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Recent Applications of Optical Measurement Techniques to Steel Industry Processes

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Synopsis :

On-line measurement of quality and dimensions of products and the condition of processes has recently become very important to keep stable production of high quality and homogeneous products. This tendency is also applicable to the steel industry. To satisfy these strong needs, optical measurement technologies and instruments have been developed because of their advantages such as noncontact, high-response and high-sensitive measurements. Recent advances of hard-ware technologies have also contributed to development of new instruments. Recent examples are dimensional measurement using optical cross sectional method and surface property measurement of steel sheets or rolls for which surface reflective characteristics and image information are utilized. In order to develop these kinds of instruments, durability against adverse environment, countermeasures to realize high response, resolution and precision measurement are taken into consideration. In this paper, the actual state of optical measurement technologies and also future trends are described.

The body can be viewed from the next page.

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1 Introduction

In the steel industry, the stable manufacture of high-quality products with homogeneous properties is essential. Therefore, the industry positively incorporates the development of (1) on-line measurement techniques for product quality and dimensions in each process, (2) observation techniques for process condition values, which become necessary for ensuring stable operation in high-speed, continuous processes, and (3) equipment diagnostic techniques. Electronics-related techniques such as laser techniques, detection devices, and image processing have been upgraded in recent years, and examples of the application of optical measurement methods and devices, which utilize the above-mentioned techniques, to steel industry processes have increased.

This paper discusses the features of optical measurement techniques and outlines the current condition and future orientation of these techniques, with its focus on recent examples of the application of the techniques studied and developed by the Technical Research Division of Kawasaki Steel Corp. to steel industry processes.

2 Features of Optical Measurement Techniques

2.1 Basic Techniques

The fact that the relationship between optics and measurement techniques has a long and closely intertwined history can be clearly seen from a review of progress in physical optics through the first half of the 20th century.[1] With the advent of the laser in the second half of the 20th century, the trend of utilizing light, in particular, as a field of engineering has become stronger, but from the viewpoint of optical measurement, the

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principles have not changed greatly. At present, optical measurement finds more frequent practical application due to rapid progress in hardware, which is discussed later. Nevertheless, the basic properties of light used in optical measurement are many, and it is expected that optical measurement will be used not only in the laboratory in the future, but also in a wide range of practical applications, as seen already in an increasing number of examples. The reason for this is that optical measurement techniques have elements which can sufficiently meet the demands of non-contact, high-sensitivity, high-response measurement. The following describes the basic priciples and properties of optical measurement techniques and gives typical examples of their application to steel industry processes:[2,3)]

(1) Interference: 3-D profile measurement of steel plate surfaces.
(2) Reflection and absorption: measurement of thin-film thickness, roughness, and glossiness of steel surfaces.
(3) Diffraction and scattering: flaw detection in cold rolled steel surfaces and measurement of micro-powder particle size distribution.
(4) Polarization: measurement of film thickness and refraction indices of oxide film, coated oil film, etc., of plated steel.
(5) Rectilinear propagation: measurement of dimensions and shapes by the optical cross sectional method.
(6) Spectroscopy: color difference measurement and measurement of gas concentration and flame temperature.

2.2 Hardware Techniques[4)]

Functionally, the features of optical measurement are: (1) high sensitivity, (2) high resolution, (3) spatial parallelism, (4) non-contact, and (5) non-destructive, non-reactive inspection. Optical measurement is a very effective tool when high-precision measurement is required in the steel manufacturing process. For practical use, hardware applications are based on the general principles mentioned in Sec. 2.1 and employ component devices such as those shown in **Table 1**. These devices have progressed along with the practical application of techniques for the use of measuring instruments, communications equipment, and computers. Through effective use of the features of individual component devices, it is possible to make optical measurement more effective and functional. In particular, recently the laser beam source has become less expensive, more durable, and easier to handle, and the construction of image processing function equipment has become easier due to the increasing availability and greater sophistication of image memories and microprocessors. As a result, the realization of compact, highly-reliable systems has become possible.

