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Recent Activities in Research of Measurement and Control

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On-line measurement and process control have recently become increasingly important to keep stable and effective production of high quality and homogeneous products. To satisfy these strong needs, optical or ultrasonic measuring instruments and control systems using advanced control theories have been developed and applied to actual steel production processes. In this paper, research activities performed at the Mechanical Processing, Instrumentation and Control Laboratory in the last ten years are described. Representative examples shown here are as follows: (1) Optical measurement: (a) Surface roughness measurement for cold rolled steel strips, (b) Glossiness and whiteness measurement for cold rolled stainless steel strips, (c) Oil film thickness measurement for cold rolled steel strips by using a laser fluorescence method, (2) Ultrasonic measurement: (a) Nondestructive orientation measurement for secondary recrystallized grains in the grain-oriented electrical steel by ultrasonic interferometry, (b) Immersion testing method for the detection of nonmetallic inclusions, (3) Dimension/position measurement: (a) Work roll profile meter for the rolling mills, (b) Detecting system of joints in endless hot rolled strips, (4) Control technology: (a) Molten steel level control for continuous casting, (b) Decentralized tension-looper control for hot strip mills.

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1 Introduction

In recent years the role of measurement and control technologies has become increasingly important for the efficient and stable production of high-quality, consistent products. This is because user demands for internal quality, external properties and dimensional accuracy, etc., have become severer than ever before, while at the same time, manufacturers are striving for higher speeds of production lines and higher quality by adopting automatic measurement and process control. Furthermore, the development of practical measurement and control technologies is also desired for the stable operation of large automated equipment.

Owing to this background, in the Mechanical Processing, Instrumentation and Control Laboratories of Kawasaki Steel, measurement and control technologies have been put to practical use by developing quality measuring instruments using light and ultrasonic waves and process control systems based on the modern control theories in order to meet the above requirements. This paper summarized the history of research and development in this field for the past ten years by giving representative examples.

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2 Outline of Environment for Development and Technological Trends

There has been an increase in the production ratio of value-added products, particularly sheet, and the recent trend has been toward the installation of new large equipment such as hot rolling mills, continuous annealing lines and stainless steel production lines. In response to this tendency, the demand for on-line continuous measurement of the internal quality and surface properties of products and the demand for an improvement in the performance of process control systems for improving quality have become strong, and many measurement and control technologies and systems based on these technologies have been developed during the past ten years.

At the same time, supported by a great improvement in hardware, represented by higher performance and lower cost of lasers, imaging devices and ultrasonic probes, and higher speeds and downsizing of computers for signal processing and image processing, a peripheral environment that can realize functions of higher performance is being constantly improved. Furthermore, there has been a ground swell for the application of control theories, neural network, and basic techniques, such as sensor fusion techniques including multifunctional measurement and integrated measurement, to actual systems. At the same time, simulation software for the design and analysis of control logic has been improved and used as an effective tool for putting control systems to practical use. It can be said that, as mentioned above, rapid progress in innovative techniques, for both hardware and software has led to the development of new measurement and control technologies during the past ten years, a remarkable feat. On-line continuous measurement must be done under the following conditions

(1) In bad environments in which steam, oil mist, etc., disperse at high temperatures
(2) Variations in the properties of products arising from differences in composition and manufacturing conditions provide background noise for the quantities to be measured
(3) High-accuracy measurement within a short time during the travel of steel strips at high speeds

Therefore, various intelligent techniques are being used to meet these demands and obtain accurate measurements[1].

The application of advanced control theories to actual processes is also a major trend in the development of control technologies.

Examples of practical application of measurement and control technologies developed in the past ten years are selected and a description of these technologies is given below.

3 Examples of Developed Technologies

3.1 Measurement Technologies

Researchers in the Mechanical Processing, Instrumentation and Control Laboratories, have focused on developing techniques and devices for measuring the surface quality and properties of steel sheets and inner quality of materials (including defect detection). Methods based on the use of light are mainly employed in the former and ultrasonic waves are frequently used in the latter. Specific examples of these techniques and systems are described below.

