KAWASAKI STEEL TECHNICAL REPORT
No.43 (October 2000)
Automative Materials and Instrumentation and Process Control

State-of-the-art Techniques for Internal Quality Measurements in Steel Sheet Production Processes

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This paper describes the state-of-the-art ultrasonic and magnetic measuring techniques developed at Kawasaki Steel and used in the production process of steel sheets. Some examples shown here are as follows: (1) Magnetic flux leakage testing system for the detection of nonmetallic inclusions, (2) Nondestructive orientation measurement for secondary re-crystallized grains in grain-oriented electrical steel by ultrasonic interferometry, (3) Immersion testing method for the detection of nonmetallic inclusion, and (4) Surface wave probe for the detection of surface flaws in rolls used in rolling mills. The development of these techniques and their applications to actual steel sheets production processes have contributed to advances in quality assurance and control. By means of these techniques, steel sheet products with advanced and uniform properties are being continuously produced to meet customers' needs.

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State-of-the-art Techniques for Internal Quality Measurements in Steel Sheet Production Processes*



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This paper describes the state-of-the-art ultrasonic and magnetic measuring techniques developed at Kawasaki Steel and used in the production process of steel sheets. Some examples shown here are as follows: (1) Magnetic flux leakage testing system for the detection of nonmetallic inclusions, (2) Nondestructive orientation measurement for secondary re-crystallized grains in grain-oriented electrical steel by ultrasonic interferometry, (3) Immersion testing method for the detection of nonmetallic inclusion, and (4) Surface wave probe for the detection of surface flaws in rolls used in rolling mills. The development of these techniques and their applications to actual steel sheets production processes have contributed to advances in quality assurance and control. By means of these techniques, steel sheet products with advanced and uniform properties are being continuously produced to meet customers' needs.

1 Introduction

Users' needs with respect to the internal quality and properties of steel sheet products are becoming increasingly strict year by year. Such user's needs arise from the improvement and the automation of users' manufacturing processes to realize cost reductions. Moreover, they also arise from the change of users' manufacturing methods for the purposes of environmental safeguards and energy saving. For example, because an automated production line is occasionally stopped by the occurrence of inferior products originated from internal flaws, steel sheets must be free from defective parts containing internal defects and the like. Moreover, changes of manufacturing methods including forming methods require advanced mechanical properties in many cases. Steel makers are producing and developing various steel sheet products with advanced properties which meet the existing and future needs of users. At the same time, as to the measurement techniques for the properties and uniformity of steel sheet products, the development of measuring methods for new objects and improvement of the performance of existing techniques are constantly needed. Kawasaki Steel has developed and installed various instruments for measurement of the quality of steel sheets to meet users' needs, and performs quality assurance and quality control by use of the measurement results. This report presents representative examples of state-of-the-art techniques and instruments developed by Kawasaki Steel for the purpose of internal quality measurements in steel sheet production processes.

2 On-line Nonmetallic Inclusion Detector Using Magnetic Flux Leakage Testing Technique

2.1 Background of Development

Many steel products, including 2-piece steel cans (cans made from two steel components) are manufactured by applying large plastic deformation to steel sheets. Because cracks and surface beaks will occur during manufacturing if nonmetallic inclusions (aluminum oxides, etc.) are present in the steel sheet, it is necessary to produce sheets which are free from internal nonmetallic inclusions, and to detect internal nonmetallic inclusions throughout the entire volume of the sheets for the purpose of quality assurance. Further, because gouge defects, which are uneven surface flaws, are also causes of defective products, it is necessary to detect them over the whole surface of steel sheets.