Table 1 Component devices for optical measurement system

Item	Device
Light source	W lamp Laser (He-Ne, Ar, semiconductor etc.) LED Xe-flash lamp
Light guide	Optical fiber Image guide
Detector	Photo diode Photo diode array ITV camera Photo multitube CCD camera Shutter camera Position sensitive detector
Interface	Optical GP-IB Optical field bus
Optics	Line scanner Poligon mirror Modulator Integrating sphere SELFOC lens
Processing	Image memory Micro-computer Display Video hard copy
Supporting technique	High accuracy positioning Auto focusing Image processing Pattern recognition

3 Objects of Measurement in Steelmaking Processes

3.1 Objectives of Measurement

Objects of measurement in steelmaking processes are broadly divided into production processes and products. Measurement applied to processes aims at achieving stabilized production, process control, and equipment diagnosis in response to the trends toward high-speed, continuous, and automated operation in recent years. This category also includes measurements made when a new production process is developed for the purpose of clarifying the behavior of the new process. When measurement is applied to products, on the other hand, the aim of the meaurement of product dimensions and surface characteristics is to enhance quality assurance, improve yield, and decrease operational loads in response to the current orientation toward composite, high-added-value, and higher-grade products. Inspection of the outer appearance of products is also carried out to detect flaws. Even when measurement is applied to processes, however, it directly affects the quality of the final or semifinished product. In any case, the basic objectives of measurement are to contribute to the stable production of high-quality products, to monitor operating conditions, and to provide timely feedback of effective information.

3.2 Features of Steelmaking Processes and Corresponding Techniques

Each of the steelmaking processes poses its own peculiar problems for measurement technology. Typical examples are given below.

(1) Measurement in Adverse Environment
Process conditions are a constant problem for measurement in steelmaking. In concrete terms, dust, fumes, vapor, oil, acid, etc., are frequently present on and around the object body, which is handled in a high-temperature environment (more than 1 500°C at the maximum) characterized by vibration and shock. Loud background noises, caused by high-temperature radiation and scale, are common.

(2) Demand for Highly Advanced Measuring Performance
Object bodies are, in many cases, moving at high speed (more than 2 000 m/min at the maximum), and measuring ranges extend from quantities on the order of meters to micro-measurements at the micrometer level. In spite of these problems, measurement must offer high-resolution, high-precision (within 0.1 to 1%) performance and high-speed response.

(3) Wide Variety of Shapes
Objects of optical measurement include strip, pipe, hot-rolled bars, sectional steels, and powder, and thus have a wide variety of shapes. Gases and liquids are also objects of measurement. All these objects require measurements along two or three axes. Measurement also at times presents contradictory requirements. For example, when high resolution is required, such as when a thin beam is used to scan the entire surface of a steel plate, high measurement speed must be sacrificed.

(4) Internal Variations in the Object Body
For the purpose of quality control, optical measurement is necessary not only for abnormalities of batch-processed objects (slabs, plates, coils, etc.) but also for unsteady portions of objects, such as the leading and tailing ends of strips and plates. Unsteady portions pose a special problem, the noise component in such areas is larger than that in steady areas.

In measures against the above-mentioned problems, the following concepts are employed, with development and practical application done according to the objects of measurement:

(1) The optical measurement system should be of compact size and permit forced cooling and purging using air or inert gas, taking into consideration the selection of materials and sealing materials. Careful consideration should also be given to maintainability by facilitating performance inspection, maintenance, and parts replacement.

(2) The system should incorporate logic capable of compensating for changes in object bodies. Various measures should also be implemented, such as the incorporation of an automatic compensation mechanism and logic, promotion of a linkage mechanism, and networking for positive use of information from upper processes, and inclusion of the self-checking and diagnostic functions.

(3) The system should incorporate high-resolution detecting elements, high-speed computation elements, processing boards and computers to improve performance. A higher overall level of function should be aimed at by effectively utilizing the advantages of analog and digital processing.

In this way, the key-point to the development of optical measurement equipment for steelmaking processes is, in addition to the establishment of measurement principles, to remove obstacles which arise when theoretical principles are put to practical application.

