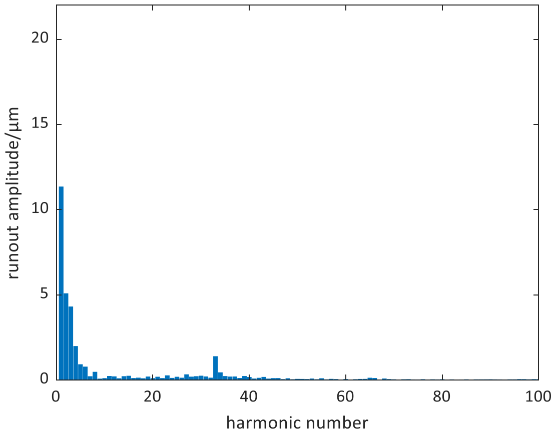

Figure 7. State after free belt grinding. Errors at higher harmonics decreased significantly, with only the main peak at 33rd harmonic. Low harmonic number errors are still present 11 µm amplitude.

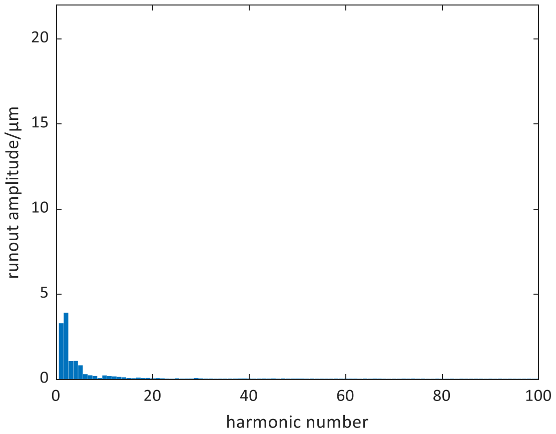

Figure 8. State after grinding with the developed tool. Errors have decreased to miniscule levels on higher harmonics, and low harmonics have decreased significantly from the initial and free belt grinding states.

4. Summary and discussion

The results indicate that grinding with the developed tool reduces the runout substantially compared to using a free-belt grinding method. The runout error at 33rd harmonic reduced from the initial 10.6 µm amplitude to 1.4 µm with free belt grinding and disappeared completely with the developed tool. The tool had positive effect on reducing errors at low harmonic numbers. For 2nd harmonic the initial runout amplitude was 20.7 µm, after free belt grinding the amplitude was 11.3 µm and after the developed tool the amplitude was 3.9 µm. Therefore the results suggest that the working principle of the developed tool is valid.

In the grinding experiments clogging of the abrasive film was problematic. Current setup did not have option to use coolant for flushing away the grinding dust and loose abrasive particles. The loose dust and particles filled the voids between the abrasive grains, preventing cutting action. The clogging was mitigated with proper selection of the rotor rotation speed and abrasive film feed rate. Heat generation becomes problematic with too high rotation speeds and the abrasive film and the rotor surface when there is no coolant used. In future studies, the grinding parameters should be optimized and coolant system should be added in order to increase the performance of the system. The parameters should include the rotation speed or the rotor, abrasive film type and feed rate. Also the mounting and positioning of the tool should be considered, as the aligning process used was quite tedious.

The arc length of the grinding tool should also be considered. Intuitively having a longer length increases the area over which the tool averages the contact with the rotor cover. Shorter tool has smaller contact area, which could help with the abrasive film clogging discussed earlier. Material elasticity is also important factor when the errors in question are on micrometer scale, the workpiece, tool and machine all deform under the load [10]. The tool face made of PE 1000 plastic and the rotor made of polymer are the least stiff parts of the system and will deform the most under the grinding loads. The elasticity can help with small alignment errors, even if the errors will lead to uneven pressure distribution on the tool face.

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