Trans. of the Society of Instrument and Control Engineers
Vol.E-1,No.1, 1/10(2001)

High-Speed 3-Channel Ellipsometer for industrial Uses

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A new high speed photometric ellipsometer consisting of simple optical elements, electronics and personal computer is developed. Data acquisition time of the new ellipsometer is only limited by the response time of the photodetector's circuitry. This ellipsometer, having no moving parts, is suitable for measuring film thickness moving fast in the process line, where no conventional ellipsometer can be applied. In this proposed apparatus, a certain polarized light(ex. linearly or circularly) is used as an incident beam and the reflected beam from the object is split into 3 beams through the beam splitter which consists of 3 or 4 optical parallels. The intensity of each beam transmitted through the analyzer with a certain azimuth angle is measured by the photodetector. Each intensity signal multiplied by the gain factor for each channel, denoted by I_1, I_2, I_3 can be used to derive the two ellipsometric parameters. The analysis with Jones vector representation shows that the ellipsometric parameters $\cos\Delta$, $\tan\Psi$ are expressed as follows;

$$\cos\Delta = \frac{I_2 - I_3}{2I_1}\sqrt{\frac{I_1}{I_2 + I_3 - I_1}} \quad , \quad \tan\psi = \sigma_1\sigma_2\sqrt{\frac{I_1}{I_2 + I_3 - I_1}}$$

where incident beam is linearly polarized(azimuth -45 °), the azimuth angle of each analyzer is 0 ° (ch.1), 45 ° (ch.2), -45 ° (ch.3) respectively, and $\sigma_1\sigma_2$ is a constant determined by the refractive index and the angle between the reflected beam and the beam splitter. The precision of $\cos\Delta$ and $\tan\Psi$ by this ellipsometer is on the order of 5.0×10^{-4}. This new ellipsometer is applied to measure oil film with thickness order of 0 ~ 100Å coated on tinned steel sheet moving at a speed of 300 m/min. In this case, the following considerations are further taken into account.

1) Linear relation between ellipsometric parameter $\cos\Delta$ and film thickness d is used.
2) Two lasers (He-Ne laser, Ar laser) with different wavelength λ_1, λ_2 are used to eliminate the ellipsometric parameter $\cos\Delta_0$ of substrate which changes continuously.

Oil film thickness measured by the new ellipsometer and those by the conventional off-line method (hydrophil balance method) are agreed within the uncertainty of 1 mg/m^2 (corresponding thickness is about 11Å).

Key Words: high speed ellipsometer, personal computer, beam splitter, analyzer, film thickness in-line measurement

1. Introduction

Ellipsometer is known as an instrument which measures film thickness or complex index of refraction of a surface of the object. In the steel- manufacturing industry, there is a great need to adopt this instrument for the on-line measurement of thin films thickness such as oil films or oxidized chromate films on steel sheet's surfaces. In steel-manufacturing processes, however, there are some problems which make it difficult to adopt this instrument for actual operation, such that an object to be measured moves fast more than several m per sec, there exists severe environmental conditions such as vibrations and large temperature change, and optical characteristics of the surface of steel sheet can be changed considerably from point to point. In order to overcome these problems, a 3-channel ellipsometer consisting of simple optical elements, electronics and personal computer is developed. The speed of data acquisition of the new ellipsometer is extremely fast and only limited by the

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photodetector's response time. To eliminate the influence of changes of optical characteristics of a surface on a real time basis, two lasers with different wavelength are used as a light source of the ellipsometer. The new ellipsometer was applied to an on-line oil film thickness meter for the tinned steel manufacturing line. In this study, the principles of the 3-channel ellipsometer, the real time correction method for surface change and the results of the on-line test of the ellipsometer are described.

2. Measurement Principles

2.1 Descripsion of ellipsometry

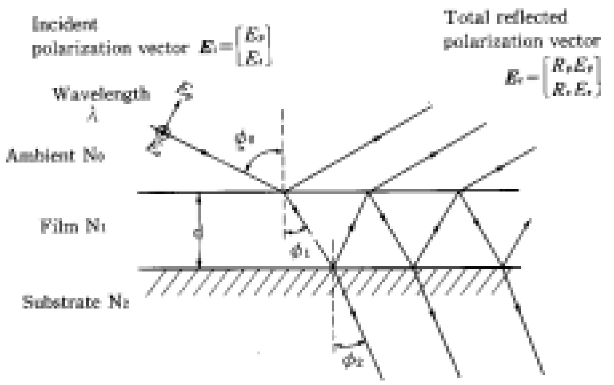

Fig. 1 Reflection and transmission of a plane wave by an ambient-film-substrate system