* Originally published in *Kawasaki Steel Giho*, **31**(1999)4, 211–215

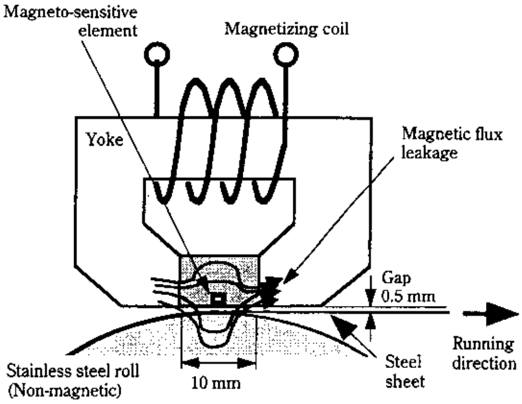


Fig. 1 Schematic geometry of detecting head

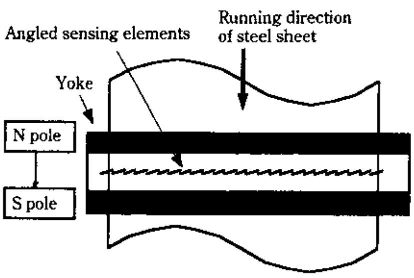


Fig. 2 Schematic geometry of detecting head (top view)

2.2 Principle of Measurement and Constitution of Detector

Based on the results of previous research and development[1,2], a nonmetallic inclusion detector using the magnetic flux leakage testing technique was installed in No. 2 electrolytic tinning line at Kawasaki Steel's Chiba Works. An outline of the detector is presented below. **Figures 1** and **2** show the principles of detection and structure of the detecting head. By magnetizing a steel strip to be tested, magnetic flux leaks in the space near the steel strip surface if a magnetic discontinuity, such as a nonmetallic inclusion or a gouge defect, is present. That magnetic flux leakage is detected by a magnetic sensor in the detector (detection sensitivity, 0.8 V/0.1 T in sensing horizontal magnetic flux). The detecting head is compactly housed in one body by arranging both the magnetic sensors and the magnetizing direct-current coils on the same side of the strip surface. The magnetizing direct-current coils are used to magnetize the steel strip in the running direction. To prevent deterioration of sensitivity owing to the gaps between the sensing elements, a dense and angled arrangement of the sensing elements was adopted, as shown in Fig. 2. The detector is equipped with various noise reduction circuits, such as a high-pass filter whose cut-off frequency is adjustable according to the running speed of the strip, in order to improve the signal-to-noise ratio. In the detection of nonmetallic inclusions, the magnetic discontinuity is not exposed at the strip surface, and consequently, the density of the magnetic flux leakage is low. For this reason, it is necessary to minimize the gap between the magnetic sensor and the strip to catch the relatively strong magnetic flux leakage near the strip surface. Conversely, with gouge defects, the discontinuity is exposed at the surface and the density of the magnetic flux leakage is comparatively large. In this case, the gap between the magnetic sensor and the strip can be increased to a larger value than in the inclusion detection. The developed detector can be used for both nonmetallic inclusion detection and gouge defect detection. The object for the detection is changeable at every coil by means of an adjustable mechanism for the gap between the magnetic sensor and the strip. This detector has other advantages as follows:

(1) Inspection of the full width of the product is possible.
(2) Flaws in the strip with running speeds as high as 700 m/min can be detected.

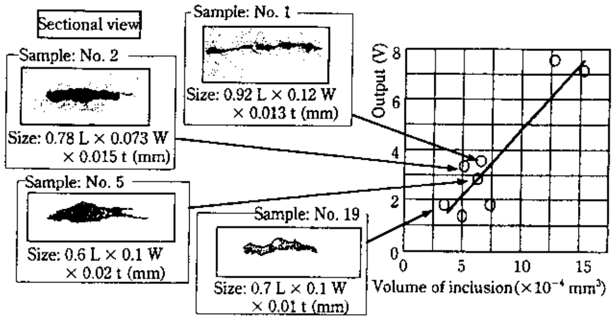


Fig. 3 Detctability of nonmetallic inclusions

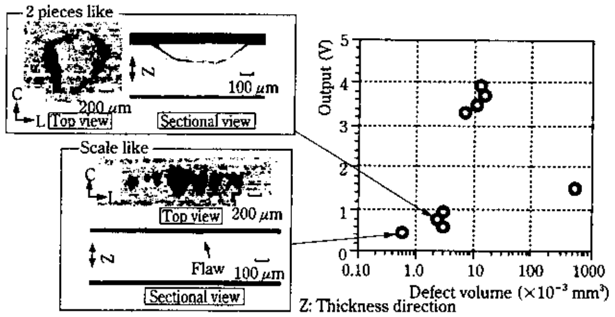


Fig. 4 Detectability of gouge defects

2.3 Detectability

Examples of the detection of nonmetallic inclusions and gouge defects[2,3] are shown in **Figs. 3** and **4**, respectively. This detector is capable of detecting nonmetallic inclusions with volume of more than $5 \times 10^{-4}\,mm^3$ at the gap of 0.5 mm and gouge defects with volume of more than $15 \times 10^{-4}\,mm^3$ in volume at the gap of 2.0 mm.

