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In-process inspection of surface-profile properties by detecting laser beam deflection

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Abstract. An inspection system for the surface-profile properties of an organic photoconductor (OPC) drum substrate is studied. Defective substrates have approximately 1-mm-period waves in their surface profiles along the axial direction. The slope distribution of the surface profile is measured with an optical inspection system, which detects the angular deflection of a laser beam scanned over the surface at a high speed of 15 mm/ms. To discriminate between good and defective substrates, a threshold decision is made on components of the experimentally measured power spectrum of the slope distribution around 1-mm spatial period. The inspection system provides the same results as visual inspection with an accuracy better than 6σ. The setup dose not require any vibration isolators, because of its short inspection time of 2 ms. [DOI: 10.1117/1.2150821]

Subject terms: in-process inspection; surface profile; fast scanning; slope measurement.

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1 Introduction

In the development of high-precision technologies for surface processing, the control and inspection of the surface-profile properties during manufacturing are important, and in-process 100% inspection of products should be carried out to prevent the shipment of defective products.

We describe an inspection method for the surface-profile properties of the aluminum substrate of organic photoconductor (OPC) drums, which are used in laser printers, copying machines, and so on. Automatic visual inspection using CCD cameras for detecting contaminations, particles, scratches, and uneven physical defects have been performed for in-process 100% inspection on today's OPC drum manufacturing lines. On the other hand, the surface-profile properties of the OPC drum substrate have been inspected by sampling inspection with instruments using a stylus or by in-process visual inspection with human eyes. The sampling inspection cannot prevent the shipment of defective OPC drums, and the visual inspection cannot be expected to be stable in inspection quality. Therefore the development of an in-process inspection system for surface-profile properties is necessary for the automation of manufacturing lines and the quality control of the OPC drums.

We have described already a fast scanning method using a laser beam for one-dimensional surface-profile measurement by integrating a slope distribution that is obtained by detection of the angular deflection of the laser beam.[1] In this paper, this method is applied to the inspection of the surface-profile properties of OPC drum substrates. The inspection system discriminates between good and defective OPC drums by calculating the power spectrum of the output signal of a photosensor in the optical system. The system is insensitive to mechanical vibration, because the scanning speed is on the order of milliseconds. Hence the inspection system can be set up near the lathe that processes the OPC drum substrates, and it is possible to perform in-process automatic inspection on OPC drum manufacturing lines.

2 Inspection Method for OPC Drums

Aluminum OPC drum substrates inspected in this paper have 25-mm diameter and 250-mm axial length; they are machined on a lathe. These drums have approximately 1-mm periodic waves in their surface profile along the axial direction, which are caused by variations in the static accuracy of the lathe and the environment of manufacture. Printers using these defective OPC drums produce conspicuously mottled prints. To confirm surface-profile properties of the OPC drum substrates, a good substrate and a defective one, which were discriminated by a visual inspection with human eyes, were measured with a Taylor Hobson Form Talysurf-S6 profiler. The measured power spectrum of the surface's slope distribution of the defective OPC drum substrate has a peak near 1-mm spatial period, representing a defect, as shown in Fig. 1(b). On the other hand, the power spectrum of the good substrate has peaks near 0.1- and 0.25-mm spatial period, as shown in Fig. 1(a). These peaks are related to the feed intervals of a turning tool, but do not constitute defects. Therefore, in order to discriminate between good and defective OPC drum substrates, we set the threshold level for the components of the power spectrum around 1-mm spatial period.

