Characteristic of a Plastic Film Thickness Measuring System Using a Slit Beam X-ray

Fumio Tojo Member (Yamabun Electronics, yamabun@mx.mesh.ne.jp)

Shunzo Hirakawa Non-member (Yamabun Electronics, yamabun@mx.mesh.ne.jp)

Toshiyasu Toyoda Non-member (Yamabun Electronics, yamabun@mx.mesh.ne.jp)

Masaru Iguchi Non-member (Yamabun Electronics, yamabun@mx.mesh.ne.jp)

Yusuke Katayama Non-member (Yamabun Electronics, yamabun@mx.mesh.ne.jp)

Mineo Itoh Member (Grad. School of Sci. and Engi., Grad. School of Kinki Univ., itoh@ele.kindai.ac.jp)

Keywords: film thickness, thickness measurement, slit beam X-ray, X-ray thickness measuring system

We describe a new measuring system using a slit beam X-ray of 0.4 mm to accurately measure the thickness of plastic films. Recently, the employment of Plastic films has increased rapidly with use in flat-panel displays, secondary cells, and electronic devices, to make such devices lighter, thinner, and more compact. Therefore, there has been an increased need for the measurement of film thickness with a high accuracy during the manufacturing process. The measurement of film thickness is conventionally accomplished using beta-, gamma-, X-, or infrared-ray methods. In these methods, the basic weight of the films is measured, based on the attenuation of the transmitted radiation, with the X-ray method commonly used. Conventionally, the X-ray thickness measuring system usually employs an X-ray spot beam of 10–20 mm in diameter. However, this beam area is too large to measure some films such as small size film components used in electronic devices. Therefore, it is necessary to improve the resolution ability. A new measuring system for solving this problem has been developed using a slit beam X-ray of 0.4 mm in width and 14 mm in length.

Figure 1 is a schematic diagram of the sensing head used in the measurement of the film thickness, with use of a slit beam X-ray. As schematically illustrated in Fig. 1, a film is placed between the X-ray generator and the detector. The measuring system is composed of an X-ray tube, a high-voltage power supply, a slit, and an ionization chamber as the X-ray detector, a power supply, and the

op-amp. By depending on a variety of different films, the voltage of the X-ray tube is regulated from 4.90 kV to 10.79 kV, under a constant current of 250 μ A to 330 μ A. The strength of the X-ray beam is then measured by an ionization chamber having a constant voltage of 500 V.

The use of this system can drastically improve the resolution in the measurement of plastic film thickness, resulting in an accuracy of $\pm 2.7\%$ or less, for a sample film by the superposition of a polypropylene tape (PP, thickness: 30 μ m, width: 1 or 20 mm) over a PP film (thickness: 30 μ m), as shown in Fig. 2.

Fig. 1. Schematic diagram illustrating the principle of the film thickness measuring system by use of a slit beam X-ray

Fig. 2. The measured sample film thickness t as a function of the direction of film width. Here (a) and (b) are the results for PP tapes with widths of 20 mm and 1 mm, respectively

Characteristic of a Plastic Film Thickness Measuring System Using a Slit Beam X-ray

Fumio Tojo ^{*,**}	Member
Shunzo Hirakawa ^{**}	Non-member
Toshiyasu Toyoda ^{**}	Non-member
Masaru Iguchi ^{***}	Non-member
Yusuke Katayama ^{**}	Non-member
Mineo Itoh [*]	Member

The employment of plastic films has increased rapidly with use in flat-panel displays, secondary cells, and electronic devices, in order to make such devices lighter, thinner, and denser. Conventionally, the X-ray thickness measuring system for plastic films usually employs an X-ray spot beam of 10–20 mm in diameter. However, this beam area is too large to measure some films, such as small size film components used in electronic devices. Therefore, it is necessary to improve the resolution ability. In the present study for solving this problem, the authors describe a new measuring system using a slit beam X-ray of 0.4 mm to accurately measure the thickness of plastic films. The use of this system can drastically improve the resolution in the measurement of plastic film thickness, resulting in an accuracy of $\pm 2.7\%$ or less, for the sample film by the superposition of a polypropylene tape (PP, thickness: $30\mu\text{m}$, width: 1 or 20 mm) over a PP film (thickness: $30\mu\text{m}$).