3 Measurement System for Grain Orientation of Grain-Oriented Electrical Steel Sheets

3.1 Background of Development

Magnetic properties of grain-oriented electrical steel sheets are governed by the orientation and the size of secondary recrystallized grains. In particular, the alignment of the orientation of the secondary recrystallized grains with the Goss texture is extremely important for good magnetic properties. Conventionally, the Epstein test and the single sheet test were used in the tests of magnetic properties, and the X-ray diffraction method was used in orientation measurements of grains. The single sheet test is a test method for magnetic properties of sheets for stacked iron cores, etc. In that, magnetic flux density and iron loss are measured using a single sheet. However, because all these tests were performed using test pieces which were cut from the product, a method that can be applied to the continuous measurement of properties in the production line of grain-oriented steel sheets was desired.

3.2 Principle of Measurement and Constitution of Measurement System

A method based on ultrasonic interferometry and a system for measuring the orientation of secondary recrystallized grains was developed and applied practically in continuous measurement in the production line.

Because a single crystal of steel has elastic anisotropy, the velocity of ultrasound passing through it varies according to the direction of propagation.[4] The orientation of crystals in the thickness direction shows a difference between the grains aligned with the Goss texture (hereinafter referred to as normal grains) and grains deviating from it (miss-oriented grains), and the propagation velocity of ultrasound also differs. Accordingly, it is possible to distinguish miss-oriented grains by measuring the propagation velocity of ultrasound, but because it is necessary to measure the transit time with a high resolution under nanosecond, a method which utilizes the interference of the train of echoes traveling through the whole thickness of the steel sheet more than twice was developed.[5] The double sound transmission method shown in **Fig. 5**, or the through transmission method, is used in measurements of the amplitude of the echo train. Rf bursts (hereinafter referred to as burst wave) are used as the transmitting pulse. **Figure 6** shows the results of a numerical calculation of the relation between the amplitude of the echo train and the velocity of ultrasound on the assumptions that would maximize the amplitude of the echo train in the normal grains, as follows:

(1) Thickness of a sheet is 0.20 mm.

(2) Frequency of a burst wave is 15.5 MHz.

The pulse duration N (integral multiple of wavelength) of the burst wave is varied from 5 cycles to 40 cycles. From this figure, it can be understood that the amplitude of the echo train is smaller in crystals having an ultrasound velocity which differs from that of crystals aligned with the Goss texture, and the change in amplitude is proportional to the pulse duration of the burst wave. This pulse duration is set appropriately, based on the allowable deviation of the orientation of the secondary recrystallized grains.

