One-dimensional surface profile measurement with a fast scanning method by detecting angular deflection of a laser beam

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ABSTRACT

The rough surface of a aluminum cylindrical drum cut by turning tool is measured with a fast scanning method by detecting angular deflection of a laser beam. Reflection pattern from the surface extended into a large region, and contained two kinds of components of narrow and wide patterns. To detect rough surface's sloop, the barycentric position of the wide pattern was measured with a PSD, and a beam diameter of 5mm on the surface was adopted. After a proportionality coefficient to convert from PSD output to the surface's slope was determined, an one-dimensional surface profile measurement of the rough surface was performed without a vibration isolator. Measurement error was estimated to be 0.27μm.

Keywords: Height measurements, Metrology, Optical instruments, Scanners, Surface measurements, Rough surface

1. INTRODUCTION

In the development of high-precision technology for surface processing, the control and inspection of surface profiles during manufacturing are important, and in-process 100% inspection of products should be carried out to prevent the shipment of defective products. In general, interferometers or instruments make by the stylus method have been used for inspections. However, these instruments need a specialized measurement room because they are vulnerable to mechanical vibration. Therefore in-process 100% inspection cannot be expected as long as these measurement instruments are used.

We described a fast beam scanning method for one-dimensional surface profile measurement by integral of a slope distribution which was obtained by detection of angular deflection of a laser beam.[1] The scanning method was insensitive to mechanical vibration because the high measurement speed was of the order of milliseconds. It was shown that the scanning method was very effective in measurement of a specular surface without a vibration isolator. So that it was possible to apply the scanning method to an in-process automatic profile inspection system for the manufacture of precision products.

On the other hand, since there are various products with rough surface manufactured with turning and/or milling tool, surface profile measurement for them is also important. In this paper, the rough surface of aluminum cylindrical drum cut by turning tool is measured. The cylindrical drums are used mainly in the laser beam printer, the copying machine. Their surface are coated with electrostatic chargeable photosensitive emulsions for attracting toner, and should be uniformly coated for high quality printing. The influence of substrate profile is significant on the thickness of the photosensitive emulsions. There fore the surface profile of the cylindrical drum should be inspected.

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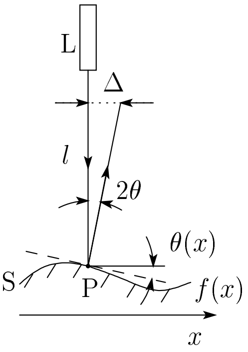


Figure 1. Basic schematic of measurement of a one-dimensional surface profile by detection of angular deflection.

2. PRINCIPLE OF MEASUREMENT EQUIPMENT

2.1. Basic Scheme for Measurement

A basic schematic of one-dimensional surface profile measurement by detection of angular deflection is shown in Fig.1. A beam emitted from light source L is scanned on sample surface S. Let the x axis be the scanning direction, which is perpendicular to the incident beam. The surface profile and the slope of the surface along the x axis direction are expressed by $f(x)$ and $\theta(x)$, respectively, as shown in Fig.1. If $\theta \ll 1$, the differential of $f(x)$ is given by

$$\frac{d\,f(x)}{d\,x} = \tan\theta(x) \sim \theta(x). \tag{1}$$

Now the beam is incident onto point P on the surface. The reflected beam deviates from the incident beam by angle 2θ. We find this angle 2θ by measuring beam deflection $\Delta = 2\theta l$ at distance l from point P. Carrying out the same measurement of many points on the surface, we obtain a distribution of deflection $\Delta(x)$. Integration of distribution $\Delta(x)$ and expression (1) gives the one-dimensional surface profile $f(x)$ as follows:

$$f(x) = \frac{1}{2l}\int \Delta(x)\,dx. \tag{2}$$

We make use of a photosensor such as a position-sensing detector (PSD) to make the measurement of the deflection $\Delta(x)$. Because the output of the sensor is proportional to the position of the beam spot on the sensor, we have to determine proportionality coefficient α for transformation from the output of the PSD to the slope of the surface.

2.2. Optical System and Equation

To make a high-speed measurement of distribution of deflection $\Delta(x)$ with the basic scheme shown in Sect.2.1, we must scan the beam spot along the surface at a high speed, and reflected beam must reach a PSD.