Keywords: film thickness, thickness measurement, slit beam X-ray, X-ray thickness measuring system

1. Introduction

Recently, the demand for plastic films for use in various applications has increased, such as in flat-panel displays, secondary cells, and electronic devices, to make such devices lighter, thinner, and more compact. Accordingly, the need to save resources and to produce thin films has increased⁽¹⁾. Furthermore, there has been an increased need for the measurement of film thickness with a high accuracy⁽²⁾⁽³⁾, the thickness being within less than $\pm 3\%$ of the required film thickness, during the manufacturing process which operates at speeds of 30 m/min or more. In this paper, sheets is used thickness $250\mu\text{m}$ or more, and films is used less than $250\mu\text{m}$ ⁽⁴⁾. The measurement of film thickness is conventionally accomplished using beta-, gamma-, X-, or infrared-ray methods. In these methods, the basic weight of the films is measured, based on the attenuation of the transmitted radiation, with the X-ray method commonly used.

Conventionally, the X-ray thickness measuring system usually employs an X-ray spot beam of 10–20 mm in diameter⁽⁵⁾⁽⁶⁾. However, this beam area is too large to measure some films, such as small size film components used in electronic devices. Therefore, it is necessary to improve the resolution ability. A new measuring system for solving this problem has been developed using a slit beam X-ray of 0.4 mm in width and 14 mm in length. The present system is capable

of measurement of thickness for films and sheets. Using this system, an accuracy of $\pm 2.7\%$ was realized in the measurement of a sample film by the superposition of a polypropylene tape (PP, thickness: $30\mu\text{m}$, width: 1 or 20 mm) over a PP film (thickness: $30\mu\text{m}$).

In the present paper, discussion is focused on the development of the new measuring system that provides greater accuracy. The results demonstrate the ability for the thickness measurement of flat polypropylene (PP) film and polymethylmethacrylate (PMMA) sheets with semicircle ridges.

2. Film Thickness Measuring System

2.1 Principle of the Thickness Measuring System Using a Slit Beam X-Ray Figure 1 is a schematic diagram of the sensing head used in the measurement of the film thickness, with use of a slit beam X-ray (Yamabun Electronics Co. Ltd., NSW/X). As schematically illustrated in Fig. 1, a film (1) is placed between the X-ray generator (2) and the detector (3). The measuring system is composed of an X-ray tube (4), a high-voltage power supply (maximum rating: 15 kV, $400\mu\text{A}$), a slit (6), and an ionization chamber (7) as the X-ray detector, a power supply, and the op-amp. By depending on a variety of different films, the voltage of the X-ray tube is regulated from 4.90 kV to 10.79 kV, under a constant current of $250\mu\text{A}$ to $330\mu\text{A}$. The strength of the X-ray beam is then measured by an ionization chamber (7) having a constant voltage of 500 V.

The film thickness t is calculated according to the following equation, being defined in terms of the reduction in the strength of the slit beam X-ray that occurs due to the

* Interdisci. Grad. School of Sci. and Engi., Grad. School of Kinki Univ. 3-4-1, Kowakae, Higashi-Osaka 577-8502

** Yamabun electronics. Co., Ltd.
632-2, Nakano, Higashi-Osaka, Osaka 578-0913

absorption of the ray. That is, the value of t is obtained from

$$I = I_0 \exp(-\mu t), \dots \dots \dots (1)$$

where I_0 is the strength of the X-ray without a film in the measuring system, such as shown in Fig. 1, I the strength of the X-ray with a film, and μ the absorption coefficient of the X-ray for the measured film. The value of μ varies according to the material used as the film ⁽⁷⁾⁽⁸⁾.

