

Method for Three-dimensional Evaluation of Surface Form of Metal Rings for CVT Metal Pushing V-belts

Kenta UMETSU*

Hiroyoshi MIKOGAI*

ABSTRACT

In order to respond to the increased amounts of torque being transmitted by the metal pushing V-belts in CVTs, it was necessary to increase precision in the formation of the metal rings employed in the belts. This necessitated the achievement of a higher level of precision in the surface forms of the rings, a requirement that demanded the development of a three-dimensional surface form measurement technology enabling quantitative evaluation of the manufacturing processes and manufacturing history of the rings. While there is a standard method of evaluating the precision of the surface form of the rings in the direction of width, no integrated method of evaluating the continuous sectional form in the direction of the circumference has been available. The developed method uses general purpose laser sensors to gather continuous data on the sectional form of the rings, enabling reproduction of the three-dimensional surface form of the rings around the entire circumference. This has enabled quantification of the cyclic deviations in surface form that occur during the manufacturing process.

1. Introduction

A change in specifications from a start clutch to a torque converter-type CVT amplifies torque at take-off and when the vehicle stalls, thus increasing the torque transmitted by the metal pushing V-belt. It is necessary to increase the accuracy of the shape of the rings used in the belts in order to stabilize their behavior when high tensile force is acting on them during torque amplification. This is because amplifying the dynamic behavior of the rings results in interference between the rings and the elements (Fig. 1), which is a factor producing wear of the ring edges. This makes it necessary to control the profile deviation in the rings, i.e., the difference between the design dimensions and actual shape of the rings in the direction of the circumference.

Conventionally, the profile deviation in the direction of width of the plate, i.e., across the entire circumference of the ring, has been controlled using a device that employs a measurement method that does not involve cutting the ring⁽¹⁾. Using this device, cyclic high-frequency form components originating in the accuracy of the roller employed in the ring rolling process can be evaluated, and a high level of accuracy achieved in the form of the ring in the direction of the width of the steel plate⁽²⁾. However,

the accuracy of the roller also contributes to the accuracy of the surface form of the rings, demanding a method of evaluating the three-dimensional surface form. In addition, interference of the jig during the application of the heat treatment used in the manufacture of the rings can prevent the treatment from being properly applied in some areas, changing the surface form of the rings. However, no measurement method has been available, and it has been challenging to measure and evaluate the surface form of the thin rings. The developed method of evaluating the form of the rings discussed in this paper uses a device

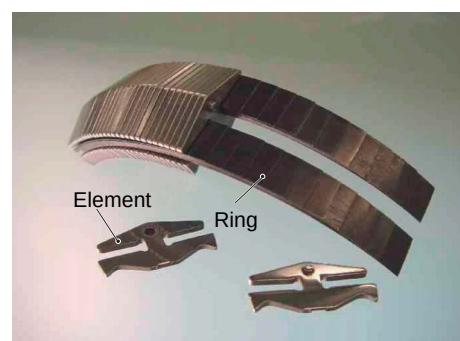


Fig. 1 Components of metal pushing belt

* Automobile R&D Center

made up of a general-purpose line laser sensor and simple positioning mechanism to measure the three-dimensional form of the ring surface. The application of a frequency analysis to the results enables the production history of the rings, over multiple processes, to be quantified as the degree of profile deviation of the ring.

With regard to the goal of achieving a high level of accuracy in the form of the rings, this method offers the advantage of enabling the efficient identification of the processes that produce profile deviations in the rings.