For this measurement a conceptual optical system shown in Fig.2, which consists of a spherical concave mirror and a rotating scanner mirror, is proposed. The rotating axis of scanner mirror SM coincides with the center of curvature of spherical concave mirror CM. The beam reflected from scanner mirror SM is incident perpendicularly onto concave mirror CM, and the beam reflected concave mirror CM retraces the path of the incident beam precisely. Hence the position of the beam spot on detector D is constant, independently of the rotation angle of the scanner mirror.

In this optical system one must consider where sample surface S should be put to produce deflection Δ on detector D. Plane mirror PM and sample surface S are put into incident path SM-CM and reflected path CM-SM, respectively. The practical arrangement in the z-x plane is shown in Fig.3, where a Cartesian-coordinate system is defined and the optical axis is the z axis. Surface S is distant from plane mirror PM by ΔL, with the distance between concave mirror CM and surface S maintained at $R/2$ for provision of maximization of lateral resolution

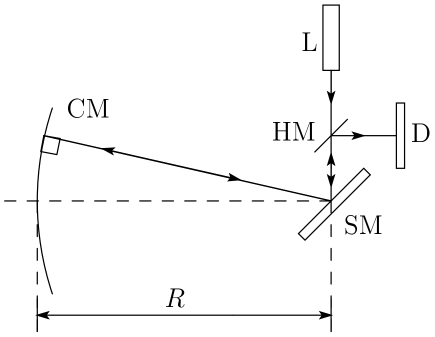


Figure 2. Optical system for scanning a beam by use of spherical concave mirror CM and scanner mirror SM, where R is the radius of curvature of the concave mirror.

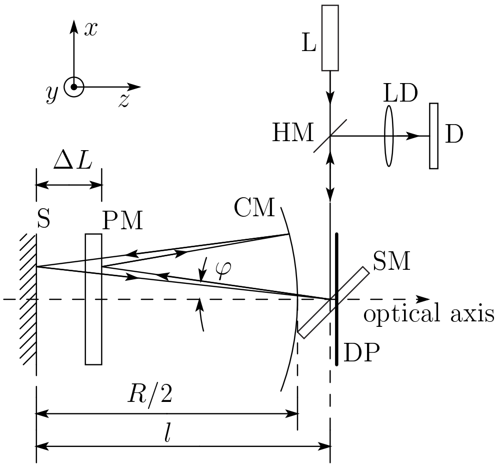


Figure 3. Introduction of plane mirror PM and sample surface S into Fig.2. PM and S are put into incident path SM-CM and reflected path CM-SM, respectively. S is detached from PM by ΔL, with the distance between CM and S maintained at $R/2$.

in the scanning. The beam reflected from scanner mirror SM is incident onto concave mirror CM through plane mirror PM. The beam reflected from concave mirror CM is incident onto scanner mirror SM through surface S. The rotation of scanner mirror SM makes the beam spot move on surface S. When the beam scans a flat plane as sample surface S, a x-y plane exists on which the movement of the spot of reflected beam from the flat plane is minimum. We call the x-y plane detecting plane DP. Plane DP coincide with the plane including the rotation axis of scanner mirror SM if we adopt ΔL and l properly, where l is distance between sample surface S and scanner mirror SM. In this condition the center of scanner mirror SM and detecting plane DP are conjugate points of concave mirror CM. If sample surface S has sloop θ, the resultant deflection Δ of the beam spot on detecting plane DP is produced and is given by

$$\Delta = -2l\theta - 2l\theta\varphi^2 - d^2\varphi^3, \tag{3}$$

where φ is an angle formed by the optical axis and beam path SM-PM, $\Delta L = d(1-d)/(1-2d)$ and $R = 1$. The second term is by the variation of beam path length |S-DP| with angle φ, and the third term is by the spherical aberration of concave mirror CM. As the relative magnitude of the second and third term to the first term is small,[1] we only consider the first term which is proportional to differential of the surface. Lens LD makes the image of detecting plane DP onto detector D.

3. PROPERTIES OF REFLECTED LIGHT FROM ROUGH SURFACE AND OUTPUT OF PSD

3.1. Reflection Pattern from Rough Surface on Detecting Plane

A sample surface was a rough surface of a 25mm-diameter aluminum cylindrical drum cut by turning tool. Its cylinder axis was the measurement direction along the x-axis as shown in Fig.3.