2.2 Construction of Measuring System Figure 2 shows a schematic diagram illustrating the construction of the film thickness measuring system, which has been developed during the present research. The sensing unit (16) is

Fig. 1. Schematic diagram illustrating the principle of the film thickness measuring system by use of a slit beam X-ray. Here, (1) is the film, (2) the X-ray generator, (3) the detector, (4) the X-ray tube, (5) the X-ray beam, (6) the slit, (7) the ionization chamber, and (8) the air gap.

composed of the X-ray generator (2) and the detector (3). These are attached to slides (13) on the scanning frame (11). The sensing unit (16) scans with a scanning speed of 1–50 mm/s and measures the thickness of film (1) in the direction of the film width, using the servomotor (9), the ball screw (12), the timing pulleys (14), and the timing belt (15). The control unit on the right side of Fig. 2 is composed of a monitor, an interface, and a CPU (central processing unit). The measurement width of this system is 700 mm, and the measurement pitch in the film-width direction can be varied 1 mm or 0.1 mm with a resolution for the film width of 10 μ m. The lead of the ball screw is 10 mm in diameter, and the repetition-positioning precision by a servomotor (9) and the lead of the ball screw is controlled to less than ± 0.02 mm. The air gap (8) between the X-ray generator (2) and the detector (3) is 20 ± 0.2 mm in the scanning area.

As a new trial, the X-ray beam is shaped using the slit (6), such as shown Figs. 3(a) and (b); termed the slit beam X-ray. The slit is made in a stainless steel plate (1.0 mm in thickness), which was processed by laser beam machining. Figure 3(c) displays for reference, a typical photograph of an X-ray spot beam (diameter: 14 mm) of the conventional X-ray thickness measuring system. Figures 3(a) and (b) are photographs of the slit beam X-rays (width: 0.4 mm, 3 mm, length: 14 mm) used in the present system. As schematically illustrated in Fig. 1, X-ray spot beams (5) are generated by a tungsten anode in the X-ray tube (4). The X-ray beam passes through the slit (6). Namely, a measuring area is determined when an X-ray beam passes through the slit. The beams then travel through the air gap (8) and the film (1)

Fig. 2. Schematic diagram of the measuring system for film thickness using an X-ray slit beam. Here, (1) is the film, (2) the X-ray generator, (3) the detector, (4) the X-ray tube, (5) the X-ray beams, (6) the slit, (7) the ionization chamber, (8) the air gap, (9) the scanning servomotor, (10) the pulse generator for the position of the X-ray generator and the detector, (11) the scanning frame, (12) the ball screw, (13) the slider, (14) the timing belt pulley, (15) the timing belt, and (16) the sensing unit.

into the ionization chamber (7). The detected X-ray beam induces an ionization, which is changed into a current signal in the ionization chamber⁽⁷⁾.

The magnitude of the current signal determines the film thickness. To calculate the values of I , a commercially available signal processing system is employed. During the measurements of film thickness, the X-ray generator and the detector are moved to a location where there is no film, i.e., the standard point s , such as illustrated in Fig. 2. The air gap (8) is measured by use of a dosage of X-ray that is detected by the ionization chamber (7).

Zero thickness is defined at the position s as the reference point. The X-ray generator (2) and the detector (3) are then scanned in the direction of the film width for measurement of the film thickness from position l to m . Using the measured values of X-ray intensity I_0 , the film thickness values t are calculated from equation (1). The values of t , however, include measurement errors due to non-uniform air gaps in the measuring area from the point l to m , such as shown Fig. 2. In

Fig. 3. Photographs of the X-ray beams; (a) and (b) are slit beam X-rays in 0.4 and 3 mm width 14 mm in length, respectively. (c) is a conventional X-ray spot beam 14 mm in diameter.

Fig. 4. Typical photographs of the sensing unit by use of a slit beam X-ray (a) and thickness measuring system (b), respectively.

order to correct this, the non-uniform air gaps have been measured and stored in a computer prior to the measurement of film thickness, to create an error map. The measured values t can then be corrected with use of the stored error distribution map⁽⁹⁾.

Figures 4(a) and (b) are shown photographs for the sensing unit by use of a slit beam X-ray and thickness measuring system, respectively.