4 Recent Examples of Development

Table 2 shows major examples of optical measurement techniques developed by the Kawasaki Steel Technical Research Division.[5-11] Four examples are dis-

Table 2 Examples of optical measurement systems

Measurement	Example	Reference
Dimension	1. Laser type burden profile meter at blast furnace	5)
	2. Brick wall profile meter for torpedo cars	
	3. Off-center sensor for hot strip mill	6)
	4. Gap sensor for the laser welder	7)
	5. Widthmeter for cold steel strips	
	6. Seam locating system for ERW pipe	8)
Surface property	1. Surface roughness meter for cold steel strips	
	2. Glossiness meter for stainless steel strips	9)
	3. Oxide thin film thickness meter for tin free steel	10)
	4. Telescopic color measurement system for steel strips	11)
	5. Surface micro pattern measurement system for laser-textured dull roll	

cussed in detail below.

4.1 Dimension and Shape Measuring Techniques

4.1.1 Torpedo-ladle brick wall profile meter[12)]

Pretreatment of pig iron in a torpedo ladle is effective to making steel of high-purity. This processing makes brick wall wear much more than the previous process because of agitated pig iron due to blowing flux. Since the time of repairing and rebuilding of brick wall should be scheduled, it is necessary to measure the brick wall profile of a torpedo ladle and change of the brick thickness. Kawasaki Steel has developed a brick wall profile meter incorporating a laser distance meter for a torpedo ladle at Mizushima Works.

The laser distance meter detects, using a linear array image sensor, the position of a light spot on the sensor, which changes in proportion to changes in the distance between the laser source and the reflected spot point of the laser beam irradiated onto the object of measurement. This laser distance meter is inserted into the torpedo ladle, and the irradiation position and direction of the laser beam to scan in three axis directions to measure distances between the entire area and the reference point, allowing computation of the wall surface profile.

The construction of the brick wall profile meter is shown schematically in **Fig. 1**. This system consists of a frame, position adjustment mechanism, sensor head, machine-side control panel, and computation controller. The position adjustment mechanism adjusts the longitudinal and lateral positions and height of the sensor head using three motors. The sensor head has a rotational mechanism, and rotates in three directions (θ, ψ, ϕ), thereby permitting the measurement of nearly the entire interior surface of the torpedo ladle. **Table 3** shows the specifications of this sensor head.

This sensor head was developed with consideration given to the problems mentioned in Sec. 3.2. Its features are given below.

(1) Since the temperature in the torpedo ladle during measurement is high at about 300°C, cooling of the inserted electronic unit is important. For this purpose, the sensor head is forced-cooled using a spot cooler, and the interior of the sensor box is maintained at 50°C or below.

(2) To ascertain changes in brick thickness over time, torpedo ladle are examined periodically. It is necessary to determine changes during each period with precision. Since the reproducibility of torpedo ladle positioning, including stopping accuracy and tilting accuracy relative to the frame, is poor, the sensor head incorporates a mechanism for correcting the sensor head position. Two marks each are fitted on the flank and top sides of the torpedo ladle and are measured using position measuring jigs installed on the frame, thereby improving the accuracy of repeated measurements.

(3) The accuracy of positional and rotational control is improved when the distance meter is driven in three axis directions, thereby enhancing positional reproducibility and thus measurement resolution.

(4) To shorten the time required for measurement when the surface of the measured object is extensive, scanning speed is increased and the measuring period and computation time shortened.