An another setup consisting of light source L, sample surface S and detecting plane DP shown in Fig.3 was constructed to examine reflection patterns from the sample surface. The reflection patterns on detecting plane DP of $l = 200$mm from sample surface S was observed with a CCD camera, as shown in the upper part of Fig.4 whose horizontal axis is paralle4.8×10^{-3}radl to the axis of the cylindrical drum. The intensity distribution of the pattern is shown in the lower part and its values are indicated along the vertical axis. In Figs.4(a) and (b), the beam diameter w were 0.5mm and 0.2mm, respectively, whose horizontal axis is parallel to the axis of the cylindrical drum. Squares plotted in the pattern represent the detection size of PSD which was 12mm. The values written above the squares are the barycentric position $B_{\rm C}$ of the pattern inside the square along the horizontal axis. An intensity distribution of the reflection pattern in Fig.4(a) is shown in Fig.5 with the thin line. It is found from Fig.5 that a periodic cutting mark on the surface produces the reflection pattern which contains two kinds of components. First component is a wide pattern whose shape is represented with the envelope curve of the thick line. The width of the wide pattern is comparable to the PSD size of 12mm. It is considered from the width of the wide pattern that the wide pattern is caused by about 0.01mm periodic structure of the surface. Second component is a narrow pattern which consists of small grains of light intensity caused by the cutting period of 0.1 mm of the turning tool. A wide pattern contains a number of narrow patterns inside itself.

If a change in barycentric position $B_{\rm C}$ of the wide pattern depends only on the slope of a sample surface, the slope can be detected with PSD whose output is a barycentric position of the incident pattern. There are two different reflection patterns corresponding to the two different beam diameters on the surface. To examine which patterns is better for the measurement of the surface's slope, we regarded the surface to be flat within 1mm-width. The beam spot on the surface was scanned into the direction of cylindr4.8×10^{-3}radical drum axis at intervals of 0.05mm and the barycentric position $B_{\rm C}$ of the reflection pattern inside the squares shown in Fig.4 was calculated at each scanning points.

The results are shown in Fig.6, where the barycentric position $B_{\rm C}$ has a large fluctuation in (a) at $w = 0.2$mm compared to (b) at $w = 0.5$mm. It was observed that the narrow patterns moved with the scanning of the beam spot on the surface, while the wide pattern did not move. At $w = 0.2$mm the influence of the movement of the narrow patterns on the barycentric position was significant because number of the narrow patterns within the square in Fig.4 was smaller at $w = 0.2$mm than at $w = 0.5$mm. From these characteristics of the reflection pattern it can be concluded that the fluctuation in the barycentric position was cased by the movement of the narrow patterns. Therefore a beam diameter of 0.5mm was adopted to detect the slope of the sample surface.

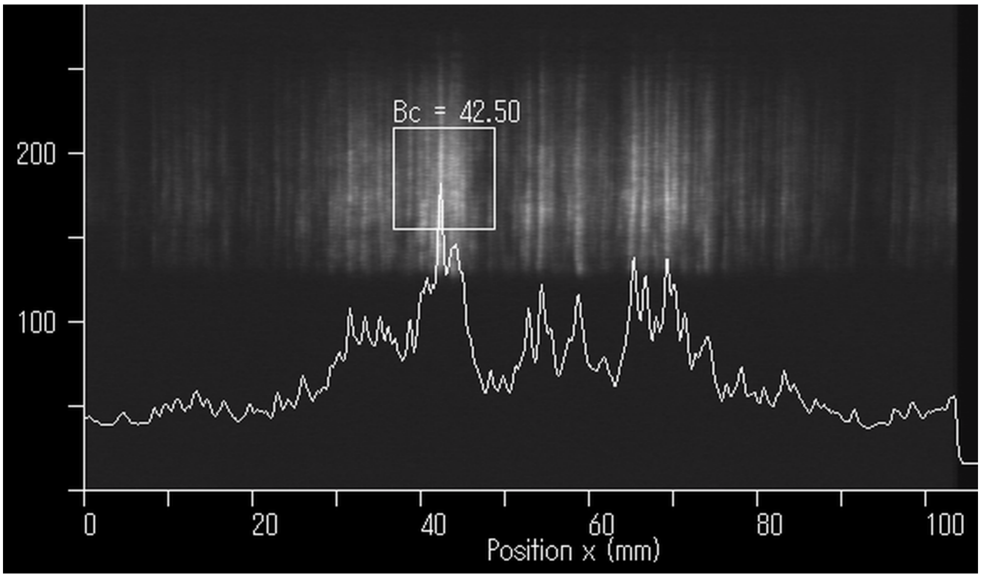
3.2. Movement of Reflection Pattern by Slope of Sample Surface