3.1.1 Surface property measuring technologies based on application of optical methods

The basic characteristics of light are diverse and various properties can be used depending on the steel sheets to be measured[2]. In the case of measurement of surface quality and properties, measurements are obtained for reflection, absorption, diffraction, scattering, polarization, fluorescence and radiation of light under specific optical conditions and are indirectly estimated with the aid of the relationship between estimates of these measured values and true values obtained from destructive testing and analyses. Because actual measurements are carried out with on-line measurement in mind, robustness in required against the background noise peculiar to steel sheets (variations in reflectance, etc.) and noises from the environment in which equipment is installed (fluttering of steel sheets, variations in temperature, flying of steam, oil mist and the like). For this reason, attempts are being made to expand the scope of measurement and to increase measurement sensitivity and accuracy by increasing the quantity of information obtained and by integrating and synthesizing these results. In this case, the quantity of information obtained is increased by taking many measurements at the same time under multiple measurement conditions, for example, with varied detection angles and measurement wavelengths.

First, an example of a roughness measuring system of steel sheets is described. The surface roughness of steel sheets transferred from mill rolls and printed onto steel surfaces during skinpass rolling must be appropriately controlled according to the application of the steel sheets and user. However, due to changes in operating conditions, such as rolling speed, rolling force, and roll surface wear, surface roughness undergoes temporal changes in the span of hundreds of kilometers (in terms of rolling distance per roll) in addition to variations within a coil. Therefore, this measuring system was developed to control roughness along the full length of a steel sheet by carrying out continuous on-line measurements.

The basic principle behind this system is that the average roughness Ra (μm) of steel sheets is estimated from values of the intensity of reflected light under such optical conditions that a specific relationship exists between the intensity of specular reflection of light from steel sheets and surface texture. Specifically, a semiconductor laser with a wavelength of 0.78 μm and an He-Ne laser with a wavelength of 3.39 μm are used and an expansion of the measurement range and an increase in the measurement accuracy are realized by appropriately using these two lasers according to the roughness measurement range, as compared with the case where a single wavelength is used. A 32-channel diodearray is used as a photodetector in order to reduce errors due to the inclination of a strip and pass line variations during the traveling of the strip. This system is installed in a continuous annealing line. The accuracy of on-line measurements was so high that Ra agreed with an error of about $\pm 10\%$ in a wide range of 0.2 to 1.2 μm compared with measured values obtained from stylus roughness meters. This system can be used for rolling roll control and roughness control[3,4].

Furthermore, a system for measuring the glossiness and whiteness of stainless steel sheets has been developed as another application of reflection measurement[5]. Light with one wavelength selected from the line spectrum of a mercury lamp is applied and the intensity of specular reflection and that of diffused reflection of the reflected light are simultaneously measured. Glossiness and whiteness are determined from the value of the intensity of specular reflection and the value of the intensity of diffused reflection respectively. In this case also, a photodiode array is used to measure the special spread of reflection and to reduce errors resulting from the inclination of a strip and pass line variations. Information on finer surface irregularities is also obtained by simultaneously measuring the intensity of reflection of an Ar-ion laser. Thus, classification close to visual judgment can be determined from these three kinds of information with the aid of a neural network.

Other examples of measuring information relating to surface irregularities include the development of an inspection system using still visions for measuring the surface fine patterns of laser-textured dull rolls for producing steel sheets with increased surface image clarity[6], and a device for measuring the surface reflection characteritics of dull-finished stainless steels for architectural materials in which irregularities are artificially made to add dazzle to the steel surface[7]. Although these examples are measurement technologies developed for the special purpose of controlling the new functions given to the steel sheet surface because of diverse applications, they have expandability in measurement principles and can be applied to other processes and products.