2. Mechanism of Occurrence of Profile Deviation in Rings

The processes that generate conspicuous profile deviations during ring manufacture are the rolling and heat treatment processes. Figure 2 shows a two-dimensional schematic diagram of the rolling process. The rings are formed by rolling at clearance f between a rolling roller and receiver roller. On a system of X-Y coordinates, with the axis of rotation of the rolling roller as o , the eccentricity of the axis, og , in relation to the center of the roller, g , is termed e , the initial angle of eccentricity is termed ϕ_0 , and the angle of rotation of the rolling roller is termed θ . With the X axis as the benchmark, the angle towards the Y axis is positive. If the ideal radius of the rolling roller is termed R , the profile deviation in the

direction of the radius can be termed ΔR , and the change in the clearance f , Δf , can be expressed by Eq. (1).

$$\begin{aligned} \Delta f(\theta) &= \sqrt{(R + \Delta R)^2 - e^2 \cos^2(\theta + \phi_0)} + e \sin(\theta + \phi_0) - R \\ &\approx \Delta R + e \sin(\theta + \phi_0) \end{aligned} \quad (1)$$

As Fig. 3(a) shows, actual measurements of the surface form of the rolling roller indicate oval-shaped second-order profile deviations. ΔR , the surface profile deviation of the rolling roller in Eq. (1), can be modeled by Eq. (2), where a is the amplitude and k is the order. ε_0 is the initial angle in relation to θ . Figure 3(b) shows a model of DR for $k=3$.

$$\Delta R(\theta) = a \sin(k\theta + \varepsilon_0) \quad (2)$$

If 360 deg is termed one cycle for angle θ in Eqs. (1) and (2), Δf displays a 1st-order and k^{th} -order cyclicity for one revolution of the rolling roller. Given this, the pressure applied to the ring is cyclically non-uniform, and it can be predicted that when it is necessary to use m revolutions of the rolling roller in rolling the entire length of the circumference of the ring, undulations displaying m^{th} -order and $m \times k^{\text{th}}$ -order cyclicity will be formed on the surface of the ring.

In the heat treatment process, local deformation in the surface of the ring is generated by physical interference when the ring is placed in the jig.

3. Principle of Measurement

The surface form of the rings across their entire circumference is measured using the instrument shown in Fig. 4. The ring revolves around two connected pulleys. A weight of approximately 5 kg is applied to pulley B, which sits on top of the guide mechanism, via a roller. This exerts tensile force on the ring. A line laser sensor (an LJ-G030, manufactured by Keyence), is positioned at the median point between pulleys A and B, and acquires instantaneous data on the surface form of the ring across its entire width, as shown in Fig. 5. The measurement time per cross-section is approximately 4 ms, and approximately 300 measurement points are employed for the 10 mm width under evaluation. The acquired data is rotationally transformed in order to render it parallel with

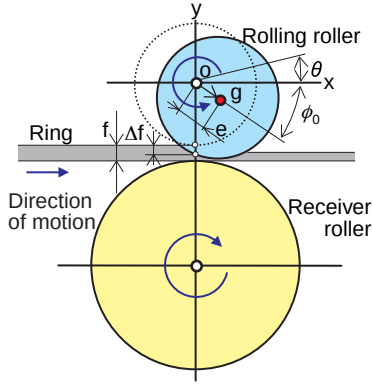
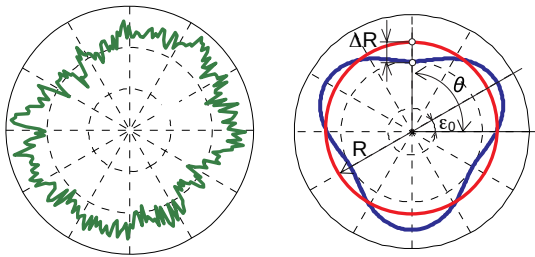


Fig. 2 Schematic diagram of rolling of steel ring



(a) Deviation of real form (b) Deviation of modeled form

Fig. 3 Deviation of real and modeled forms on rolling roller

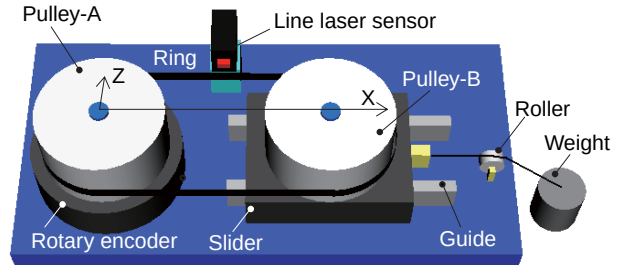


Fig. 4 Ring surface 3D measurement instrument

the y axis with the two edge points of the ring as the benchmarks, and the maximum height of the arc, h , is calculated.