Fig.1 shows an example of a single-layer film with a film thickness of d on the substrate. Ellipsometry is a method to measure the ratio ρ of R_p, amplitude reflection coefficient of the polarization vector parallel to the plane of incidence and R_s, amplitude reflection coefficient of the polarization vector perpendicular to the plane of incidence. ρ is a complex number and is defined by two real parameters Δ and Ψ. ρ is also related to N_0 the complex index of refraction of the ambient, N_1 the complex index of refraction of the film N_2 the complex index of refraction of the substrate, film thickness d, incident angle ϕ_0, and wavelength λ by a certain equation. Please refer to references 1) and 2) for the details of the equation. In this report, ρ shall be defined by the equation (1) as follows:

$$\rho = \frac{R_p}{R_s} = \tan\psi e^{j\Delta} = F(N_0, N_1, N_2, \phi_0, \lambda, d) \quad (1)$$

If the values for Δ and Ψ are known by measurement, it is possible to obtain the film thickness d by solving the equation (1) with known values N_0, N_1, N_2 ϕ_0, and λ. The instrument to measure these two parameters Δ and Ψ is called the ellipsometer and various types of ellipsometers have been proposed to date.

2.2 Conventional ellipsometers

The ellipsometers widely used at present can be divided into two types, the null ellipsometer and the photometric ellipsometer, well known as a rotating analyzer ellipsometer. Fig.2 shows a basic optical system of those conventional ellipsometers.

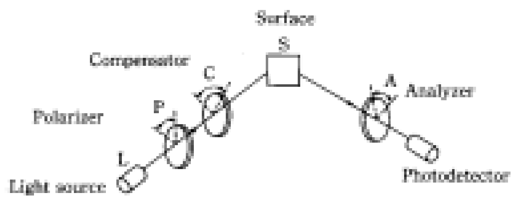

Fig. 2 Schematic optical system of conventional ellipsometer

As an example of null ellipsometers, a fully computerized automatic ellipsometer which servo-controls the angles of the polarizer **P** and the analyzer **A** was developed[3], however, it is slow and usually takes more than one second to measure Δ and Ψ. For the demands of high-speed operation, another instrument which uses Faraday cell for polarizer and analyzer[4], as well as the instrument which uses Pockels cell for compensator have also been proposed[5]. However, these types of instruments have not been practically used much because the thermal and dispersive characteristics of such cells are too large, and also the actual instruments would be too complex. The rotating analyzer type, on the other hand, is most widely used as a high-speed ellipsometer. Its optical system is such that analyzer **A** rotates at a constant speed with the polarizer **P** and the compensator **C** being fixed, the optical intensity signal synchronized with the angular position is fed to a computer to calculate both Δ and Ψ by discrete Fourier transform[6].
The rotation speed of the analyzer is 300 rpm and both Δ and Ψ can be measured at a speed as high as 0.2 second. If this instrument is to be adopted for a steel-making process line which runs at a speed of 5

m/s, however, the measurement point will move 1 m during the course of one measurement. As the surface characteristics such as the index of refraction and roughness continuously change, accurate measurement cannot be expected without improving measurement speed.

2.3 3-Channel ellipsometer

The ellipsometer to be used for on-line processes is required to be durable against temperature variations and vibrations in addition to high-speed performance. As an optical system which satisfies these requirements, a 3-channel ellipsometer shown in Fig.3 has been developed.

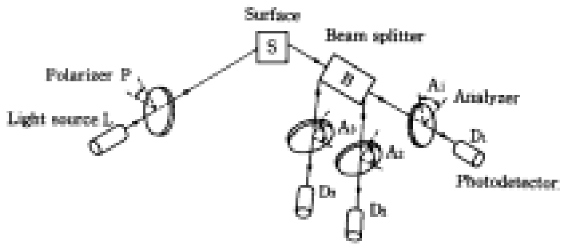

Fig. 3 Schematic optical system of 3-channel ellipsometer

In this optical system, the polarizer is fixed and a compensator is not always necessary. A beam splitter provided in the reflected light beam to divide it into three beams. Each divided beam is sent to the analyzers with transmission azimuth angles of 0° ,45° , and -45° and two ellipsometric parameters Δ and Ψ are obtained through the calculation by the personal computer with the three optical power signals from each photodetecter. At this time, it is necessary that the changes in amplitude and phase due to transmission and reflection at the beam splitter be the same in at least two channels. For beam splitters, the one consisting of three or four optical parallels made of a transparent and homogeneous optical glass, arranged in parallel as shown in Fig.4, is used. It is also necessary to use only the beam transmitted or reflected once at each optical parallel, as shown in Fig.5.