In this subsection, variations of the reflection pattern are investigated when an inclination is given to the sample surface. The patterns were observed with a CCD camera which was set on the position of detector D in Fig.3. The view field of the CCD was equal to the PSD size. A tilt stage mounting the sample was inclined by 4.8×10^{-3}rad at intervals of 0.60×10^{-3}rad. Results of the observation are shown in Fig.7, where the reflection pattern was translated in response to inclination angle θ.

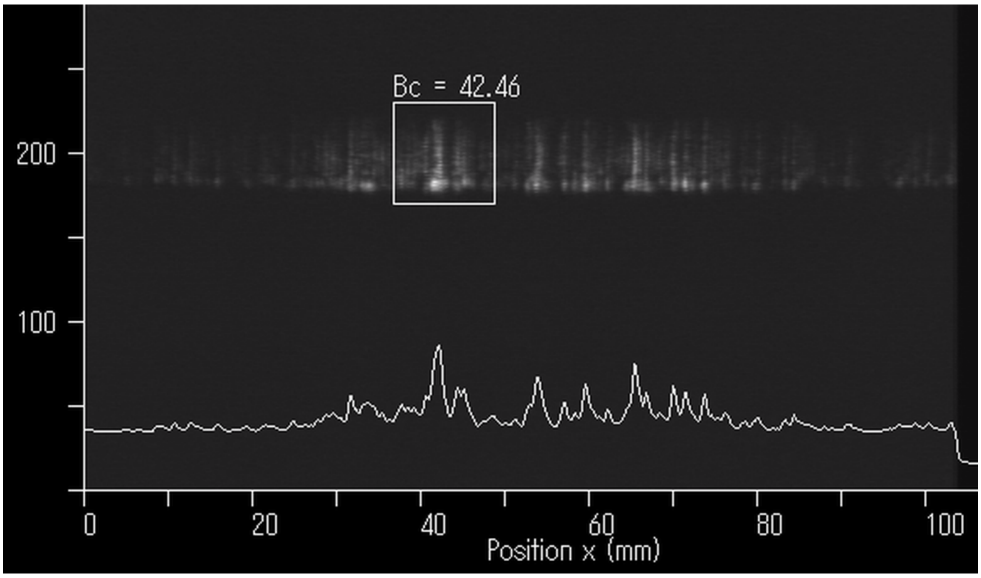
The barycentric position $B_{\rm C}$ of the observed reflection patterns was plotted, as shown in Fig.8. The barycentric position was nearly proportional to the inclination angle of the sample which produced the translation of a wide pattern inside the view field of the CCD. Therefore it is made clear that the slope of the sample surface is obtained by detecting the barycentric position of the reflection pattern.

3.3. Output of PSD and Measurement for Proportionality Coefficient α

The PSD outputs a voltage which is proportional to barycentric position of a wide pattern in the reflection pattern. Since the output voltage dose not has dimension of angle measure, following experiment was carried out to determine the proportionality coefficient α for conversion of unit from voltage into angle.



4.8×10^{-3}rad (a)Beam diameter $w = 0.5$mm on the sample surface.



(b)Beam diameter $w = 0.2$mm on the sample surface.

Figure 4. Reflection patterns from the aluminum cylindrical drum is observed on detecting plane DP with a CCD camera.