When data has been acquired for one cross-section, the pulleys are successively rotated in identical angular increments, enabling continuous ring cross-section data to be acquired. This equally spaced feed is converted into length, and the cross-sectional form is arrayed along this length to create a three-dimensional surface form. In order to do so, it is necessary to reduce the noise that is generated by the optical characteristics of the laser sensor to help ensure accurate measurement of the individual cross-sectional surface forms.

3.1. Method of Evaluation of Ring Cross-sectional Form

The reduction of ring surface roughness and noise in the data acquired by the laser sensor was studied.

Figure 6 shows an example of surface form data acquired by the laser sensor. Oscillation of short-wavelength components can be seen on the arc-shaped surface. Because ring surface roughness components and noise exist in the short-wavelength components, a low-order approximate curve, P , is determined for the cross-sectional form data, as shown in Fig. 6, and the residual error is separated out as surface form Q , as shown in Fig. 7. The power spectrum of Q and its integrated frequency is then calculated, as shown in Fig. 8(a).

The same cross-section on the same ring is then measured using a contact-type form measurement machine (a CV-500 manufactured by Mitutoyo) with a stylus of 25 μm in radius, and the power spectrum of the surface form and its integrated frequency is calculated, as shown in Fig. 8(b). The integrated frequency distribution in Fig. 8(b)

increases logarithmically up to approximately the 10th-order, and includes approximately 80% of the form components. In addition, the form components up to the 10th-order are in the range of undulations with wavelengths of 0.9 mm and higher, and do not correspond to the wavelength range of roughness.

The integrated frequencies of the power spectrum calculated from the surface form measurements obtained using the contact-type form measurement machine and the laser sensor exceed 80% at the 12th and 32nd orders respectively. Given this, it was judged that the short wavelength components of the 12th-order and above in the surface form data acquired using the laser sensor represented noise occurring due to the optical characteristics of the laser, and it was therefore decided to employ a Gaussian filter⁽³⁾, which would shield the short-wavelength components. The cutoff frequency, λ_c , was set at 0.8 mm. As a result of using this filter, amplitude transmission characteristics of approximately