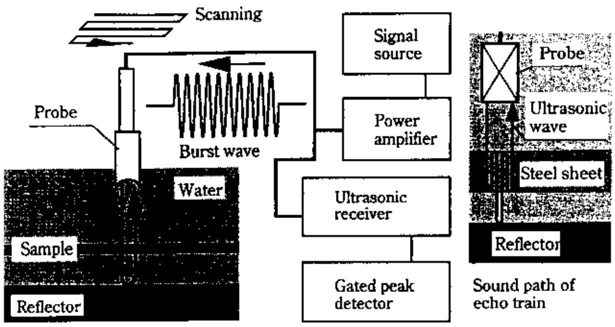


Fig. 5 Block diagram of echo amplitude measurement system

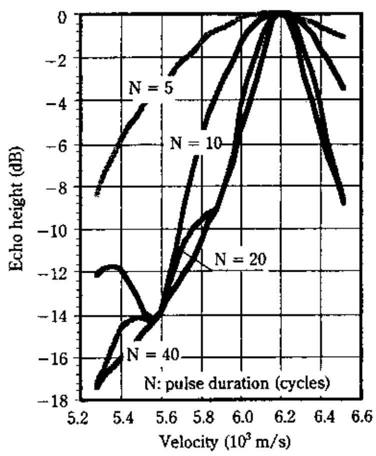
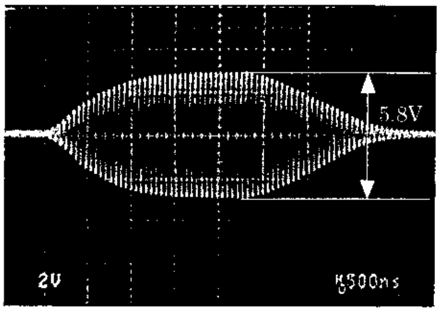


Fig. 6 Relation between echo amplitude and ultrasonic wave velocity in material (calculated)

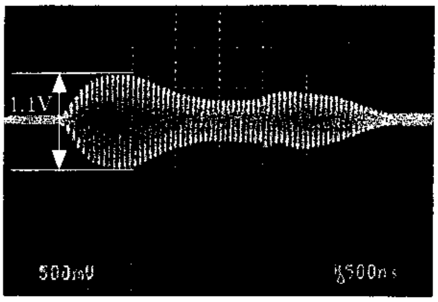
Figure 5 shows the constitution of the measurement system. An electrical signal of 20 to 40 cycles of sine waves in a train is generated at a constant repetition frequency by a signal source. This signal is amplified by a broad bandwidth power amplifier. A burst wave of a variable frequency and a variable pulse duration is transmitted with a ultrasonic probe by applying the amplified signal to a piezoelectric element in the ultrasonic probe. The echo train mentioned above is received by the ultrasonic probe. Miss-oriented grains can be distinguished by detecting the amplitude of this echo train with a gated peak detector.

3.3 Results of Development

Photo 1 shows the waveform of the echo train



(a) Echo train at grains aligned with Goss texture



(b) Echo train at miss-oriented grains

Photo 1 Comparison of waveforms of echo train

observed in normal grains and miss-oriented grains in a grain-oriented electrical steel sheet with a thickness of 0.18 mm using a burst wave with a pulse duration of 40 cycles and a frequency of 17 MHz. The difference δ (dB) in the amplitude of the echo train between the normal grains and the miss-oriented grains is large, by approximately 14 dB, and the miss-oriented grains can be satisfactorily distinguished.

$$\delta = 20 \log_{10}(5.8/1.1) \fallingdotseq 14 \text{ (dB)} \cdots\cdots\cdots\cdots (1)$$

This measurement system was installed in an electrical steel sheet production line and is of help in quality assurance for grain-oriented steel sheets. Furthermore, a system for observing the growth of secondary recrystallized grains in test samples in the laboratory was also developed using the principle described above.[6)]

4 Detection Technique for Nonmetallic Inclusions in As-pickled Steel Sheets Using "Ultrasonic Line Sensor"

The following presents an example of a new method for detecting nonmetallic inclusions and other internal flaws in steel sheets by use of ultrasound.

4.1 Problems with Conventional Techniques

Conventionally, methods such as the Lamb wave testing[7)] and the ultrasonic C-scan testing[8)] have been used in detecting internal flaws in steel sheets. However, both had drawbacks, as the former is low in detectability and the latter requires long time for testing because of the scanning of an ultrasonic probe in two coordinates.