3 Inspection System

3.1 *Slope Measurement*

A basic schematic of surface-slope measurement by detection of the angular deflection of a laser beam, which is a

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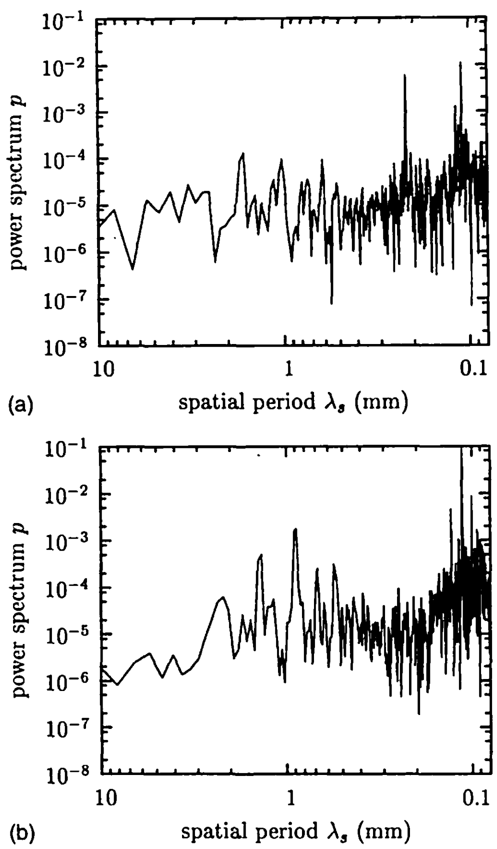

Fig. 1 Power spectra of the surface's slope distribution measured with Taylor Hobson Form Talysurf-S6 profiler: (a) good OPC drum substrate (drum name: OK1) and (b) defective OPC drum substrate (drum name: NG1).

well-known method,[2] is shown in Fig. 2. A beam emitted from the light source L is scanned on the sample surface S. Let the x axis be in the scanning direction, which is perpendicular to the incident beam. The surface's slope along the x direction is expressed by $\theta(x)$, as shown in Fig. 2. Now the beam is incident on a point P on the surface. The reflected beam deviates from the incident beam by an angle 2θ. If $\theta \ll 1$, we can find 2θ by measuring beam deflection $\Delta = 2\theta l$ at distance l from P. Carrying out the same measurement at many points on the surface, we obtain a distribution of the deflection $\Delta(x)$. We make use of a photosensor such as a position-sensitive detector (PSD) to make the measurement of $\Delta(x)$, because the output of the PSD is proportional to the barycentric position of incident beam.

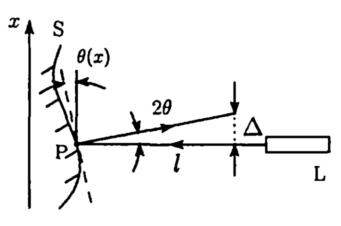

Fig. 2 Basic schematic of surface-slope measurement by detection of angular deflection of a laser beam.

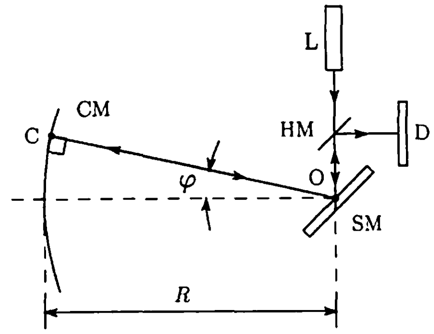

Fig. 3 Optical system for scanning a beam by use of spherical concave mirror CM and scanner mirror SM, where R is the curvature radius of CM.

3.2 *Optical Scanning System and Deflection of a Beam*

To make a high-speed measurement of the distribution of the deflection $\Delta(x)$ with the basic scheme shown in Fig. 2, we must scan the beam spot on the surface at a high speed, and the reflected beam must reach a PSD. For this measurement the conceptual optical system shown in Fig. 3, which consists of a spherical concave mirror and a rotating scanner mirror, has been proposed in Ref. 1. The rotation-axis O of the scanner mirror SM passes through the center of curvature of the spherical concave mirror CM. The beam reflected from SM is incident perpendicularly on CM, as shown by the incident beam path OC in Fig. 3, where point O is on the rotation axis of SM. The beam reflected from CM retraces the incident beam path OC precisely, thus appearing as the reflected beam path CO in Fig. 3. Hence the position of the beam spot on the detector D is constant and independent of the rotation angle of the scanner mirror if we use a half mirror HM.