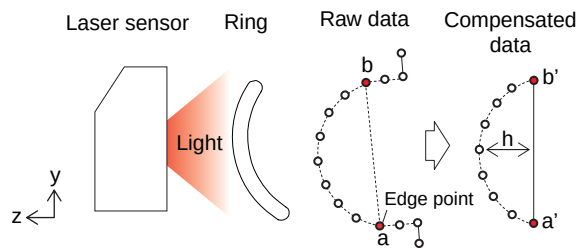


Fig. 5 Principle of data acquisition and compensation

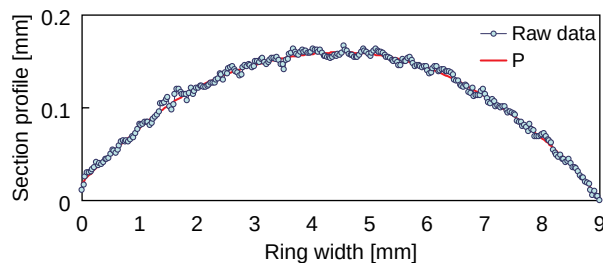


Fig. 6 Example of data acquisition by line laser sensor

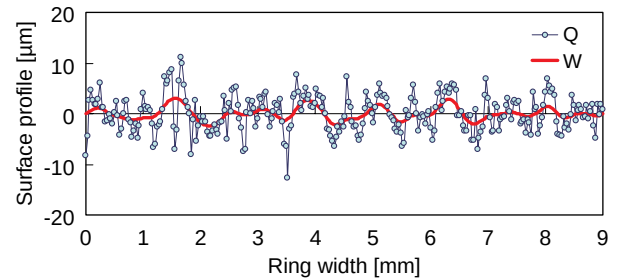
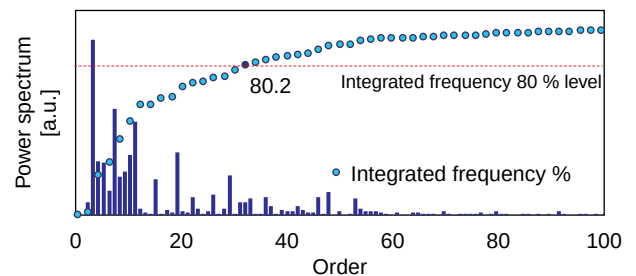
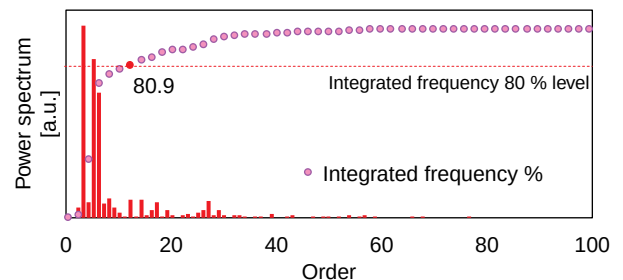


Fig. 7 Ring surface measured by line laser sensor and filtering



(a) Line laser measurement



(b) Contact-type form measurement machine

Fig. 8 Comparison of power spectrum on ring surface

50% and 10% were obtained for the 10th-order and 20th-order form components respectively.

The effect of the filter on the surface form Q is shown as undulation W in Fig. 7. The surface form of the ring is defined as the form obtained from the addition of P to the extracted undulation W. By separating the noise that is prone to occur at the ring edges from the surface form, this method stabilizes the accuracy of the measurement of the height of the arc, h, which is the object of measurement.

3.2. Evaluation of Accuracy of Non-contact-type Measurement

The developed measurement instrument was used to measure the arc heights, h, of ten cross-sections of a randomly-selected ring, and the results were compared with results obtained using the contact-type form measurement machine. As Fig. 9 shows, the average deviation for the ten cross-sections was 4.3 μm , and the coefficient of correlation was 0.99. The perpendicularity of the angle of incidence of the laser light on the ring surfaces was the main factor producing the deviation between measurements of h at the ten cross-sections made using the contact-type measurement machine and the laser sensor, and this was amenable to geometric correction.

The ten cross-sections of the randomly-selected ring were each measured ten times and an analysis of variance was conducted on the results in order to verify the repeatability of results obtained using the developed measurement instrument. The factors listed below were evaluated by resetting the roller in the measurement instrument for each measurement. σ represents standard deviation.

- (a) σ_R : Variation in the height, h, of the arc shape obtained from measurement points across the entire ring
- (b) σ_E : Variation in the height, h, of the arc shape obtained from repeated measurements in the same position
- (c) σ_M : Repeatability of the measurements including positioning of the pulleys and setting of the ring in the instrument

Using Eq. (3), X_{ij} was calculated for the data format shown in Table 1 as the measurement result for the ith

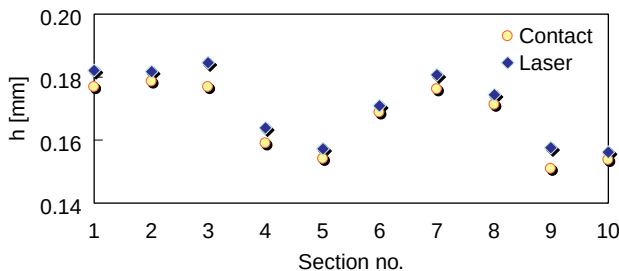


Fig. 9 Measurement accuracy based on laser sensor

Table 1 Raw data for evaluation of measurement repeatability

h mm	No. 1	...	No. 10	Average
Section 1	0.1796	...	0.1855	0.1820
...				
Section 10	0.1525	...	0.1543	0.1562
Average	0.1659	...	0.1720	0.1709

Table 2 Result of ANOV for measurement repeatability

$S_i \mu\text{m}^2$		n_i	$M_i=S_i/n_i \mu\text{m}^2$		μm^2
S_1	2.9204	1	M_1	2.92038	—
S_2	0.0117	9	M_2	0.001303	$\sigma_M^2 + 10 \sigma_R^2$
S_3	0.0004	9	M_3	4.05×10^{-5}	$\sigma_M^2 + 10 \sigma_E^2$
S_4	0.0017	81	M_4	2.06×10^{-5}	σ_M^2

measurement of the jth cross-section. σ_R , σ_E , and σ_M were calculated from an analysis of variance table (Table 2) and Eq. (4). n in Table 2 is the degree of freedom.