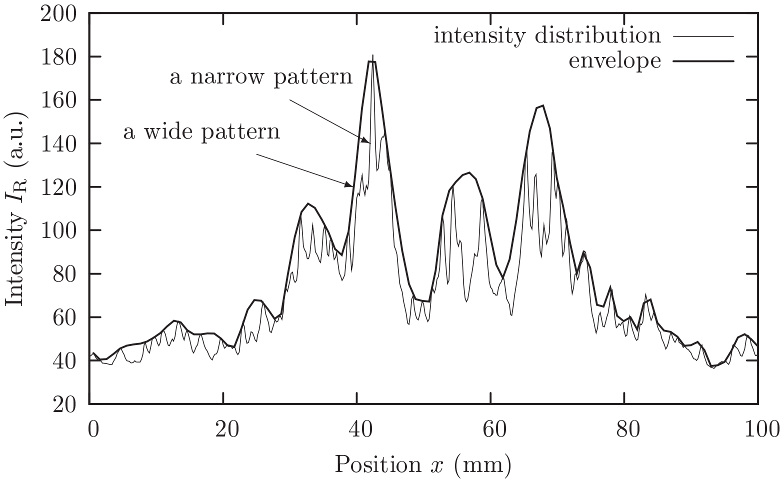
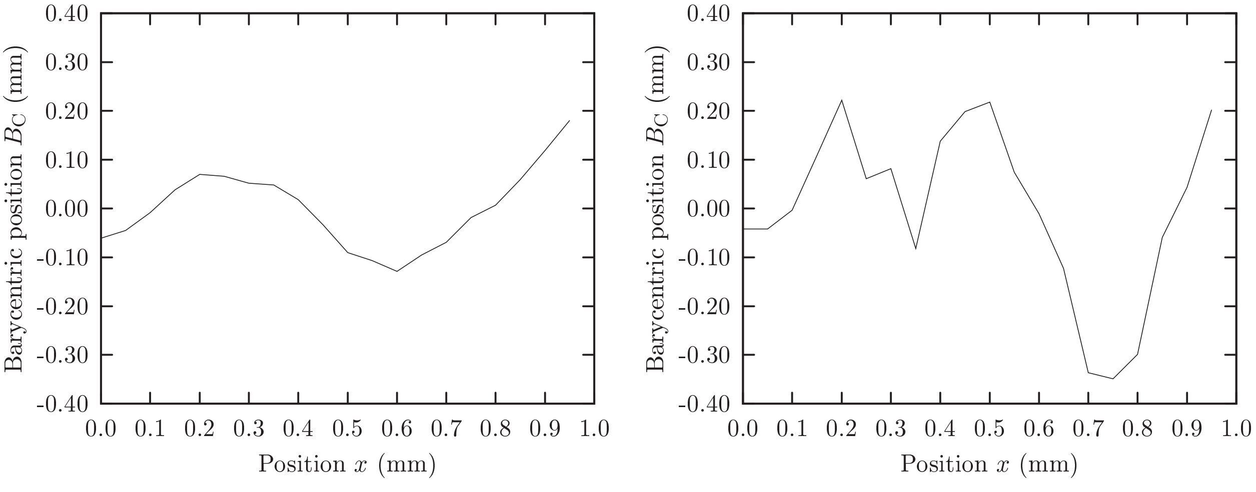


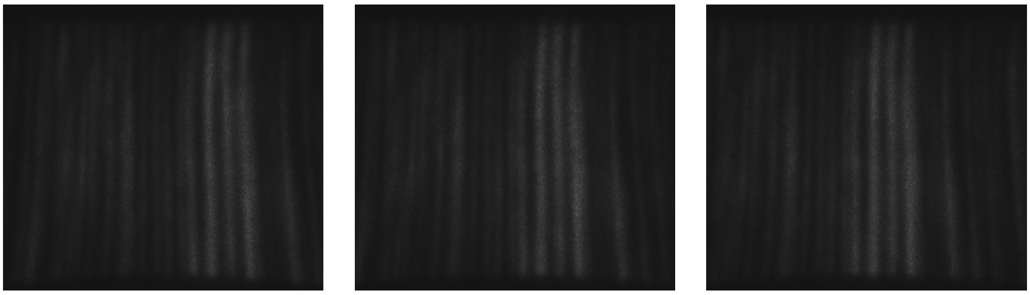
Figure 5. 'Wide' and 'narrow' patterns in the pattern of Fig.4(a). The wide pattern is an envelope of peaks of the intensity distribution, which includes a number of narrow patterns.