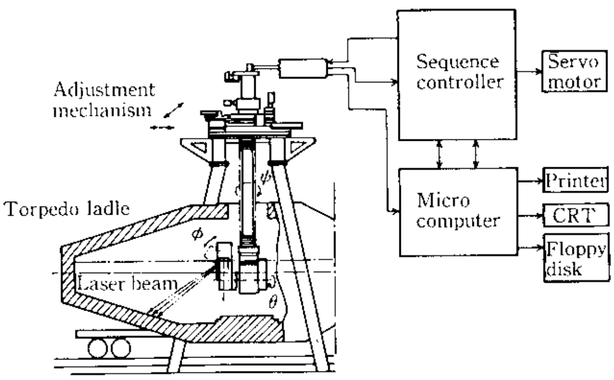

Fig. 1 Construction of the brick wall profile meter

Table 3 Specifications of the sensor head

Light source	He-Ne laser
Wavelength (μm)	0.633
Power (mW)	5
Detecting device	MOS-type linear array image sensor 2 048 bit
Measuring area (mm)	1 400~4 500
Sampling cycle (msec)	30
Sensor size (mm)	400 x 320 x 800

The sensor head can measure the profile of the entire internal area of the torpedo ladle; the scope of measurement can also be arbitrarily designated. Data for torpedo ladles is stored on floppy disks. Thus historical data for each torpedo ladle beginning with its initial period of use is preserved, giving easy access to information on changes in brick thickness and wear. Twenty-two cross sections of a torpedo ladle can be measured in the longitudinal direction in about 30 min, covering the entire length of the vessel. In off-line measurement using a newly developed reference plate, an accuracy of ± 3 mm has been achieved, with a reproducibility of ± 5 mm. **Figure 2** shows the measurement results of the shell, initial profile and profile after 665 charges. The sensor thus gives the targeted performance and is presently in regular use. In the future, this sensor head will find further use in determining the optimum brick material and means of reducing production costs. In

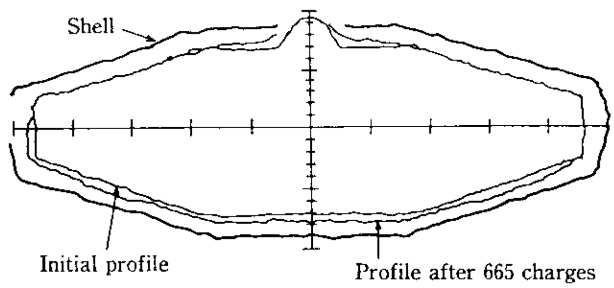

Fig. 2 An example of measured brick wall profile after 665 charges

addition, shape measurement using the laser distance meter is also an effective technique for measuring interval furnace profiles and steel-product dimensions, and can be applied to many other fields.

4.1.2 High-precision width meter for cold-rolled steel strip[13)]

With the aim of improving the width control of the total length of the cold-rolled steel strip and decreasing the burden on operators, efforts were made to develop a high-precision, continuous method of measuring strip width, but the measurement accuracy of the width meters was nevertheless limited to only ± 0.5 mm, posing problems of width control and assurance. The main reasons for this were the large error factor which accompanies pass line variations, and the fact that it is impossible to reduce the error resulting from thermal expansion of the width meter because no calibration with an absolute reference length was possible. The authors developed a width meter which solved these problems and offers higher-precision measuring performance, and installed it at the temper-processing line at Chiba Works.

A schematic diagram of the width meter is shown in **Fig. 3**. a halogen lamp above the steel strip and a CCD light sensor, which consists of 5 000 elements, below the steel strip are installed opposite each other, and measure the strip width by detecting points where light is obstructed by the edges of the steel strip. Further, an outstanding feature of the device is that a reference plate of Invar alloy provided with a staggered pattern of identical rectangular holes parallel to the roll shaft is installed between the steel strip and the photo detector.

Measures for achieving higher precision are:

(1) Adoption of a parallel-beam pick-up method to decrease the adverse effects of pass-line variations and disturbing light sources.
(2) Introduction of a deflection measurement method which detects the difference between the measured length of the steel strip and a reference plate of known absolute length.
(3) Addition of a temperature compensation function which takes into consideration the difference between the product temperature during measurement and that at room temperature.