2.4 Derivation of equations for 3-channel ellipsometer

When Jones vector representation[1], which is convenient for analysis of the polarization field, is used,

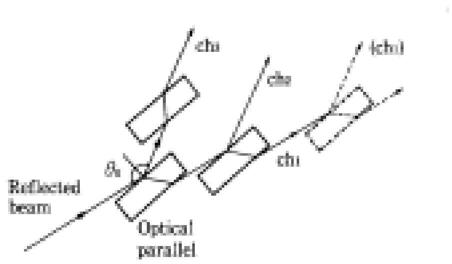

Fig. 4 Beam splitter consists of 3 or (4) optical parallels

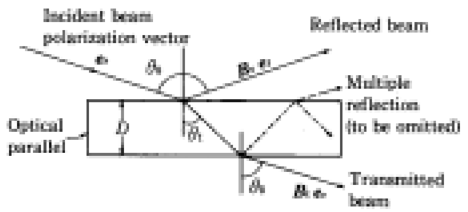

Fig. 5 Reflection and transmission at an optical parallel

the polarized electric field vector incident to each photodetector of the 3-channel ellipsometer shown in Fig.3 can be expressed by equations (2) to (4).

$$\text{ch. 1} \quad \mathbf{E_1}=k_1\mathbf{R}(-A_1)\begin{vmatrix}1 & 0\\ 0 & 0\end{vmatrix}\mathbf{R}(A_1)\,\mathbf{B_t}^2\ \mathbf{S}\ \mathbf{E_i} \qquad (2)$$

$$\text{ch. 2} \quad \mathbf{E_2}=k_2\mathbf{R}(-A_2)\begin{vmatrix}1 & 0\\ 0 & 0\end{vmatrix}\mathbf{R}(A_2)\,\mathbf{B_r}\ \mathbf{B_t}\ \mathbf{S}\ \mathbf{E_i} \qquad (3)$$

$$\text{ch. 3} \quad \mathbf{E_3}=k_3\mathbf{R}(-A_3)\begin{vmatrix}1 & 0\\ 0 & 0\end{vmatrix}\mathbf{R}(A_3)\,\mathbf{B_t}\ \mathbf{B_r}\ \mathbf{S}\ \mathbf{E_i} \qquad (4)$$

Here, it is assumed that the basis of the Jones vectors would be taken at the axis P parallel to the plane of incidence and at the axis S which is perpendicular to the axis P, and the beam splitter consisting of three optical parallels as shown in Fig.4 would be used. The following are the descriptions of the quantities used in the equations (2) to (4).

1) Constants k_1 to k_3 : total transmission coefficients at each channel
2) $\mathbf{E_i}$: polarization vector of incident light, and can be defined as follows;

$$\mathbf{E_i}=\begin{vmatrix}E_p\\ E_s\end{vmatrix}=E_p\begin{vmatrix}1\\ \chi_i\end{vmatrix} \qquad (5)$$

$$\chi_i=\left|\frac{E_s}{E_p}\right|e^{j\varphi_i}\equiv\tan Pe^{j\varphi_i}$$

P = azimuth angle , φ_i = phase difference

3) **S**： Jones reflection matrix of the object to be measured, and can be defined as follows;
(It is assumed that the matrix is isotropic.)

$$\mathbf{S} = \begin{vmatrix} R_p & 0 \\ 0 & R_s \end{vmatrix} = R_s \begin{vmatrix} \rho & 0 \\ 0 & 1 \end{vmatrix} \qquad (6)$$

$$\rho = \frac{R_p}{R_s} = \tan\Psi e^{j\Delta}$$

4) $\mathbf{B_r}$, $\mathbf{B_t}$ ： Jone's matrix which expresses the reflection and transmission characteristics at optical parallel. By excluding multiple reflection, the diagonal elements σ_1 and σ_2 will be real positive values.

$$\mathbf{B_r} = (r_{01})_p \begin{vmatrix} 1 & 0 \\ 0 & \sigma_1 \end{vmatrix}, \quad \mathbf{B_t} = \{1-(r_{01})_p{}^2\} e^{-j\delta} \begin{vmatrix} 1 & 0 \\ 0 & \sigma_2 \end{vmatrix} \qquad (7)$$

$$\sigma_1 = \frac{(r_{01})_s}{(r_{01})_p}, \sigma_2 = \frac{1-(r_{01})_s{}^2}{1-(r_{01})_p{}^2}, \delta = \frac{2\pi D}{\lambda}\sqrt{n^2 - \sin^2\theta_0} \qquad (8)$$

where,

$(r_{01})_{p,s}$: Fresnel reflection cofficient of an optical parallel

D, n : thickness and index of refraction of an optical parallel

θ_0: incident angle to an optical parallel, to be greater than Brewster angle θ_B

λ : wavelength

It should be noted that both σ_1 and σ_2 do not include D and are not influenced by D. If multiple reflection is not excluded, both σ_1 and σ_2 will become complex numbers including D and it will be difficult to assume them as constants.