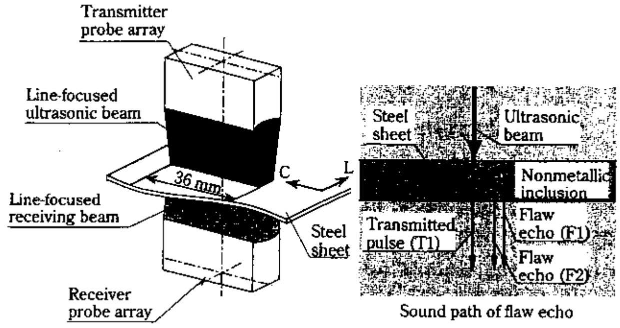


Fig. 7 Schematic geometry of ultrasonic probes

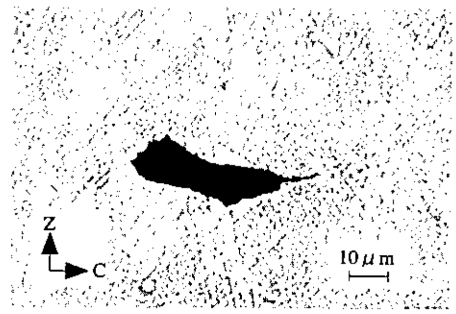


Photo 2 Sectional view of detected internal flaw

4.2 Developed Technique and Its Detectability

The schematic of the developed method is shown in **Fig. 7.**[9)] In this method, it has a constitution in which a transmitting probe array and a receiving probe array are arranged face-to-face on opposite sides of the steel sheet in water, and flaw echoes which are reflected once each at a internal flaw and the surface or back wall of the sheet are received by the receiving probe array. Thus the conventional pulse-echo method and through transmission method are combined in this new method. By combining electronic scanning of the probe array with this method, it is possible to detect minute internal flaws in a short testing time. **Photo 2** shows a cross-sectional view of a nonmetallic inclusion which was detected using the instrument with the constitution described above, and demonstrates that it is possible to detect microscopic nonmetallic inclusions of approximately 50 μm in diameter.

This instrument is currently being used as an off-line flaw detector for sample sheets, and also has strong potential for being applied to flaw detection in production line.

5 Roll Surface Testing Technique Using Broad Bandwidth Surface Wave Probe

This chapter describes a surface flaw detector for work rolls used in rolling, which have a direct effect on the quality of the steel sheet surface.

5.1 Problems with Conventional Techniques

Occasionally, surface flaws are formed in rolling work rolls under abnormal rolling conditions. If left untreated, these surface flaws can cause problems such as roll spalling and marking on the strip. Work rolls are ground by a grinder after rolling of a prescribed amount of strips. Re-profiled roll surface by a grinder is tested by a surface flaw detector. If a surface flaw is detected, the surface of work roll is re-ground until the surface flaw is removed.

Ultrasonic surface wave testing is usually used in the surface testing of hot finish rolling rolls made from high-speed tool steel.[10,11] Conventionally, a narrow bandwidth probe has been used in this testing. However, in the surface testing of a rolling roll, back-scattered waves with small amplitude are caused by the presence of coarse grains, a rough surface and a large number of minute fire cracks produced in hot rolling (hereinafter referred to as "collective fine reflectors"). In the surface testing with the conventional probe, these back-scattered waves tend to become large by superimposing each other. Therefore, deterioration of detectability and some false indications have happened in the surface testing with the conventional probe.

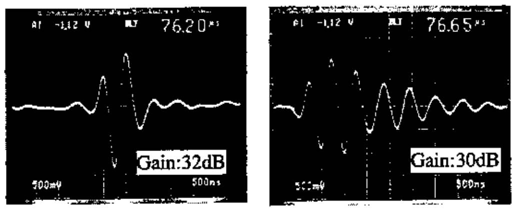
5.2 Development of a Broad Bandwidth Surface Wave Probe with High Sensitivity

The height Pg of echoes from collective fine reflectors in the path of ultrasound is expressed as Eq. (2), and is proportional to the square root of pulse duration of the ultrasound.[12)]

$$\mathrm{Pg} \propto (\alpha_0 \cdot \tau)^{1/2} \cdot \exp(-2\alpha_0 x)/x \cdots\cdots\cdots\cdots (2)$$

Where, x is a distance from the ultrasonic probe to the reflector, α_0 is the attenuation coefficient. From Eq. (2), it is understood that shortening the pulse duration of the ultrasound (by broadening the frequency bandwidth of the surface wave probe) is effective to make Pg small. Because the reflectivity of ultrasound at a flaw does not depend on the pulse duration, signal-to-noise ratio of a flaw echo can be raised by use of a broad bandwidth probe. Consequently, detectability can be raised by use of a broad bandwidth probe. As the conventional surface wave probe send out the oscillation of piezoelectric element without damping to get high sensitivity, τ of ultrasound pulse is several times longer than its wavelength. Therefore Pg has a large value in the test with the conventional probe.