Calibration using the reference plate is carried out as follows: First, the reference-side detector head is automatically set to the steel strip edge by a servomotor according to the strip width instruction. On the reference plate, one square hole is arranged at the reference side and 41 square holes are arranged at the non-reference side. Their respective dimensions are stored in the microcomputer. Therefore, when the gaps between the square-hole edge and the steel strip edge (X_1, X_2) are measured, it is possible to obtain the strip width value W from the value of selected square-hole distance L using the following formula:

$$W = L - (X_1 + X_2) \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

In an off-line performance evaluation test and an on-line test in skin-pass rolling, the width meter has satisfied a performance target of ± 0.2 mm measurement accuracy even with a high-speed line operating at 1 600 m/min, and achieved a response speed of 50 ms and a tolerance value of pass-line variation of ± 10 mm. With the dimensional accuracy demanded by users in recent years bcoming very high, the width meter can contribute to the enhancement of strip width control levels, and its effective application to other lines is also expected.

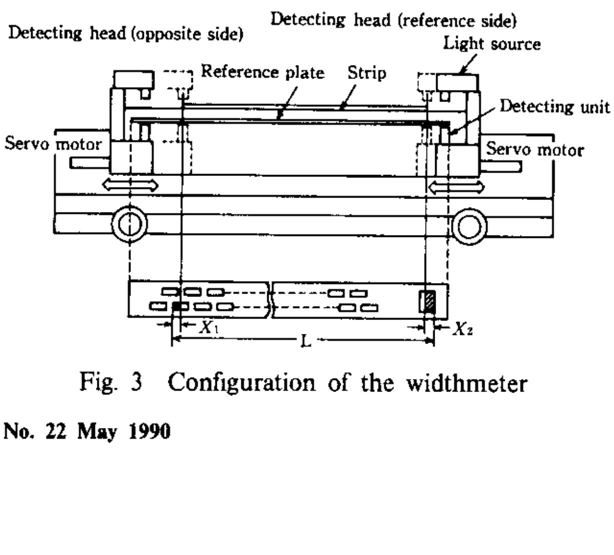

Fig. 3 Configuration of the widthmeter

4.2 Surface Property Measuring Techniques

4.2.1 On-line surface roughness meter for cold strip

Of the surface properties of cold-rolled steel strips, roughness is one of the most important factors, governing not only the appearance of the product but also its performance in painting, plating, working, and forming. Therefore, total-length, continuous inspection by on-line measurement is desired for quality control. To satisfy this demand, Kawasaki Steel developed an on-line roughness meter and put it to practical use in the temper-processing line at the cold-rolling mill, and is further developing a roughness meter featuring smaller size and higher responsiveness by enhancing the functions of the

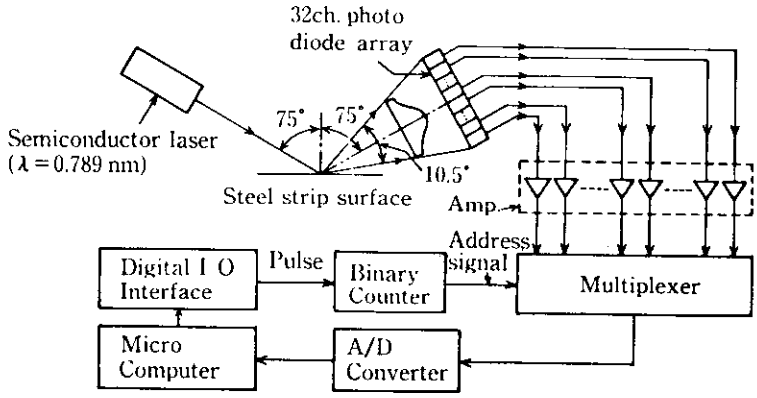

Fig. 4 Blockdiagram of the on-line roughness (R_a) meter

current roughness meter.[16]

The basic principle of the roughness meter consists of irradiating laser beams onto the steel strip in an oblique direction and obtaining surface roughness (center-line average roughness R_a) indirectly from specular reflection intensity value. This roughness meter has been implemented by obtaining, using numerical calculation, the mutual relationship between the statistical properties of the rough surface and its light reflectivity, and by determining the wavelength of incident light and incident/detection angles which satisfy the roughness-measurement range specified for the object steel strip. Further, the use of moving parts was avoided in designing the system in order to make high-speed meaurement possible.