5) $R(-A_j)\begin{vmatrix} 1 & 0 \\ 0 & 0 \end{vmatrix} R(A_j)$: Jones matrix which expresses the analyzer of the azimuth angle A_j of the transmission axis. $\mathbf{R}(A_j)$ is a matrix which rotates a coordinate system by A_j degree around the axis along which light propagates.

$$\mathbf{R}(A_j) = \begin{vmatrix} \cos A_j & -\sin A_j \\ \sin A_j & \cos A_j \end{vmatrix} \qquad (9)$$

The optical power Φ_j of each channel can be expressed by the square of the absolute value of the Jones vectors expressed in equations (2) to (4).

$$\Phi_j = \left|\mathbf{E}_j\right|^2 = \mathbf{E}_j{}^t \mathbf{E}_j{}^*, \quad j=1\sim3 \qquad (10)$$

(t denotes transposition)

When the equations (5), (6), (7), and (9) are substituted for equation (10), the following equations (11) to (13) are obtained.

$$\Phi_1 = |k_1|^2|c_1|^2\{\tan^2\Psi\cos^2 A_1 + 2\sigma_2{}^2 \tan P \tan\Psi\cos(\Delta-\varphi_i)\times \sin A_1 \cos A_1 + \sigma_2{}^4 \tan^2 P \sin^2 A_1\} \qquad (11)$$

$$\Phi_2 = |k_2|^2|c_2|^2\{\tan^2\Psi\cos^2 A_2 + 2\sigma_1\sigma_2 \tan P \tan\Psi\cos(\Delta-\varphi_i)\times \sin A_2 \cos A_2 + \sigma_1{}^2\sigma_2{}^2 \tan^2 P \sin^2 A_2\} \qquad (12)$$

$$\Phi_3 = |k_3|^2|c_3|^2\{\tan^2\Psi\cos^2 A_3 + 2\sigma_1\sigma_2 \tan P \tan\Psi\cos(\Delta-\varphi_i)\times \sin A_3 \cos A_3 + \sigma_1{}^2\sigma_2{}^2 \tan^2 P \sin^2 A_3\} \qquad (13)$$

c_1 to c_3 are the constants indicating the product of all the amplitude coefficients outside each matrix and vector. The optical power Φ_j is converted into voltage signal by the photodiode with linear characteristics. When the total gain of the measurement system of each channel including the conversion coefficient and the gain factor of the electronic circuit are expressed by G_1 to G_3, the voltage output I_j of each channel is expressed by equation (14).

$$I_j = G_j \Phi_j, \quad j=1\sim3 \qquad (14)$$

The value for the gain G_j should be determined in such a manner that the voltage output from all channels would be equal when the analyzer angle A_j of each channel is set to 0°. Here, let the output of each channel (for a some measurement point $\rho_0 = \tan\Psi_0 \times e^{j\Delta_0}$) with A_1, A_2, and A_3 being all set to zero be expressed by equation (15).

$$I_1(A_1=0) = I_2(A_2=0) = I_3(A_3=0) = I_0 \tan^2\Psi_0 \qquad (15)$$

On inserting equation (15) into equations (11) to (13), the gain G_j is determined as follows.

$$G_1 = \frac{I_0}{|k_1|^2|c_1|^2}, G_2 = \frac{I_0}{|k_2|^2|c_2|^2}, G_3 = \frac{I_0}{|k_3|^2|c_3|^2} \qquad (16)$$

When equation (16) is substituted for equation (14), and the analyzer angle of each channel is set to A_1= 0°, A_2= 45°, and A_3 = -45°, the output voltage of each channel is expressed by equations (17) to (19).

$$I_1 = I_0 \tan^2 \Psi \tag{17}$$

$$I_2 = \frac{I_0}{2}\{\tan^2 \Psi + 2\sigma_1\sigma_2 \tan P \tan \Psi \cos(\Delta - \varphi_i) + \sigma_1{}^2\sigma_2{}^2 \tan^2 P\} \tag{18}$$

$$I_3 = \frac{I_0}{2}\{\tan^2 \Psi - 2\sigma_1\sigma_2 \tan P \tan \Psi \cos(\Delta - \varphi_i) + \sigma_1{}^2\sigma_2{}^2 \tan^2 P\} \tag{19}$$

Then, two ellipsometric parameters Ψ and Δ are given by equations (20) and (21) through the equations (17) to (19).

$$\cos(\Delta - \varphi_i) = \frac{I_3 - I_2}{2I_1}\sqrt{\frac{I_1}{I_2 + I_3 - I_1}} \tag{20}$$

$$\tan \Psi = \sigma_1\sigma_2 \tan P \sqrt{\frac{I_1}{I_2 + I_3 - I_1}} \tag{21}$$

where, tanP and φ_i are the polarization parameters defined by equation (5). For example, when an incident light is assumed to be a linearly polarized light with an azimuth angle of -45 °, P and φ_i can be set to 45 ° and π, respectively, and the equations (20) and (21) are rewritten as equations (20)' and (21)'.