In this optical system it must be considered where the sample surface S should be put to produce the deflection Δ on the detector D. The plane mirror PM and sample-surface S are put into the incident beam path OC and reflected beam path CO, respectively. The practical arrangement in the z-x plane is shown in Fig. 4, where a Cartesian coordinate system is defined and the optical axis is the z axis. The

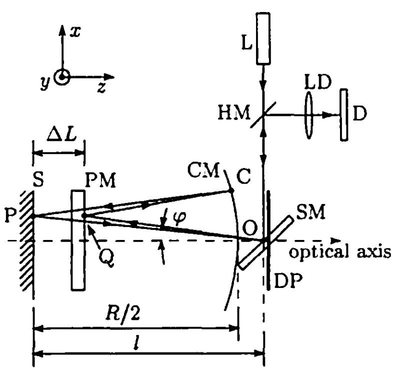

Fig. 4 Optical system for surface-slope distribution measurement. Plane mirror PM and sample surface S are put into beam incident path OP and beam reflected path CM-SM, respectively. S is displaced from PM by ΔL, keeping the distance between CM and S at $R/2$.

surface S is separated from PM by ΔL, keeping the distance between concave mirror CM and S at $R/2$ for highest lateral resolution in the scanning. The beam reflected from point O on the scanner mirror SM is incident on point C on CM through point Q on PM. The beam reflected from point C on CM returns to point O on SM through point P on S. The rotation of SM produces the beam spot movement on S. When the beam scans a flat plane such as the sample surface S, an x-y plane exists on which the deviation of the spot of the reflected beam from the plane is minimum. We call this x-y plane the *detecting plane* DP. It coincides with the plane including the rotation axis of SM when the values of ΔL and l satisfy the following condition:

$$\frac{1}{l+R/2-2\Delta L}+\frac{1}{l+R/2}=\frac{2}{R}, \quad (1)$$

where l is the distance between S and SM. Under that condition point O on SM and the intersection of DP with the optical axis are conjugate points of the concave mirror CM. If S has slope θ, the resultant deflection Δ of the beam spot is produced on the DP and is given by

$$\Delta=-2l\theta-2l\theta\varphi^2-d^2\varphi^3, \quad (2)$$

where φ is the angle formed by the optical axis and the beam path OQ, $d=\Delta L+1/2-(\Delta L^2+1/4)^{1/2}$ and $R=1$. The second term in Eq. (2) is due to the variation of the beam path length $|PO|$ with the angle φ, and the third term is due to the spherical aberration of the concave mirror CM. The lens LD produces an image of the detecting plane DP on the detector D at unit magnification. Details of the scanning optical system and the derivation of Eq. (2) can be seen in Ref. 1.

4 Experimental Setup

The optical system for the inspection was the same as shown in Fig. 4, and the sample surface S was the OPC drum substrate described in Sec. 2. The power spectrum of the surface slope distribution for the inspection was obtained from the slope measurement over a 30.3-mm width on S. The optical system, in which a beam spot on S was scanned over 30.3-mm width in the direction of the cylinder axis of the drum, was constructed as follows: The light source L was a He–Ne laser, and the laser beam emitted from it was collimated to 5-mm half-width by a collimator lens. The spherical concave mirror CM had an 80-mm diameter, a radius of curvature $R=400$ mm, and $\lambda/4$ surface flatness. The half-width of the beam spot diameter on S was 50 μm. The mirrors PM, SM, and HM had $\lambda/10$ surface flatness. The lens LD with 100-mm focal distance was achromatic. The distance ΔL was 7 mm. The distance between CM and the surface S was $l=207$ mm to satisfy Eq. (1) when R and ΔL were 400 and 7 mm, respectively.

The scanner mirror SM was mounted on a motor with a 570-rpm rotating speed. The distance between SM and the surface S was approximately 200 mm, so the scan speed of the beam spot on S was 15 mm/ms. Because the scan time for the 30-mm width was 2 ms, the optical system was insensitive to vibrations lower than 500 Hz in frequency. Therefore the experiment could be performed with no vibration isolators.