In concrete terms, semiconductor laser beams having a wavelength of 789 nm are projected onto the steel strip at an incident angle of 75°, and a 32-element photodiode array is used at the reflected light receptor to detect light distribution and peak strength simultaneously. As a result, no moving parts are needed to detect peak positions, and the distribution strength can be obtained at high speed, minimizing the effect of strip surface vibration and permitting measurement with good responsiveness. The makeup of the meter system is shown in **Fig. 4**. Since a single scan of the reflected light is performed at a high speed of about 4 ms, the sizes of the light projecting and receiving parts are small, at about 470 mm × 80 mm × 70 mm, allowing easy installation. The unit can also scan in the strip width direction.

Figure 5 shows the results of a comparison of values measured by a stylus instrument and by the on-line roughness meter within the measuring range of a center-line average roughness $R_a = 0.1$ to $0.5\,\mu m$. The meaured values show good agreement with an error of less than ±10%.

Through the experiments conducted with the on-line roughness meter at the temper-processing line, the following results were obtained:

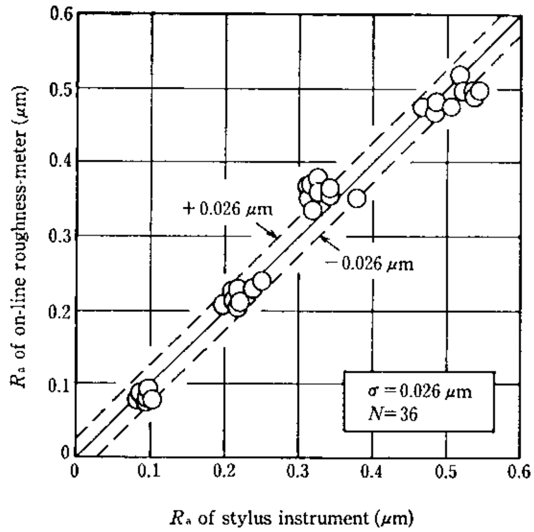

Fig. 5 Relationship between measured surface roughness data (R_a) obtained by the stylus instrument and those by the newly developed equipment

(1) Since a smooth reflected light distribution can be obtained even at a strip speed of about 1 600 m/min, stabilized measurement can be obtained even at a high-speed line. Deterioration in measurement accuracy due to steel strip vibration is small.

(2) The mean and dispersion of 16 values measured by the on-line roughness meter show good correspondence to those measured by a stylus instrument, thus the performance of this roughness meter as an on-line measuring instrument is satisfactory. An example of the results of continuous measurement by the on-line roughness meter is shown in **Fig. 6**.

In view of these results, this meter is highly suitable for practical use because of its small size and high-speed response function, and in the future, it is expected that this meter will be applied to various fields, contributing to the strengthening of quality control.

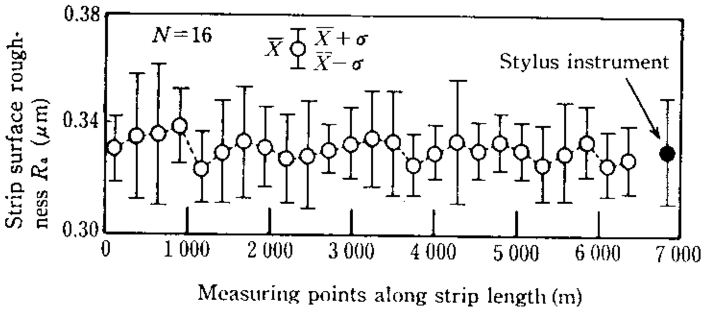

Fig. 6 On-line experimental result with the equipment newly applied to the cold-rolled strip preparation line