Next is an example of a system for measuring the amount of oil applied to the steel surface (oil film thickness meter) based on the use of fluorescence measurement. In order to appropriately control the amount of anti-rust oil applied to the steel surface after skinpass rolling, it is necessary to continuously measure the amount of oil along the entire length of a steel strip. Therefore, Kawasaki Steel developed a system based on the phenomenon that anti-rust oil emits fluorescent radiation when it is irradiated with excited light having a specific wavelength. An Ar-ion or LD-YAG laser is used as the light source for excitation and only an optimum wavelength is taken out of the fluorescence from the oil with the aid of a dispersing device. In the required range of measurements of amount of oil, the relation in which the intensity of fluorescence received is proportional to the amount of oil is used to full advantage. The function of correcting the intensity of reflected excited light by its constant measurement is added because when the surface roughness and reflectance of the steel sheet under the oil film change, the reflection condition of reflected light changes, influencing the intensity of fluorescence detected.

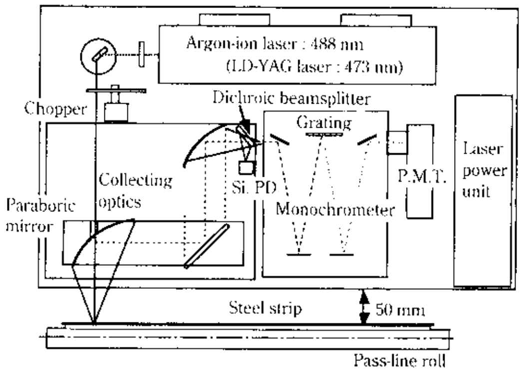

Fig. 1 Schematic diagram of the detecting head of the oil film thickness meter

The composition of the detecting head of the oil film thickness meter is shown in **Fig. 1**[8]. This system is installed in the continuous annealing line, helping to raise the level of oil film thickness control[9]. Furthermore, a small tabletop oil film thickness meter for off-line measurement has been developed[10]. This device, based on a similar measurement principle, uses an N_2 laser emitting ultraviolet wavelengths as the light source for excitation and permits short-time measurement (one spot, several seconds). Examples of surface property measuring technologies based on application of light were described earlier. There is a tendency toward increasingly severe surface requirements in the future and further development of technologies and system is expected.

3.1.2 Measuring technologies based on application of ultrasonic waves

Ultrasonic waves, which can propagate into a solid body, are used for characterizing the internal quality of materials and detecting internal flaws such as nonmetallic inclusions. In ultrasonic measurement, echoes from and shadows of discontinuities in acoustic impedance, propagation velocity, attenuation, scattering, etc. of ultrasonic waves may be measured, depending on the object to be measured. The immersion method, in which both an ultrasonic probe and test specimens are immersed in water, is suitable for continuous automatic testing. By use of this method, it is easy to keep constant coupling of the ultrasonic probe to test specimens. Therefore, the company has utilized immersion method in the development of ultrasonic measuring systems. Some examples are described below.

First, a system for measuring the orientation of grains in grain-oriented electrical steel sheets is described[11]. Grain-oriented electrical steel sheets are used mainly as transformer core materials and the orientation of secondary recrystallized grains is aligned with the Goss texture. Because the magnetic properties of grain-oriented electrical steel sheets are damaged by the misori-

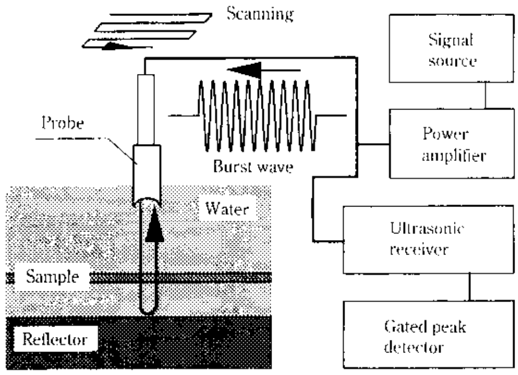

Fig. 2 Block diagram of the measurement system

entation of secondary recrystallized grains from the Goss texture, it is necessary to measure the orientation of secondary recrystallized grains in products for quality assurance. In this system, the orientation of grains is measured on the basis of the physical property that secondary recrystallized grains are close to single crystals and that the velocity of ultrasound varies according to the direction of the grains. Because the steel sheet to be measured is as thin as 0.2 mm in thickness, a method based on ultrasonic interferometry has been developed that does not require transit time measurement.