(a)Beam diameter $w = 0.5$mm.

(b)Beam diameter $w = 0.2$mm.

Figure 6. Barycentric position B_C of the reflection pattern inside the squares in Fig.4. Beam diameter w were (a)0.5mm and (b)0.2mm. Horizontal axis is the beam spot position on the surface, and B_C is indicated as the deviation from a mean barycentric position.



(a) $\theta = 0.0$ rad (b) $\theta = 2.3 \times 10^{-3}$ rad (c) $\theta = 4.8 \times 10^{-3}$ rad

Figure 7. Variations of the reflection pattern when an inclination was given to the sample surface. An angle of inclination θ is indicated below each figures. Horizontal width of the figure is equal to PSD size of 12mm.

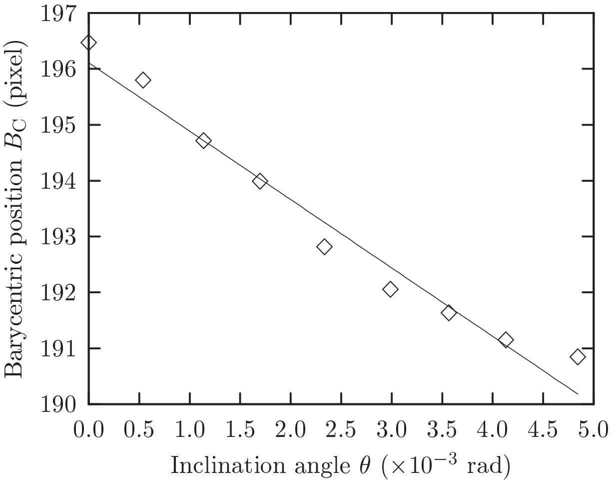


Figure 8. Barycentric position B_{C} of the reflection pattern versus the inclination angle of the sample. The barycentric position B_{C} were obtained from the observed patterns as shown Fig.7. A solid line is a least-squares line of $B_{\mathrm{C}}(\theta) = 1224\theta + 196.1$.

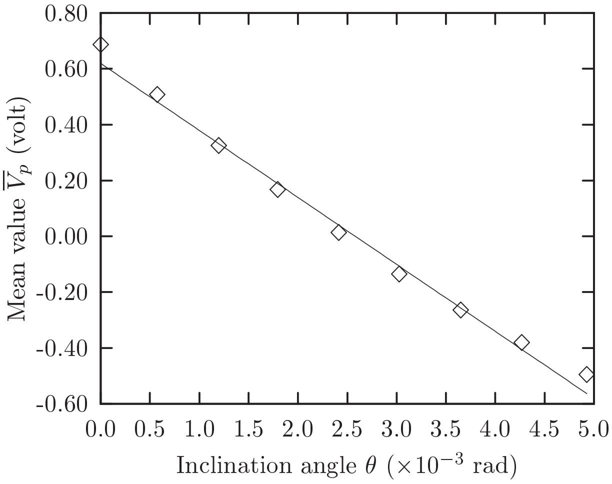


Figure 9. Mean value $\overline{V_p}$ of PSD output generated by the inclination of the sample. Solid line is least-squares line of $v(\theta) = -240\theta + 0.61$.

Sample surface S in Fig.3 was the rough surface of 32mm-width of the cylindrical drum. The curvature radius R of concave mirror CM was 400mm. Detector D was a PSD, whose outputs fed to computer through 12bit A/D converter. The sample surface was inclined by a tilt stage from zero to 4.0×10^{-3}rad at interval of about 0.62×10^{-3}rad. The PSD outputs a continuous signal while the beam was scanned over a width of 32mm on the sample surface. The continuous values of the PSD output were averaged to obtain a mean value $\overline{V_p}$ of the PSD output.