$$\cos\Delta = \frac{I_2 - I_3}{2I_1}\sqrt{\frac{I_1}{I_2 + I_3 - I_1}} \qquad (20)'$$

$$\tan\Psi = \sigma_1\sigma_2\sqrt{\frac{I_1}{I_2 + I_3 - I_1}} \qquad (21)'$$

As is clear from equation (21), the expression of parameter Ψ of the 3-channel ellipsometer incorporates the constants σ_1 and σ_2. These values, however, can be calculated by using equation (8). When four optical parallels as shown in Fig. 4 are used, only the matrix $\mathbf{B_t^2}$ in equation (2) changes to $\mathbf{B_r B_t^2}$ and the final equations (20) and (21) remain valid as they are.

2.5 Characteristics of 3-channel ellipsometer

The characteristics of a 3-channel ellipsometer can be outlined as follows:

(1) Since the ellipsometric parameters Δ and Ψ can be obtained from the simultaneous information I_1 to I_3, it can be applicable to the object which moves at an extremely high speed.

(2) The entire optical system is fixed and has no moving portions. As the optical system consists of only simple and stable elements, it is rugged and suitable for on-line use.

(3) As the parameters cosΔ and tanΨ are given by I_1 to I_3 in a dimensionless form, they are not affected by the fluctuation of optical power.

(4) As the reflected light is divided and a certain amount of light is lost by the beam splitter, the effective amount of light is only 10% of the total reflected light. Therefore, a strong light source like laser is necessary.

(5) when a linearly polarized light is used as an incident light, the measurement accuracy is degraded around Δ= 0 ° and π since the phase parameter Δ is given in a form of cosΔ.

This problem can be solved, however, as the parameter Δ will be given in a form of sinΔ, by changing incident light into circular polarization.

2.6 Thickness measurement of the thin film coated on the steel sheet

1) Linear approximation

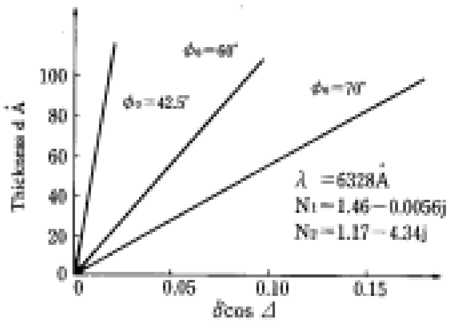

Fig. 6 Oil film thickness vs. change of cos Δ from that of substrate δ cos Δ (= cos Δ−cos Δ_0)

Generally, it is necessary to solve the equation shown in equation (1) to measure film thickness by means of an ellipsometer. However, as to a transparent and extremely thin film on an opaque substrate such as a steel sheet, a linear relation is generally formed between the film thickness d and ellipsometric parameters Δ,Ψ or cosΔ, tanΨ[7]. Fig.6 shows the relationship between the oil film thickness and the difference of cos Δ from that of the substrate, calculated through the equation (1). The coefficient for each line remains constant within 2% of uncertainty, as far as the deviation of the complex refractive index of the substrate N_2 from its average value is within 10% in magnitude. Accordingly following equation (22) can be assumed between thin oil film thickness d and cos Δ for certain wavelength and incident angle.

$$\cos\Delta - \cos\Delta_0 = kd \qquad (22)$$

where,

cos Δ : ellipspmetric phase parameter of the object to be measured

$\cos\Delta_0$: ellipspmetric phase parameter of the substrate

k : constant (sensitivity coefficient)

d : oil film thickness

With regard to tan Ψ, there exists also a linear relationship. However, as the sensitivity is less by one order as compared with cos Δ in this case, tan Ψ is not used here.

2) Correction method for variation of the substrate's $\cos\Delta_0$

On-line measurement, cos Δ is the only parameter we can measure. A problematic point in equation (22) is that the substrate phase value $\cos\Delta_0$ fluctuates due to surface roughness and so on. According to the data obtained by measuring substrate samples, the fluctuation width of $\cos\Delta_0$ will be large enough to require some correction method. A method to take the difference between the phase values before and after oiling being considered, but it is difficult to take measurements at the same point before and after oiling, and hard to expect a good measurement accuracy. It is desirable that the substrate is corrected at a measurement point in real time. The following two methods are examined here.

1) A method with which two different incident angles ϕ_1 and ϕ_2 are used with the wavelength λ being constant.
2) A method with which two different wavelengths λ_1 and λ_2 are used with the incident angle ϕ_0 being constant.