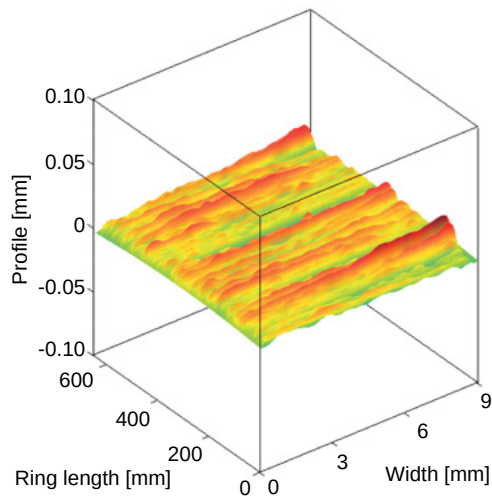
$$\begin{aligned} \bar{X}_i &= \frac{1}{10} \sum_{j=1}^{10} X_{ij}, \bar{X}_j = \frac{1}{10} \sum_{i=1}^{10} X_{ij}, \bar{X} = \frac{1}{100} \sum_{i=1}^{10} \sum_{j=1}^{10} X_{ij} \\ S_1 &= 100\bar{X}^2, S_2 = 10 \sum_{j=1}^{10} (\bar{X}_j - \bar{X})^2 \\ S_3 &= 10 \sum_{j=1}^{10} (\bar{X}_j - \bar{X})^2, S_4 = \sum_{j=1}^{10} \sum_{i=1}^{10} (X_{ij} - \bar{X}_i - \bar{X}_j + \bar{X})^2 \end{aligned} \quad (3)$$

$$\begin{aligned} \sigma_R &= \sqrt{(M_2 - M_4)/10} = 11.3 \mu\text{m} \\ \sigma_E &= \sqrt{(M_3 - M_4)/10} = 1.4 \mu\text{m} \\ \sigma_M &= \sqrt{M_4} = 4.5 \mu\text{m} \end{aligned} \quad (4)$$

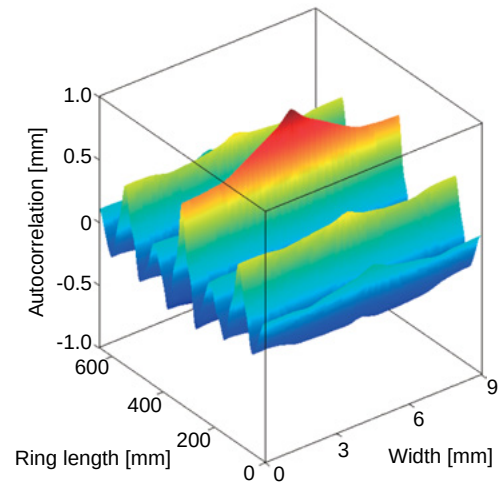
The measurement accuracy for the arc shape per cross-section for the measurement instrument, σ_E , was 1.4 μm , and the repeatability, σ_M , was 4.5 μm . This cannot be regarded as a high level of accuracy when compared to the accuracy of the contact-type measurement machine. However, the measurement principle employs a low-cost, general-purpose laser sensor and simple positioning mechanism, and can therefore be expected to find application at sites of manufacture of rings.