The mean value $\overline{V_p}$ versus the inclination angle θ is shown in Fig.9. The mean value $\overline{V_p}$ of the PSD outputs was proportional to the inclination angle θ of the sample, and proportionality factor was 240 V/rad from the result. Therefor the proportionality coefficient α for the conversion from volt to angle measure is given by

$$\alpha = 1/240 = 4.2 \times 10^{-3} \text{ rad/V}. \tag{4}$$

4. A MEASUREMENT OF ROUGH SURFACE

The rough surface of the cylindrical drum was measured with the same experiment setup used in Sect.3.3. The setup did not require a vibration isolator because of its high speed measurement of 0.5msec

To obtain the profile F_i of the surface, integration of

$$F_i = \sum_i \theta_i \Delta x = 1.57 \times 10^{-2} \times \alpha \sum_i v_i, \tag{5}$$

is required, where θ_i is the slope of the surface, Δx is the spatial interval of sampling of 1.53×10^{-2}mm on the surface, suffix i represents position on the surface. The slope θ_i is given by αv_i, where v_i is the output of the PSD and proportionality coefficient α is given by Eq.(4).

Surface profile obtained at 2048 points is shown in Fig.10. Cutting period of 0.1mm did not appear in the profile in Fig.10 because fine structure on the surface was averaged out with beam diameter of 0.5mm.

5. ERROR ESTIMATION

The observed barycentric positions B_C deviate from the least-squares line in Fig.8, and this deviation provides an error ϵ_F to the measured profile in Fig.10. The measurement error is estimated from the result of Fig.8.

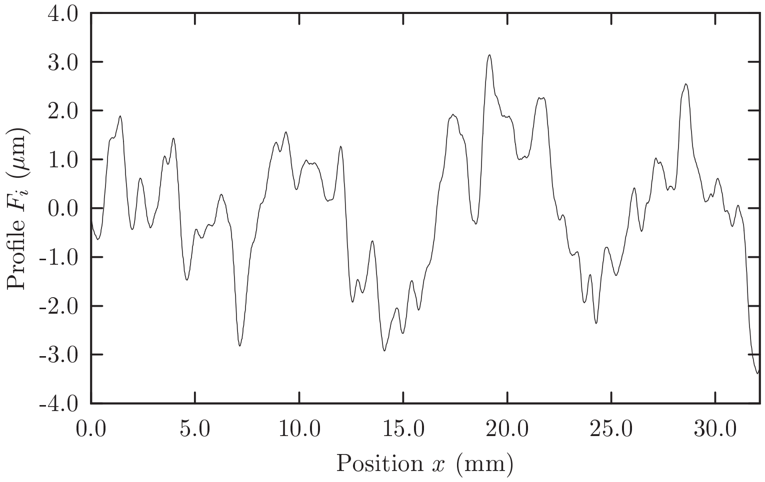


Figure 10. One-dimensional profile of the surface of an aluminum cylindrical drum cut by turning tool.

The root mean square value of distant between the barycentric positions B_{C} and the least-squares line was $\epsilon_\theta = 0.27 \times 10^{-3}$rad, which was an error in angle measurement for surface's slope. An measurement error ϵ_F included in the profile in Fig.10 is obtained by multiplying the error angle ϵ_θ by a certain length. This length was considered to be 1mm because the profile in Fig.10 had about 1mm-periodicity in its form and the variation in the magnitude of the error angle ϵ_θ also had about the 1mm-periodicity. Therefore the measurement error ϵ_F on the profile in Fig.10 was estimated to be 0.27μm.

6. CONCLUSION

The rough surface of a aluminum cylindrical drum cut by turning tool was measured with the fast scanning method by detecting angular deflection of a laser beam. The reflection pattern from the surface extended into a large region. The reflection pattern has two kinds of components such as narrow and wide pattern. A wide pattern, which dose not move with movement of beam spot on the surface, contains a number of narrow patterns which move with the movement of the beam spot. Therefore the measurement of the slope on the surface was carried out by detection of barycentric position of a wide pattern. Beam spot diameter of 0.5mm on the surface was adopted because the influence of the movement of narrow patterns on the measurement of barycentric position of a wide pattern is small. It was confirmed that the wide pattern translated in proportional to inclination of the surface. After proportionality coefficient α was determined, one-dimensional surface profile measurement of the rough surface was performed without a vibration isolator. Measurement error was estimated to be 0.27μm.

REFERENCES

1. R. Shinozaki, O. Sasaki, and T. Suzuki, “Fast scanning method for one-dimensional surface profile measurement by detecting angular deflection of a laser beam,” *Appl. Opt.* **43**, pp. 4157-4163, 2004.