The quantitative analysis about the influence of the roughness of substrate surface to the ellipsometric parameters Δ and Ψ being insufficient[7),8)], the determination as to which method is more advantageous should be made based on the results of experiments. We concluded that method 2) is superior to the other in term of accuracy and the simplicity of the optical system. If the quantities related to the wavelengths λ_1 and λ_2 are denoted by subscripts 1 and 2, equation (22) is rewritten for each wavelength and equation (23) is obtained.

$$\left.\begin{array}{ll} x_1 - x_{01} = k_1 d & (\text{for wavelength}\ _1) \\ x_2 - x_{02} = k_2 d & (\text{for wavelength}\ _2) \end{array}\right\} \quad (23)$$

where,

$x_1, x_2 \equiv \cos\Delta_1, \cos\Delta_2$, $x_{01}, x_{02} \equiv \cos\Delta_{01}, \cos\Delta_{02}$,

k_1, k_2 : proportional coefficient,

d : oil film thickness

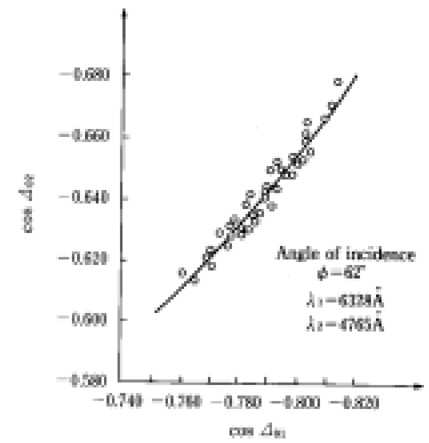

Fig. 7 Plots of cos Δ_0 at wavelength λ_1 against that at wavelength λ_2 of tinned steel surfaces with various surface roughness

A certain functional relation has been confirmed experimentally between x_{01} and x_{02} for substrate samples with various surface roughness.

$$x_{02} = f(x_{01}) \qquad (24)$$

Fig.7 shows a measurement result of x_{01} ,x_{02} for various samples of actual tinned steel sheets. Generally, the greater the surface roughness, the absolute values x_{01} and x_{02} tend to be small. According to the experimental results, it is confirmed that equation (24) can be approximated by a quadratic.

$$x_{02} = f(x_{01}) = \alpha x_{01}^2 + \beta x_{01} + \gamma \qquad (25)$$

here, α, β, and γ are the constants which are experimentally determined. Elimination x_{01} and x_{02} by substituting equation (23) into equation (25), the phase change X which is proportional to the oil film thickness is given by the following equation.

$$X \equiv k_2 d = c_0 + \frac{1}{\kappa} x_1 - c_1 \sqrt{c_2 - \kappa x_2 + x_1} \qquad (26)$$

where, $\kappa = k_1/k_2$: proportional coefficient ratio at wavelengths λ_1 and λ_2

$c_0 = (\kappa\beta - 1)/2\alpha\kappa^2$, $c_1 = (-\alpha\kappa^3)^{-0.5}$,

$c_2 = \gamma\kappa - (\kappa\beta - 1)^2/4\alpha\kappa$

c_0 to c_2 : constants experimentally determined

3. Prototype of 3-channel ellipsometer for on-line use

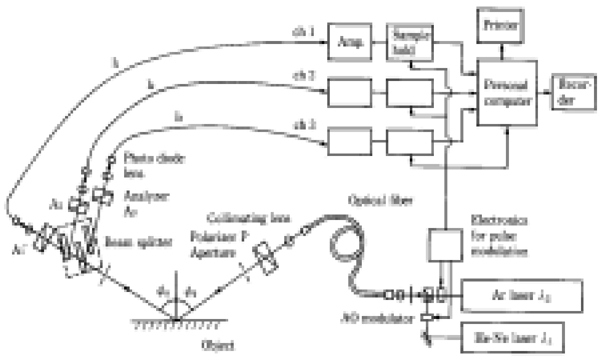

Fig. 8 Schematic diagram of 3-channel ellipsometer for on-line use

Prototype of a 3-channel ellipsometer for on-line application which employs He-Ne and Ar lasers as light sources, and a personal computer as a signal processing unit has been developed. Fig.8 shows the outline of the prototype. The measurement head and the light sources are connected by an optical fiber which has a core diameter of 300 μm. Optical fiber is effective in the points that light beam of different wavelengths can be launched together at the same incident angle, and that it acts as a depolarizer which changes linearly polarized light of the light sources to non-polarized light, in addition to the improved flexibility of the equipment. Two laser beams are modulated to emit alternatively in a pulse form by acousto-optic modulators. Multiplexed detected signals from the photodiodes is distinguished with each wavelength by the sampling hold circuit synchronized with the modulation signal. Sampled data are fed to the data processing system. Table 1 shows the main specifications of the prototype. As the measurement precision of Δ is 0.03 ° (when Δ is around 90 °),0.04 ° (when Δ is 140 °), and 1.81 ° (when Δ is 0 or 180 °) respectively, it may be considered to be satisfactory for the on-line use excluding the areas around where Δ is 0 ° or 180 ° .