4. Measurement and Analysis Results

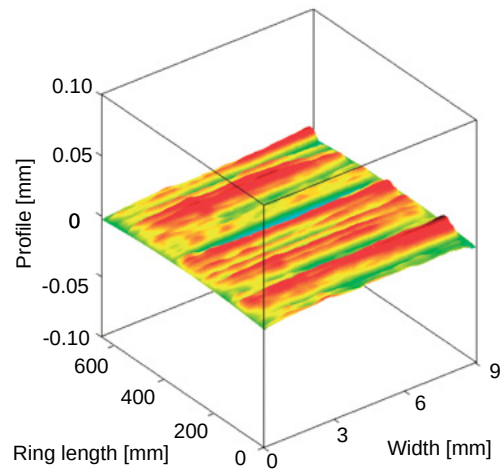
In order to help enable quantitative understanding of the processing history of the rings through the different manufacturing processes, the newly developed measurement instrument was used to evaluate the surface forms of (1) rings following rolling, (2) manufactured



(a) Raw data of ring surface after rolling



(c) Autocorrelation of the surface in Fig. 10 (b)



(b) After low pass filtering of the surface in Fig. 10 (a)

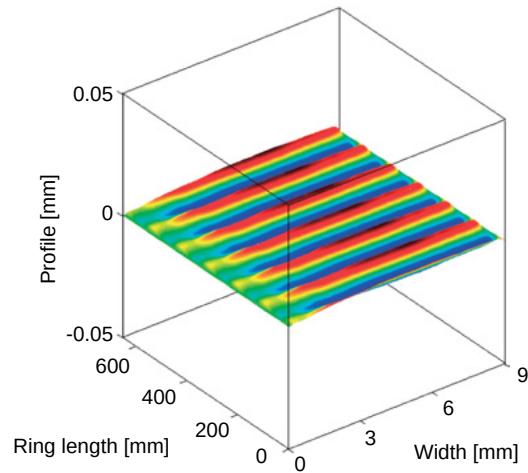
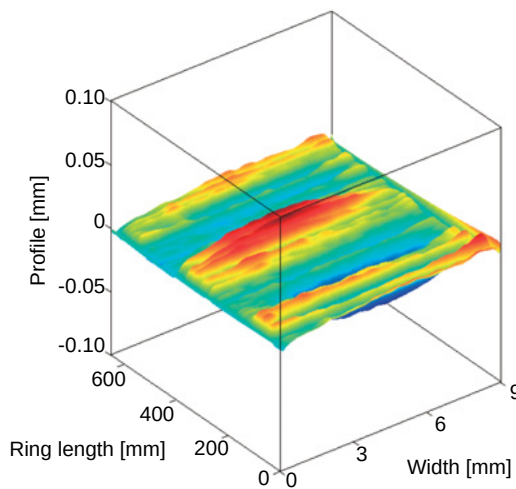
(d) Extraction of 6th-order form from Fig. 10 (b)

Fig. 10 Measurement results of ring surface after rolling



(a) After low pass filtering of raw surface data

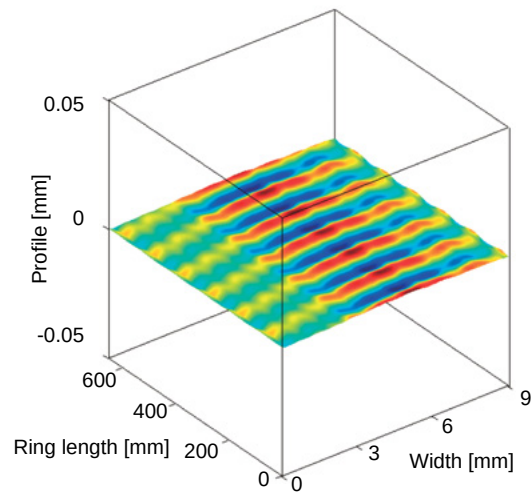
(b) Extraction of 6th-order form from Fig. 11 (a)

Fig. 11 Measurement results of ring surface of product

rings, and (3) areas of the rings that undergo distortion during heat treatment. The results of evaluation of (1), (2) and (3) are shown in Figs. 10, 11, and 12, respectively.

For the evaluations, the minimum angle of rotation of the pulley in the instrument was set at 3 deg, and approximately 250 cross-sections were used across the entire length of the rings. The number of cross-sections was arbitrarily set.