In case of a general type of broad bandwidth probe, the oscillation of a piezoelectric element is damped by a damping block in order to obtain short pulse. As a result, the sensitivity of such probe is much lower than that of the conventional narrow bandwidth probe without being damped by a damping block. It is therefore necessary to increase the gain of a receiving amplifier to compensate this decline in sensitivity, so miss-detection owing to electrical noises coming over the air is liable to happen.



(a) Developed probe (b) Conventional probe

Photo 3 Waveforms of side wall echoes observed

For this reason, a broad bandwidth surface wave probe with the improved sensitivity was developed by making the following two improvements.

5.2.1 Selection of materials (piezoelectric element, resin wedge)

To get high sensitivity and to lower the amplitude of spurious echo, a piezoelectric element with a high electromechanical coupling factor in the thickness direction and a low electromechanical coupling factor in the radius direction is used as the oscillator of ultrasound. A resin with low ultrasound attenuation and high acoustic impedance is used as the wedge material in order to reduce the attenuation in the wedge and transmission loss from the piezoelectric element to the wedge.

5.2.2 Modification of incident angle

Incident angle θ_i from the wedge to the roll surface is determined on the basis of surface wave velocity in high-speed tool steel to satisfy the Snell's law defined as Eq. (3).

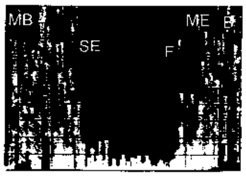
$$C_w/\sin\theta_i = C_R/\sin\theta_t \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Here, C_w is the ultrasound velocity in the resin wedge, C_R is the surface wave velocity in the material to be tested, and θ_t is the refraction angle (90° in the case of surface waves).

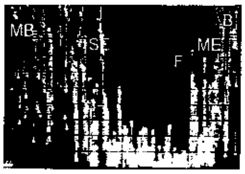
5.3 Performance and Usefulness of the Developed Probe

Photo 3 shows the waveform of surface wave transmitted by the developed broad bandwidth surface wave probe, as contrasted with the waveform of surface wave transmitted by a conventional surface wave probe. Sensitivity of the developed probe with the center frequency of 2 MHz and the pulse duration of 1.5 times the wavelength is equal to that of the conventional probe.

Photo 4 shows a comparison between the test result with the developed probe and that with conventional probe using an artificial surface flaw having a depth of 0.2 mm and a width of 0.5 mm (slit-like shape) in a block of high-speed tool steel of 10 mm in thickness. Distance between the probe and the flaw is 100 mm. Small, shallow surface flaws can be detected with a high



(a) Developed probe (gain: 68 dB)



(b) Conventional probe (gain: 74 dB)

MB: Main bang F: Flaw echo B: Edge echo
SE: Spurious echo in wedge
ME: Mode converted echo

Photo 4 Test results of artificial surface flaws detection

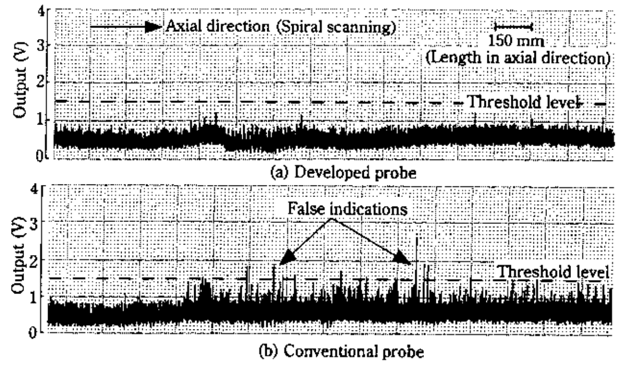


Fig. 8 Comparison between the test result for roll surface with harmless small fire cracks by using the developed probe and that by using the conventional one

signal-to-noise ratio by use of the developed probe. **Figure 8** shows the test results of a hot-rolling work roll after grinding by use of the developed probe and the conventional probe installed in an automatic roll surface flaw detector. High indications are observed with the conventional probe. However, these are falsely detected collective fine fire cracks remaining in the ground surface. In contrast, no false indications can be observed with the developed probe. It can therefore be understood that the developed probe is free from false detection of collective fine fire cracks. As a result, excessive grinding of roll surface owing to false detection could be prevented, and roll consumption could be reduced more than 20% while actual operations of roll grinding in Kawasaki Steel. This probe can be applied to the surface testing of work rolls for cold rolling and backup rolls as well.