Table 1 Specifications for 3 channel-ellipsometer

Incident Beam	Linearly polarized (azimuth −45°) angle of incidence $\phi_0 = 62°$
Beam splitter	3 optical parallels, D=25mm, parallelism ≤5″, BK-7, $\sigma_1\sigma_2$=1.308 (ϕ_0=78°, λ=6 328Å)
Light source	He-Ne laser (λ_1=6 328Å), Ar laser (λ_2=4 765Å) Pulse modulation width 50 μsec, Repetition 200 μsec
Personal computer	PC-9801 VM2, A/D・D/A・DI/O 8087
Data acquisition time	200 μsec (for $(I_i)_{\lambda_1}$, $(I_i)_{\lambda_2}$, i=1−3)
Precision	$2\sigma < 5.0\times10^{-4}$ (for $\cos\Delta_1$, $\cos\Delta_2$)
Analog output	x_1, x_2 : 0~10V ($-0.5 \leq x_1, x_2 \leq -1.0$) X : 0−10V ($0 \leq X \leq 0.15$)

4. Application to on-line oil film thickness meter

4.1 Tinned steel sheet manufacturing process and oil-film thickness control

The tinned steel sheet manufacturing line is a process which electrically tin-plates a steel sheet at a line speed of 2 ~ 5 m/s. In order to prevent tinned steel sheet surface from being scratched, a thin oil film with a thickness less than 100Å is coated on the surface by an electrostatic oiler, as shown in Fig.9.

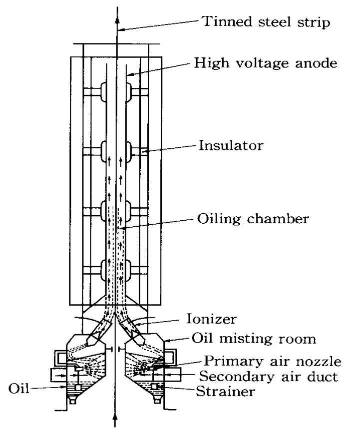

Fig. 9 Schematic illustration of electrostatic oiler (oil film thickness is controlled by secondary air frow rate)

The oil film thickness is controlled by regulating the secondary air flow rate of the electrostatic oiler. As the

note[1] Oil film on the surface of a steel sheet of a fixed area is moved onto water surface as monomolecular film by dipping the sample into the water in a certain manner and oil amount is obtained from the area of oil film on the water surface with a certain surface tension. The oil film thickness is given in the form of oil amount per unit area M (mg/m²). 1 mg/m² is equivalent to 11Å.

ability or printability of steel sheets, a strict control is done for each type of products. Currently, oil film thick ness being measured off-line by a hydrophil balance method[note1)] only for the sheet samples taken at regular intervals, no quick correctional actions can be taken for the products with oil film thickness of out-of-standard. The development of an on-line oil film thickness meter is in demand.

4.2 On-line experiments

The 3-channel ellipsometer prototype was installed in the tinned steel sheet manufacturing line as the oil film thickness meter. Through the experiments, evaluation of the measuring accuracy by comparing it with the hydrophil balance method as well as its stability and durability for long-term operation have been examined. In addition to the ellipsometer outputs, line speed signal and the secondary air flow rate signal of the electrostatic oiler have been recorded simultaneously on the charts for comparison. Coefficients in equation (26) which gives the film thickness output X is determined as (27) through on-line and off-line experiments.

$$X = 1.143 + 1.285x_1 - 0.7783\sqrt{x_1 - 0.778x_2 + 0.290} \qquad (27)$$

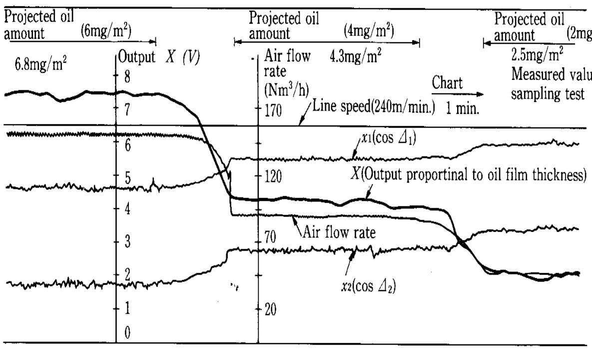

Fig. 10 A chart of calibration test of 3-channel ellipsometer applied to the on-line oil film thickness meter

Fig.10 shows the chart of the on-line test for the changes of oil film thickness. The results shown in the chart were obtained by varying the secondary air flow rate of the electrostatic oiler to get three different oil amount levels, 2 mg/m^2, 4 mg/m^2, and 6 mg/m^2, or approximately 22 ,44 ,and 66Å in terms of oil film thicktness. The ellipsometer output X changed with the changes of air flow rate levels.