The constitution of the measuring system is shown in **Fig. 2**. Rf bursts of 20 to 40 cycles of sine waves in a train are used as transmitted pulses and the amplitude of a train of echoes which travel through the whole thickness of a steel sheet at least twice and interfere with each other is measured. Due to a difference in wavelength arising from a difference in the propagation velocity of ultrasonic waves, the amplitude of this echo train shows a difference between the grains aligned with the Goss texture and the grains deviating from it. Therefore, orientation can be measured by making use of this principle. This measurement system is installed in a production line of grain-oriented electrical steel sheets and is of help in quality assurance. Furthermore, a system for observing the growth of the secondary recrystallized grains in a test sample at the halfway point of annealing has also been developed based on the above principle[12].

Next, an example of a system for detecting internal flaws such as non-metallic inclusions in steel sheets is described. To detect internal flaws, Lamb wave testing, ultrasonic C-scan testing[13], etc., have been used. However, in the former detectability is low while in the latter, the testing time is long because of the scanning of an ultrasonic probe in two coordinates. In order to overcome these disadvantages, Kawasaki Steel has developed a system capable of detecting inclusions of not less than 50 μm in diameter in a short testing time by use of probe array scanned electronically[14]. A transmitting probe array and a receiving probe array are arranged face to face with a steel sheet between them in water. The feature of this method lies in the paths of flaw echoes which are received by the receiving probe array. The paths of flaw echoes are composed of a reflection at an internal flaw and a reflection at the front or back wall of the steel sheet. Thus the conventional pulse-echo method and through transmission method are combined in this new method. Although this system is presently used as an off-line flaw detector of sample sheets, it has strong potential for being applied to on-line flaw detection.

3.1.3 Other measurement technologies

The following two examples of development are described as examples of profile and position measurement.

An on-line roll profilometer was developed and applied to work rolls in both hot and cold rolling mills. To achieve the required measurement accuracy of within 10 μm in a bad environment of heat, vibration, cooling water, etc., the company has just developed a water column coupled type ultrasonic distance meter that permits real-time temperature compensation and a thermal deformation correction method for sensor frames based on the straightness of a reference wire and verified their effects[15].

Furthermore, the company has developed a sensor for raising the tracking accuracy by measuring joint positions after finish rolling in the endless rolling process newly introduced in the No. 3 hot strip mill at Chiba Works. In order to measure the timing of passage of a joint, minute load variations during the passage of the joint through the finish rolling are detected by processing the output waveform from the existing rolling force detector installed in the finishing mill with the aid of a linear phase filter. During actual welding and rolling, this device has detected joints completely and thus proven itself effective in the optimization of shear cut timing[16].

3.2 Control Technologies

Various control theories such as modern control theories, which include observer, optimal control, and robust control represented by H_∞ control, have been proposed since the 1960s. Some of them have been applied to steel process control with success in a large number of cases. On the other hand, some cannot be used to the full extent in field systems because of structural complexity.

In the Mechanical Processing, Instrumentation and Control Laboratories, emphasis is placed on the development of methods suitable for field control systems, and several control methods have been applied to actual equipment.

The following are conceivable as requirements for control systems in the field:

(1) Continuous transition from existing control systems should be possible.