In order to separate the cylindrical and the surface form of the rings, least squares approximation was applied to the obtained three-dimensional surface form data, z , using Eq. (5). The surface form, dz , was defined as the deviation between z and z_p , the approximated cylindrical curved surface.

$$z_p(x, y) = ax^2 + by^2 + 2cxy + 2dx + 2ey + f \quad (5)$$

The surface form, dz , of the ring following rolling is shown in Fig. 10(a). Using Eq. (6), a filter that did not affect the form of the ring in the direction of width was applied in order to isolate the low-order form components of dz . λ_x and λ_y represent, respectively, the wavelength in the direction of the ring circumference, x , and in the direction of the ring width, y . The cutoff wavelength, λ_c , was set at 30 mm. This filter resulted in an amplitude transmission characteristic of approximately 50% for the 20th-order form components, and approximately 24% for the 30th-order form components.

$$H(\lambda_x, \lambda_y) = e^{-\pi \left(\frac{\alpha \lambda_c}{\lambda_x} \right)^2} \quad (6)$$

The effect of the filter applied using Eq. (6) is shown in Fig. 10(b). A series of six evenly-spaced asperities can be observed in the direction of the ring circumference. In addition, the amplitude of the form in the positive direction of ring width displays a tendency to increase.

Terming the surface area of the ring across its entire

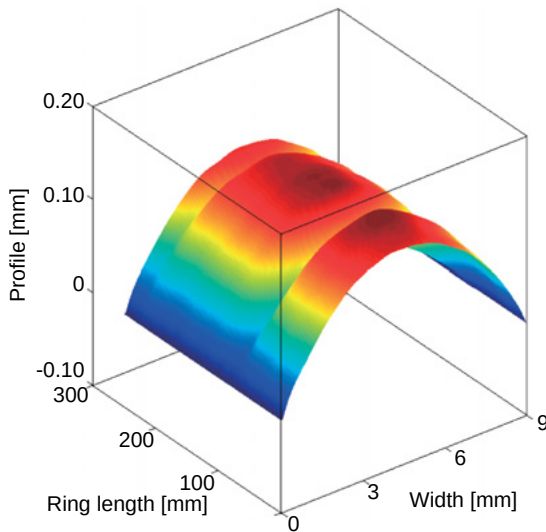


Fig. 12 Form deformation generated by heat treatment

length A , and the arithmetic mean of the surface height as found using Eq. (7) SW_a , an evaluation of the surface form shown in Fig. 10(b) resulted in a figure of 2.4 μm for SW_a .

$$SW_a = \frac{1}{A} \iint_A |dz(x, y)| dx dy \quad (7)$$

Normalization of C , calculated from a reverse Fourier transform, IFT [Eq. (9)], of S , the two-dimensional power spectrum found using Eq. (8), enables the auto-correlation function, A_c , to be found using Eq. (10).

$$S(f_x, f_y) = |\text{FT}(dz(x, y))|^2 \quad (8)$$

$$C(x, y) = \text{IFT}(S(f_x, f_y)) \quad (9)$$

$$A_c(x, y) = \frac{C(x, y)}{C(x_0, y_0)} \quad (10)$$

The auto-correlation function is employed in the study of processed surfaces in order to help enable discrimination of the direction of the main components, and as an index of directional cyclicity⁽⁴⁾. Figure 10(c) shows the results of calculation of the auto-correlation function with (x_0, y_0) , the centers of the length of the circumference and the plate width, as the benchmarks.

A 6th-order correlation that decreases in proportion to the distance from x_0 in the direction of the circumference can be observed in the results. The increases in correlation that are observable at 110 mm and 540 mm in the direction of the circumference result from the effect of the 3rd-order components. Figure 10(d) shows only the 6th-order components in the direction of the circumference extracted from the surface form shown in Fig. 10(b). The cyclical form continues across the entire width of the plate, with a maximum amplitude, S_6 , of 3.5 μm .

This results, as indicated by Eq. (1), from the eccentricity of the roller in relation to its axis of rotation, and shows that six rotations of the roller were required to roll the entire length of the circumference of the ring.