3. Results and Discussion

3.1 Evaluating the Thickness Measuring System Using a Slit Beam X-Ray

In the present research, the polypropylene (PP) film was prepared as a sample film for the evaluation of the resolution of the thickness measuring system using a slit beam X-ray. And, the sample film was constructed the superposition of a PP tape (thickness: $30\mu\text{m}$, width: 20 mm or 1 mm) over a PP film (thickness: $30\mu\text{m}$, width: 300 mm), such as shown in Fig. 5. The plotted points in Fig. 6 denote the thickness t of the sample films, as a function of the direction of film width W . In this figures, the curves in Figs. 6(a) and (b) are the results for PP tapes having widths of 20 mm and 1 mm, respectively. In the curves in Figs. 6(a) and (b), the open circles and solid circles denote the measured values using slit beam X-rays of 3 mm and 0.4 mm, respectively. In addition, the open triangles denote the results of a conventional X-ray thickness measuring system using a spot beam with a diameter of 14 mm. The pitch widths of measurement are 1 mm and 0.1 mm, such as shown in Figs. 6(a) and (b), respectively. In Figs. 6(a) and (b), it is found that the present system, using a slit beam X-ray of 0.4 mm, results in the high-resolution measurements in the direction of the PP film width. Namely, it can be seen that the results using the measuring pitch of 0.1 mm exhibit an aggressive high-resolution than those determined by the conventional X-ray thickness measuring system. Furthermore, the disparity in the measured values for the sample film thickness by the present system and those of a high precision dial gauge (Mitsutoyo, LGH-110, resolution: $0.01\mu\text{m}$) were within a precision of $\pm 2.7\%$ or less.

3.2 Measurement of a Plastic Film Figure 7 shows the results for the measurement of the thickness of polyimide (PI) film ($12.5\mu\text{m}$ in thickness, 370 mm in width) by the present system. The scanning speed of the sensing unit is

Fig. 5. Structure of the polypropylene (PP) film as a sample film. Here t_f is the thickness of the PP film ($30\mu\text{m}$), t_p the thickness of PP tape ($30\mu\text{m}$), W the width of the PP film (300 mm), and w the width of the PP tape (20 mm, 1 mm).

Fig. 6. The measured sample film thickness t as a function of the direction of film width W . Here (a) and (b) are the results for PP tapes with widths of 20 mm and 1 mm, respectively. The solid circles and open circles denote the measured values using the present system with the slit beam X-rays of 0.4 and 3 mm, respectively. The open triangles denote the results using the conventional system with an X-ray spot beam having a diameter of 14 mm. The pitch widths of the measurements are 1 mm and 0.1 mm, such as shown in present figures (a) and (b), respectively.

Fig. 7. Typical measured results for the thickness of PI film using the present system with a slit beam X-ray of 3 mm.

1 mm/s with a measurement pitch of 1 mm in the film-width direction. In this figure, the solid circles and open squares indicate the measured values by the present system and the high precision dial gauge, respectively. The differences in the results between the present system and those of the high precision dial gauge with the resolution of $0.01 \mu\text{m}$ were approximately $\pm 1.9\%$ or less.

Fig. 8. Typical measured results for the thickness of PMMA film using the present system with a slit beam X-ray of 3 mm.

Figure 8 shows the results for the measurement of the thickness of polymethylmethacrylate (PMMA) film ($200 \mu\text{m}$ in thickness, 600 mm in width) by use of the slit beam X-ray of 3 mm. The scanning speed of the sensing unit is 50 mm/s with a measurement pitch of 1 mm in the film-width direction. In this figure, the solid circles and open squares indicate the measured values by the present system and the high precision dial gauge, respectively. The differences in the results between the present system and those of the high precision dial gauge were approximately $\pm 0.5\%$ or less.

3.3 Measurement of a Plastic Sheet with Semicircle Ridges For evaluating the precision of the present thickness measuring system, a scratch mark (16 mm in length) is made on the surface of polymethylmethacrylate (PMMA) sheet with semicircle ridges as a sample sheet (15 mm in width, 30 mm in length), such as shown in Figs. 9(a), (b), and (c), for detecting flaws. The sample sheet is then installed as shown in Fig. 2 between the X-ray generator (2) and the detector (3). The sensing unit (16) scans and measures sheet thickness in the direction of the sheet width, using the ball screw (12) and servomotor (9). The scanning speed of the sensing unit is 1 mm/s with a measurement pitch of 0.1 mm in the sheet-width direction.