(2) The control structure should be simple and physical

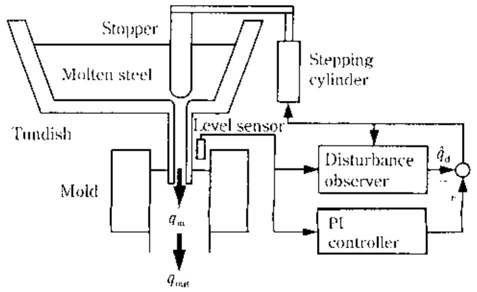

Fig. 3 Schematic diagram of the developed molten steel level control system for continuous casting

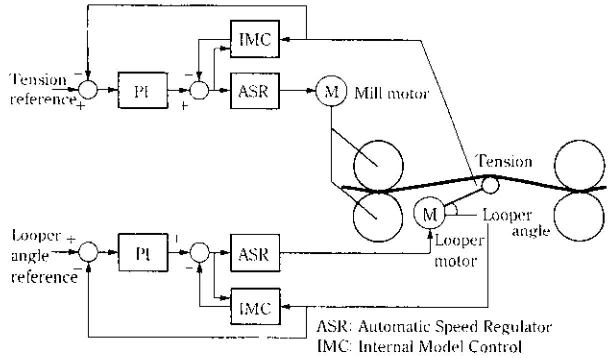

Fig. 4 Schematic diagram of the developed decentralized tension-looper controller

interpretations should be easy.

(3) The controller should be modularized and able to be started up in stages.

Examples of control systems developed with these concepts are described below.

In the molten steel level control of continuous casting mold, disturbances, such as non-steady bulging and breakaway of deposits in the immersion nozzle, are added to control system. In the developed control sheme, as shown in **Fig. 3**, the disturbance flow caused by the disturbances are estimated by using an observer and canceled out[17].

This control method has a structure easy to understand through intuition in which a disturbance is visualized and an operation which may cancel out the disturbance is applied. Therefore, this control method is easy to apply to the field and has been put to practical use in several continuous casters.

A similar structure is used also for the tension-looper control of the finishing mill of a hot strip mill. This control system is a 2-input-2-output system which controls tension and looper angle by manipulating the rolling roll speed and the angular velocity of the looper. The interaction between tension and looper systems has been considered to be problematic, so multivariable control, such as non-interaction control and optimal control, has been applied. However, as a result of an evaluation by interaction measures using the structured singular value, the above interaction is sufficiently small and it is possible to apply decentralized control in which tension and looper control systems are independent of each other[18]. As is apparent from **Fig. 4**, in the developed control[18], PI control is a basic system to which IMC (internal model control) having a structure similar to that of a disturbance observer is added, thereby increasing the capacity for suppressing disturbance. Furthermore, the function of looper coordination can be added by controlling the mechanical impedance of loopers[18].

In this control system, control elements between the tension system and the looper system are eliminated and each system is composed as an independent modules, making adjustment easy. This system has been applied to practical use in the No. 3 hot strip mill at Chiba Works.

Control theories have given birth to various design techniques for control systems. However, not much attention has been paid to their adjustment method or a selection of structures of control systems which constitute design preconditions. In the control systems described above, full exploitation of their capacity was aimed at by giving them a structure which is easy to adjust. This may be regarded as an answer to the above.

4 Conclusion

In this paper, the state of studies and the development of measurement and control techniques, conducted at the Mechanical Processing, Instrumentation & Control Laboratories for the past ten years, has been summarized. The roles of measurement and control will be important, hereafter too, for highly and efficiently providing products through stable manufacturing processes, which, in addition to satisfying rigorous quality requirements of products, have been loaded increasingly with a high-speed and continuous operations. Along with the reduction of labor powers toward the 21st century, requirements for automization of facilities, higher level of inspection processes and efficiency are assumed to be escalating. Additionally, consideration to the environment protection with the extension of the life of facilities are also needed. Accordingly, the developments of sensors for monitoring process conditions and plant diagnosis techniques, along with the contrivance of plant-wide control systems over several processes are longed for. Moreover, it is presumed that the demand in steel, concerning quality rather than the demand in quantity, will further be multiplied and the needs for the quality measurement for new high-value-added products will be increasing. In order to cope with the above-mentioned requirements, we intend to be involved in the development and materialization, for practical use, of new measurement and control techniques.

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