Figure 11 shows the results of measurement of the surface form of the manufactured ring. Figure 11(a) shows the results of application of the filter in Eq. (6) to the surface data for the manufactured ring. SW_a in Fig. 11(a) is 4.3 μm . Figure 11(b) shows only the 6th-order components extracted from Fig. 11(a). The maximum amplitude, S_6 , in these results is 1.5 μm , a reduction of 60% against the results for the ring following rolling. This is conjectured to be a result of the correction of the length of the circumference of the ring by the application of a roller of a different diameter to the rolling roller in order to increase the length of the ring following rolling.

Figure 12 shows the surface form of the ring following the application of the heat treatment. Two areas of deformation of approximately 40 μm can be observed within the 300 mm evaluation range. The positions of these areas of deformation correspond to the positions of

the white areas shown in Fig. 13. Their positions also match the positions of physical interference when the ring is placed in the jig.

Figure 14 shows the change in S_6 and SW_a between the ring following rolling and the completed ring. While S_6 decreases in the course of the processes following rolling up to the completion of the ring, SW_a increases. This is because the deformations induced by the application of the heat treatment, shown in Fig. 12, are included in the surface form. Evaluation of SW_a in isolation makes it challenging to achieve an understanding of the profile deviation resulting from the processes used in the manufacture of the rings, but simultaneous evaluation of S_6 , involving the evaluation of specific cyclical components, helps to explain the relationship between manufacturing processes and profile deviation.

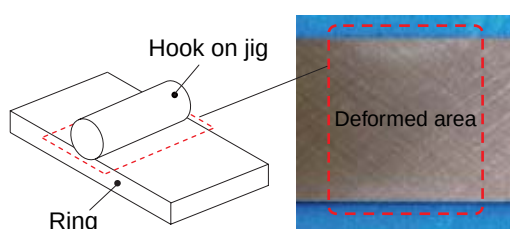


Fig. 13 Surface deformed area generated by heat treatment

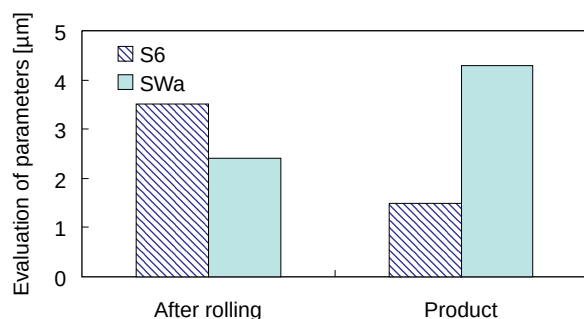


Fig. 14 Evaluation of surface height parameters

5. Conclusion

A technology enabling evaluation of the three-dimensional form of the metal rings employed in CVTs has been developed with the goal of achieving a high level of accuracy in the form of the rings. The results of this project and the benefits offered by the technology are as follows.

- (1) Acquisition of data on the cross-sectional form of the rings in the direction of the circumference using a general-purpose line laser sensor and continuous array of the data enabled the realization of three-dimensional form measurements. The developed measurement instrument has a simple configuration, is inexpensive,

and can be easily used at sites of manufacture of the rings.

- (2) The application of a frequency analysis to the three-dimensional surface form data enabled the profile deviations produced by processes employed in the manufacture of the rings to be revealed and quantified. In addition, expression of the surface form as an auto-correlation function enabled visualization of the characteristics produced by processing and the history of processing.
- (3) The eccentricity of the roller used in the rolling process produced a 6th-order cycle with a maximum amplitude, S_6 , of 3.5 μm , but this figure was reduced to 1.5 μm in the manufactured ring, following the process of correction of the length of the circumference. In addition, a case was observed in which the arithmetic mean of the height of the ring surface, SW_a , increased from 2.4 μm in the ring following rolling to 4.3 μm in the manufactured ring following heat treatment application.

This measurement and analysis technology can be expected to enable rapid detection of issues in manufacturing processes, and to contribute to enhancing the efficiency of prototype production.

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■ Author ■



Kenta UMETSU



Hiroyoshi MIKOGAI