The solid circles in Fig. 9(d) show the measured results of the PMMA sheet with semicircle ridges. Here, the solid circles and open squares in this figure denote the results of the present system and the highly precision dial gauge, respectively. The difference of the thickness on the vertex of a sheet, such as shown in Fig. 9(d), between the measured results of the present system and those of the high precision dial gauge with the resolution of $0.01 \mu\text{m}$ were about $\pm 0.9\%$ or less. And also, the average distance between the vertexes was about 0.72 mm, and the differences in the results between the measured results of the present system and those of the microscope were approximately $\pm 0.8\%$ or less. That is, it was enabled to precisely measure the distance between the vertexes in the sheet with semicircle ridges with a precision of within $\pm 0.8\%$ by use of the present system. The average depth of the trough in the sheet was about $300 \mu\text{m}$, and the differences in the results between the measured results of the present system and the observed results by cross sectional microphotograph were approximately $230 \mu\text{m}$. It is considered that the width of a trough is too narrow in size compared with

Fig. 9. The measured results of thickness t for a sample sheet (PMMA $730\mu\text{m}$ thick sheet with semicircle ridges) using the present system with the slit beam X-ray of 0.4 mm . Here, (a) is the cross-sectional schematic illustration of the sample sheet, (b) typical photograph of the surface of the sample sheet with a scratch, (c) typical cross sectional microphotograph of the sample sheet with a scratch, and (d) the measured results for the sample sheet with a scratch as shown in the area bounded by the dotted line. The solid circles and open squares in this figure denote the results of the present system and the highly precision dial gauge, respectively.

the slit beam X-ray of 0.4 mm . The authors are presently investigating to improvement these characteristics.

As can be seen in Fig. 9(d), the measurements of the semicircle ridges and the scratch mark of the sample sheet were determined with high accuracy. However, the conventional X-ray thickness measuring system by use of a spot beam could not reveal the semicircle ridges and the scratch mark, such as displayed for the new system in Fig. 9(d). That is, high-resolution flaws in sheets can be detected using the present thickness measuring system.

4. Conclusions

A new plastic film thickness measuring system has been developed employing a slit beam X-ray of 0.4 mm in width and 14 mm in length for improving the accuracy and resolution in thickness measurements of plastic films and sheets. In the present paper, the principle of the present system was described, and the system was shown to be effective in measuring film thicknesses between $12.5\mu\text{m}$ and $730\mu\text{m}$ with high accuracy and high resolution. The result can be summarized as follows:

(1) Such as was shown in Fig. 6(b), it was seen that the measured results of the sample film, by the superposition of a PP tape (thickness: $30\mu\text{m}$, width: 1 mm) over a PP film (thickness: $30\mu\text{m}$, width: 300 mm), exhibited aggressive high-resolution than those by a conventional X-ray thickness measuring system. Furthermore, the disparity in the measured values for a sample film thickness by the present system and those of a high precision dial gauge were within a precision of $\pm 2.7\%$ or less.

(2) The thickness of a $12.5\mu\text{m}$ PI film was measured with a high degree of accuracy, having a maximum error of only $\pm 1.9\%$.

(3) Such as was shown in Fig. 9(d), the difference of the thickness on the vertex of a sheet between the present system and the high precision dial gauge was about $\pm 0.9\%$ or less.

(4) Semicircles ridges and a scratch mark of a PMMA sample sheet were measured with high accuracy, such as was shown in Fig. 9(d). A conventional X-ray thickness measuring system using a spot beam could not observe the semicircles ridges and scratch mark, such as was shown for the new measuring system in Fig. 9(d). That is, the new system can be used to find high-resolution flaws in sheets that could not be found with the use of conventional measuring systems.

(5) By use of the present system, it was enabled to precisely measure the distance between the vertexes in the sheet with semicircle ridges. That is, the differences in the results between the measured results of the present system and those of the microscope were approximately $\pm 0.8\%$ or less.