4.2.2 Still vision system for micropattern of laser-textured dull-roll

In the laser dull-roll working method, CO_2 laser beams, after being converted into pulse beams by a chopper, are focused and irradiated on a rotating roll surface through a lens, and the melted material, which forms instantly, is evaporated by the assist gas, creating a large number of concave- and convex-shaped micro-craters on the roll surface.[17] By controlling the roll revolution, chopping frequency, and laser output, it is possible to control the sizes of craters (D) and clearances (S_m, S_L) at will, so that the roll surface roughness meets the target value. Temper rolling using the textured roll imparts to the steel strip a surface roughness profile free of wavelength fractions, which have an adverse effect on image clarity after painting. The product made using this technique is a high image-clarity steel sheet called "LASER MIRROR," which has already found commercial acceptance in the luxury automobile market.[18] The main factors affecting image clarity are the roughness and waviness of the steel surface and the flat area ratio.[19] Control of reflectivity, therefore, requires processing of the dull rolls in close accordance with targets; for this purpose, a measuring device has been developed for use in monitoring roll processing conditions.[20]

In the still vision system, an enlarged image of the rotating roll is captured as a still picture, and image processing is used to calculate and output (1) the diameters, shapes and pitches of craters, (2) the flat area ratio and (3) the phase shift of pitches. Key points of this system are:

(1) Photographic method for still microscopic images of microarea (and the photographic device).
(2) High-speed image processing and computation techniques for obtaining measurement parameters.
(3) High-accuracy position controller for the measuring system.

A practical measuring system with these three features was developed, as shown in **Fig. 7**. Because the tangential-direction speed of the roll surface is as high as 10 m/s and it is necessary to capture a still microscopic image having an area of about 1 mm^2, a follow-photographic method was adopted. The method features a combination of a rotary mirror synchronized with the roll tangential-direction speed and a stroboscopic light with a flash duration of about 100 μs. To minimize image astigmatism, a long-focal-length enlarging optical system using four mirrors is used; a CCD camera is used actual picture taking. To enhance the

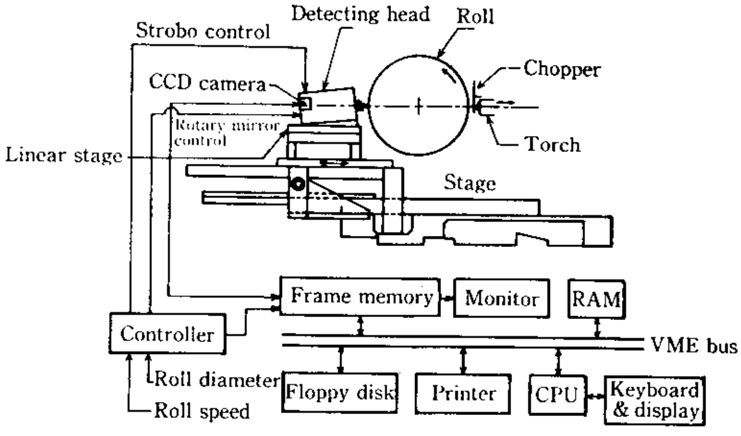

Fig. 7 Schematic blockdiagram of the measurement system for the surface micro-texture pattern

contrast of the uneven surface pattern, drop lighting is employed. The strobe light is transmitted through optical fibers. The image processor is high-performance hardware comprising a comprehensive system using an 8-bit gray scale memory and VME Bus. In the processing method, binarizing processing is performed after obtaining the optimum binarization conditions from the overall luminance of the image, and the earlier-mentioned crater dimension parameters are calculated by the addition processing in the perpendicular and horizontal line directions. Since it is necessary to obtain a clear still image, driving and position-control of the roll are carried out in the lengthwise direction and approach/retreat directions in synchronization with the movement of the working torch for the laser irradiation. Therefore, when the roll diameter changes, the detection head also moves to a prescribed position in accordance with the torch position. For the purpose of micro-positioning, the system is also provided with a remote focusing function.

On-line measurement with this system produces clear images at about 10 m/s, which is the maximum roll peripheral speed currently used. Further, the accuracy of the parameter computation results is within $\pm 10\ \mu m$, and computation time is about 5 s, fully satisfying the initially planned performance targets. Since positioning accuracy is satisfactory and the focal depth of the optical system is $\pm 300\ \mu m$, poor focusing is minimal, and there are no practical problems in this regard. **Photo 1** shows an example of a still image, including an explanation of the computation parameters. In addition, changes in crater diameters due to variations in laser power can be clearly monitored, meaning that the system can also be used for equipment diagnosis.