Fig. 11 shows the relationship between the measure-

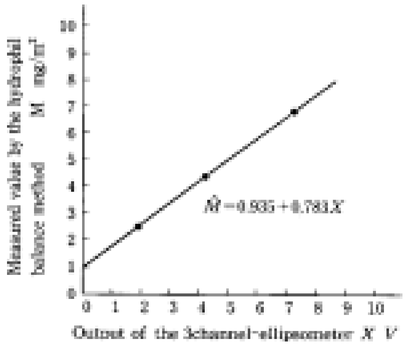

Fig. 11 Plots oil amount value measured by hydrophil balance method vs. output X of 3-channel ellipsometer (on-line calibration test)

-ment values obtained by the hydrophil balance method and the ellipsometer output values X. Both values have shown a good linear relationship.

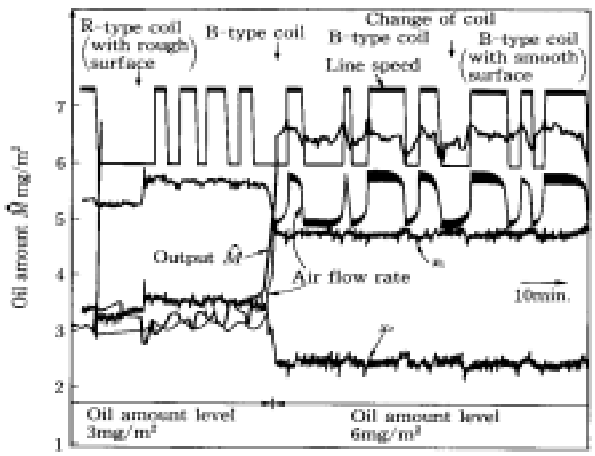

Fig. 12 A chart of x_1, x_2 and calibrated oil amount $\hat{M}$ of 3-channel ellipsometer and line speed, air flow rate signals from line controller in normal line operation

Fig. 12 shows an example of the measurement data obtained during normal line operation. In this chart, the ellipsometer output X is converted into oil amount $\hat{M}$ (mg/m^2) based on the calibration curve shown in Fig. 11. In the chart, the operational conditions for oil amount change from 6 mg/m^2 to 3 mg/m^2 around the center of the chart. During normal operation, the line speeds are sometimes changed, and it has been demonstrated that the oil amount is slightly out of control at the moment when the line speed is changed. With respect to the influence of the surface change of the steel, the fluctuation of ellipsometer output $\hat{M}$ is within ±0.3 mg/m^2 for the alteration of similar type of coils and is within±0.6 mg/m^2 for the alteration of different type of coils with different surface roughness (refer to the alteration from coil B to coil R on the left side of the chart).

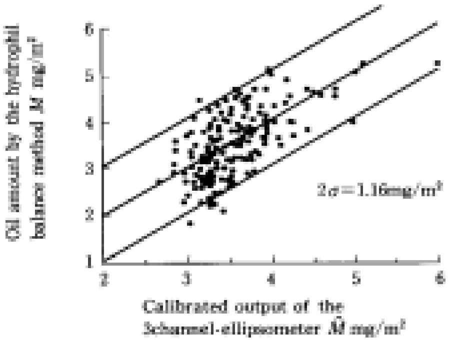

Fig. 13 Relation between oil amount values by hydrophil balance method and those by 3-channel ellipsometer in on-line operation (during one month of normal line operation)

Fig. 13 shows the relationship between oil amount M obtained by the hydrophil balance method and the oil amount output $\hat{M}$ by the ellipsometer during one month normal operation. In the course of the time, the operational levels mainly fell in the range from 3 to 4 mg/m^2, the accuracy of both values were approximately ± 1 mg/m^2 in 2σ. The ellipsometer was continuously operated for 9 months. During the operation, it was unnecessary to correct the calibration curve, confirming its durability and stability for practical application.

5. Conclusion

An ellipsometer has long been considered as a delicate instrument for use mainly in laboratories having good environmental conditions. It was confirmed, however, that the 3-channel ellipsometer proposed here, consisting of simple and stable optical elements and having no moving parts would be satisfactory for on-line use. Actually, this instrument have been applied for an oil film thickness meter in the tinned steel sheet manufacturing line and resulted in good agreement with the conventional off-line method within the accuracy of ± 1 mg/m^2 (about ± 11 Å in terms of thickness). This instrument is advantageous in the point that the data on parameter Δ and Ψ can be taken instantaneously and it can be applied for measurement of a moving object with high speed. It is expected that this instrument will be an effective means for the objects which, in the past, have been considered difficult to measure.

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Translated from Trans. of SICE, Vol.24, No.7, 670/677(1988)