The authors are now investigating methods for the improvement of precision measurement by use of the slit of 0.1 mm , and development of a measurement with high-speed scanning of the sensing unit, which is more than 30 mm/s without the decline of the accuracy.

(Manuscript received June 26, 2007,

revised Jan. 18, 2008)

References

- (1) F. Tojo: "On the Precise Measuring System for the Sheet Thickness", Japan Plastics, Vol.53, No.7, pp.23-28 (2002)
- (2) F. Tojo, S. Hirakawa, T. Toyoda, K. Yamagata, A. Omura, and M. Itoh: "Accurate Measurement of Sheet Thickness: The Planar Error Correction", IEEE Trans. on Appl. Superconductivity, pp.1810-1813 (2004-8)
- (3) F. Tojo, S. Hirakawa, T. Toyoda, and M. Itoh: "Sheet-Thickness Process Control by Self-Calibrated Optical and Magnetic Sensing", IEEE SENSORS JOURNAL, Vol.6, No.5, pp.1309-1313 (2006-10)
- (4) McGraw-Hill Dictionary of Scientific and Technical Terms Fifth Edition, ISBN4526045128, Tokyo: NIKKAN KOGYO SHIMBUN, LTD., p.733a, 1548b (2000)
- (5) Measurex: "DigitectorPLUS Basis Weight Sensor Promethium-147", USA (1993)

- (6) NDC Infrared Engineering, catalogue of Model 312, USA (2007)
- (7) K. Iguchi: "Thickness Gages for Films and Sheets Extrusion Lines", J. of Plastics, Vol.47, No.4, pp.87-94 (1996)
- (8) H. Tominaga and M. Noguchi: Measurement by Using Ionizing Radiation, Tokyo: NIKKAN KOGYO SHIMBUN, LTD., pp.24-25, 117 (2004-12)
- (9) F. Tojo, S. Hirakawa, T. Toyoda, K. Yamagata, and M. Itoh: "A Precise Measurement System for Sheet Thickness Using Magnetic and Optical Sensors", *Conf. Proc of ICEE 2004*, Vol.1, pp.585-590 (2004)

Fumio Tojo (Member) received a M.Eng. degree from Kinki University, in 2005. He presently works for Yamabun Electronics as the general manager, and is a student of the Interdisciplinary Graduate School of Science and Engineering Graduate School of Kinki University. His research includes thickness measurements and control of polymer sheets. Mr. Tojo is a member of The Japan Society of Applied Physics and The Institute of Electrical Engineers of Japan.

Shunzo Hirakawa (Non-member) graduated from Fuse Technical high school and Osaka Electronics College. He presently works for Yamabun Electronics as the director of the technology department. His research includes an algorithm of thickness measurement, the development of a precise optical thickness measuring system for plastic films, and the control of sheet thickness of polymer sheets.

Toshiyasu Toyoda (Non-member) graduated from Fuse Technical high school. He presently works for Yamabun Electronics as the manager of the production engineering department, and is engaged in the development of thickness measuring system of polymer sheets.

Masaru Iguchi (Non-member) received the B.Eng. degree from Tokyo Denki University, Tokyo, Japan, in 1995. He is currently with Yamabun Electronics as a member of technology department. His research includes the development of a precise optical thickness measuring system for plastic film.

Yusuke Katayama (Non-member) received the M.Eng. degree from Osaka University, Osaka, Japan, in 2003. He is currently with Yamabun Electronics as a member of technology department. His research includes the control of sheet thickness of polymer sheets and the algorithm of mapping for sheet formation.

Mineo Itoh (Member) received both M.Eng. and Dr. of Engineering degrees from Kobe University. He is currently a professor in the Interdisciplinary Graduate School of Science and Engineering of Kinki University. His research includes electronic measurements, the development of highly sensitive magnetic sensors made from HTS, the magnetic shielding using a superconductor, and the development of biosensors and bioenergy. Dr. Itoh is a member of the Japan Society of Applied Physics, the Society of Instrumentation and Control Engineering, and the Magnetic Society of Japan.