This system, it may be noted, can be used not only to improve quality control of sheet surface micro-profiles, but also as a surface inspection apparatus for high-speed rotary bodies of other types, if fitted with the requisite processing software for pattern recognition.

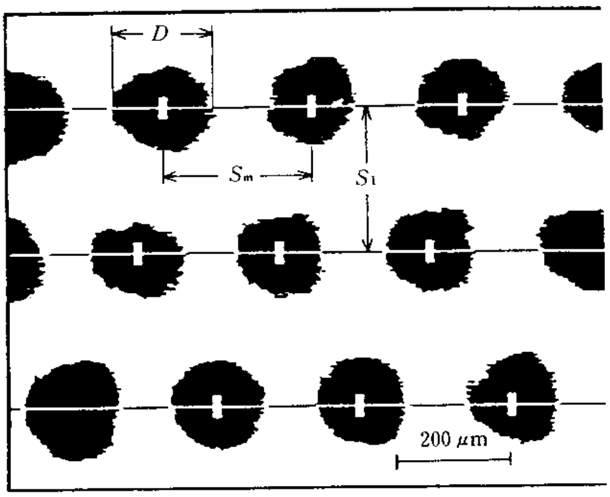

Photo 1 Binarized image of a surface micro pattern of a rotating roll

5 Future Trends

The "seed" technologies embodied in hardware created in recent years will develop rapidly in the future, making an increasingly significant contribution to optical measurement technology. For instance, enhanced hardware performance is expected in areas such as ① a broader-band oscillation line in compact lasers, ② integration and the introduction of intelligent features whereby the photo detecting device element can be provided with detection selectivity and compensation/calibration functions, ③ a broader band of fiber transmission properties. ④ increased density of image devices and memory, and ⑤ more compact and higher speed computers, including image computation and processing units. A major goal in steelmaking, on the other hand, is fully unattended operation based on automation and high speed continuous operation; this goal, in concert with the trend toward tighter quality control, is expanding the need for measurement technology in various fields. To satisfy this need, measuring equipment will be developed employing new techniques and utilizing up-to-date hardware technology. In concrete terms, technical development is expected to follow these general lines:

(1) High resolution measuring method employing spectroscopic analysis techniques with expanded time and wavelength ranges will be used for the analysis of gases and liquids and for the measurement of steel sheets material properties. For instance, the application of laser spectroscopy and FT-IR is likely.
(2) Dimensional measurement techniques, which utilize image processing units and high performance processing software cover an expanded spatial range, and product quality measurement techniques based on the visualization of "invisible information" will be developed. AI and neuron-based pattern recognition techniques will be applied to the results of flaw detection and various types of image detection. In the future, optical information processing techniques featuring parallel processing methods such as optical computers and optical associative memory may also be employed.[21]
(3) Using optical fiber-based measurement technology which integrates light projection/detection and transfer and processing systems, measuring system can be constructed for multipoint information within an object field. Such optical multipoint measurement techniques in which the fuzzy factor is processed quantitatively and output will find application in the field of equipment diagnosis. Consequently, an integrated system in which the measurement function is incorporated in the equipment itself should see increasing use in the future.

As mentioned above, future optical measurement techniques are expected to develop in response to increasingly rigorous measurement conditions, expanding from the simple "eye" function to include all five senses.

6 Concluding Remarks

The methodology on which optical measurement techniques are based has been outlined, along with the related hardware technology. Problems which occur when optical measurement is applied to steelmaking, together with the necessary measures have also been described. Further, the present level and future avenues of development in optical measurement technology have been discussed in terms of techniques developed in recent years for the measurement of the dimension/shape and surface properties of steel strip. The authors will continue to study the practical application of newly developed optical measurement systems to operational improvement and quality enhancement.

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