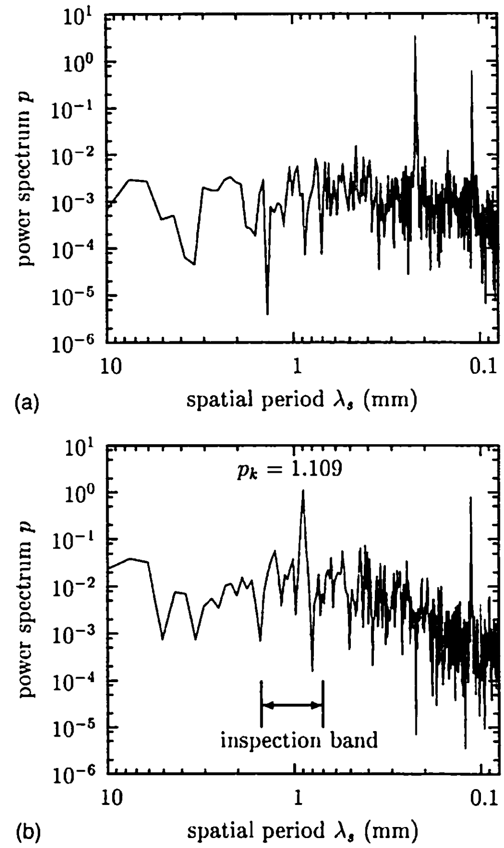

Fig. 5 Power spectra of surface slope distribution, measured with the setup using the inspection system, of (a) a good OPC drum substrate (drum name: OK1) and (b) a defective OPC drum substrate (drum name: NG1).

The detector D was the PSD of a Hamamatsu Photonics K. K. model S1880 detector. The output V of the PSD is proportional to both the barycentric position of the incident beam on its surface and the beam's intensity. To obtain V_p proportional to the beam deflection Δ given by Eq. (2), the output V was divided by a voltage proportional to the beam's intensity. A Burr Brown model MPY634 analog divider was used for the division. The output signal V_p of the divider was fed to a computer through a 12-bit analog-to-digital converter. The power spectrum p of the output V_p was obtained numerically. Welch's data window[3] was used for the calculation of the power spectrum.

5 Experimental Test

5.1 *Power Spectrum of Output V_p*

An error in the slope θ measured with the optical system might have the following two causes. First, the right side of Eq. (2) has terms that are not proportional to the slope θ of the surface S. Second, the beam reflected from S spreads over a region larger than the PSD size of 12 mm on the detecting plane DP, because the surface of the OPC drum substrate is rough. However, we need only an approximate distribution of the power spectrum around 1-mm spatial period for the inspection of the drum substrates. Therefore we ignored the error in the slope measurement.

Power spectra of the surface slope distribution obtained from the output V_p are shown in Fig. 5. The measured OPC

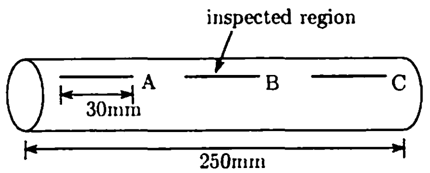

Fig. 6 Inspected regions A, B, and C of the OPC drum substrate.

drum substrates were the same as shown in Fig. 1(a) and 1(b), respectively. The details of the power spectrum were different between Fig. 1 and Fig. 5 because the region on the surface of the corresponding OPC drum substrate measured in Fig. 5 was not exactly the same as that in Fig. 1. However, peaks of the defect wave at 1 mm and peaks of the feed intervals of the turning tool at 0.1 and 0.25 mm appear in the power spectrum of Fig. 5. Therefore the scanning method was suitable for the inspection of the surface-profile properties of the OPC drum substrate.

5.2 *Inspection*

The inspection was performed on 10 samples of the OPC drum substrate, which had been already discriminated into good and defective ones by visual inspection with human eyes. Each OPC drum substrate was inspected in three different regions on its surface: two regions, denoted by A and C, were near the ends of the drum, and one region, denoted by B, was at the center of the drum, as shown in Fig. 6. Peak values of the power spectrum p of the output V_p were examined between spatial periods λ_s of 0.7 and 1.5 mm, as shown in Fig. 5, and the greatest peak value p_k was determined. The values of p_k are shown in Table 1. Drums from OK1 to OK4 were good, and drums from NG1 to NG6 were found defective in regions A, B, and C at 10 samples.

Table 1 Peak value p_k of the power spectrum p between spatial periods λ_s of 0.7 and 1.5 mm

	p_k			
Drum	A	B	C	DV
OK1	0.006	0.008	0.002	0.008
OK2	0.038	0.032	0.012	0.038
OK3	0.006	0.012	0.010	0.012
OK4	0.025	0.015	0.039	0.039
NG1	0.060	0.099	1.109	1.109
NG2	0.014	0.121	0.019	0.121
NG3	0.058	0.029	0.563	0.563
NG4	0.080	0.142	0.574	0.574
NG5	1.091	0.234	0.208	1.091
NG6	0.297	0.138	0.490	0.490

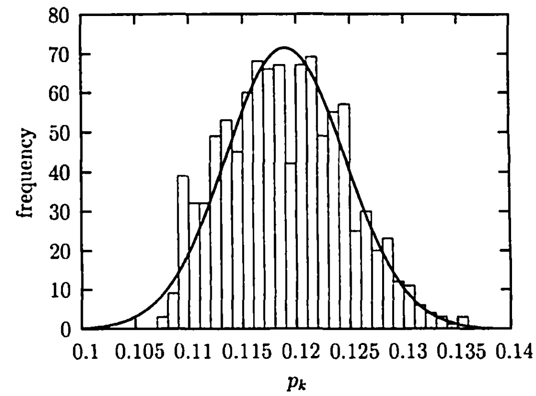

Fig. 7 Frequency of occurrence of the peak value p_k and equivalent Gaussian function for the measurement of region B of drum NG2.

The value in column DV was the maximum value among A, B, and C for each substrate. The values of DV were used to set a threshold level for the decision of the inspection, as described below.

Region B of drum NG2 gave the minimum value, 0.121, of DV among the defective drums, and region C of drum OK4 gave the maximum value, 0.039, of DV among the good drums in Table 1. To determine a threshold level for the decision, the two regions were measured 1000 times to obtain frequencies of occurrence of the peak value p_k. The distribution of region B of drum NG2 is shown in Fig. 7. The averages $\langle p_k \rangle$ of the peak value p_k in region B of drum NG2 and region C of drum OK4 were 1.19×10^{-1} and 3.89×10^{-2}, respectively. The standard deviations σ in the two regions were 5.59×10^{-3} and 5.74×10^{-4}, respectively, as shown in Table 2. Therefore, in the case of the 10 drums inspected in the experiments, the threshold level from 0.042 to 0.086 provided 6σ accuracy for the decision between the good and defective OPC drum substrates.

6 Conclusion

We have described the surface-profile properties of OPC drum substrates measured with an inspection system using a fast scanning method. The power spectra of the slope distribution of the substrates were obtained from the output of the PSD in the inspection system. The spectra were comparable to those obtained with a Talysurf-S6. Defective OPC drum substrates have approximately 1-mm periodic waves in their surface profiles. To discriminate between good and defective OPC drum substrates, we made a threshold decision on components of the power spectrum around 1-mm spatial period. Experimental inspections were performed on 10 OPC drum substrates that had been discriminated into good and defective drums by visual inspec-

Table 2 Results obtained by repeating the measurement 1000 times for region C of drum OK4 and region B of drum NG2.

Drum region	$\langle p_k \rangle$	σ	
C of OK4	3.89×10^{-2}	5.74×10^{-4}	$\langle p_k \rangle + 6\sigma = 4.23\times 10^{-2}$
B of NG2	1.19×10^{-1}	5.59×10^{-3}	$\langle p_k \rangle - 6\sigma = 8.55\times 10^{-2}$

tion with human eyes. In the experimental inspection, the system using the fast scanning method gave the same results as the visual inspection, to an accuracy better than 6σ. The inspection system did not require any vibration isolators, because the inspection time was 2 ms with a high scanning speed of 15 mm/ms.

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Biographies and photographs of authors not available.