6 Conclusion

Representative examples of state-of-the-art techniques and instruments for internal quality measurements in steel sheet production processes have been presented. In the future, users' needs with respect to the properties and uniformity of steel sheet products will become increasingly more advanced. At the same time, manufacturing methods for steel sheet products are expected to progress in the direction of higher efficiency, continuous operation, and automated operation. Accordingly, it is considered that further improvement in performance and in efficiency, and the development of measuring techniques for new objects will become necessary in product quality measurement techniques. In order to cope with these requirements, efforts to advance existing quality measurement techniques, to develop new measurement techniques, and to put them to practical use are planned.

References

1) Y. Yokota, Y. Mashino, T. Shiraishi, H. Hayashi, M. Kobayashi, and T. Kodama: "Development of Non-Metallic Inclusion On-Line Detection System", *CAMP-ISIJ*, 7(1994)5, 1270, (in Japanese)
2) Y. Yamamoto, H. Yokota, Y. Mashino, T. Shiraishi, and S. Sato: "Inclusion and Gouge Detecting System for Tin Plate", 8th Continuous Steel Strip Plating Symp., (1996)
3) M. Yoshimura, Y. Yokota, M. Mashino, K. Takezawa, and T. Yasumi: "Application of the Internal Defect Detector for Steel Sheet", *CAMP-ISIJ*, **8**(1995)2, 365, (in Japanese)
4) M. J. P. Musgrave: "Crystal Acoustics", (1970), 81, [HOLDEN-DAY, INC.]
5) H. Takada, K. Asano, F. Ichikawa, T. Miyake, M. Kawahara, and H. Yamashita: "Nondestructive Detection of Poorly Grown Grains in the Grain-Oriented Electrical Steel by Ultrasonic Interferometry", *CAMP-ISIJ*, **10**(1997)2, 290, (in Japanese)
6) H. Takada, A. Torao, and F. Ichikawa: "Nondestructive Mapping of Secondary Recrystallized Grains in Grain-Oriented Electrical Steel by Ultrasonic Interferometry", 1998 ASNT Fall Conf. and Quality Testing Show Paper Summaries Book, Nashville (USA), (1998), 199–201
7) F. Ichikawa, H. Maruyama, K. Kurita, and S. Takahashi: "Study on Optimum Conditions for Lamb Wave Ultrasonic Testing and Its Application to Product Line", *Kawasaki Steel Giho*, **18**(1986)2, 192, (in Japanese)
8) H. Takada, F. Ichikawa, Y. Okamoto, and T. Ogata: "Development of Ultrasonic C-scan Test System and its Application to Evaluation of Advanced Materials", Proc. of the 3rd Jpn. Int. SAMPE Symp., Chiba (Japan), **2**(1993), 2305–2309
9) H. Takada, A. Torao, I. Yarita, and F. Ichikawa: "Development of an Ultrasonic Immersion Testing Method for the Detection of Nonmetallic Inclusions in Steel Products by Use of Double Line-focused Probe Allay Technique", Proc. of the JSNDI Spring Conf., Tokyo (Japan), (1997), 225–228, (in Japanese)
10) Y. Ando, H. Sorano, and Y. Sano: "Surface Crack Detector for Rolling Mill Rolls by Surface Ultrasonic Wave", *CAMP-ISIJ*, **5**(1992)2, 515, (in Japanese)
11) Y. Tsuchiya, Y. Ohnishi, A. Koido, K. Shiraishi, K. Masuda, and K. Okimoto: "Application of Surface Crack Detector for Work Rolls of Hot Strip Mill", *CAMP-ISIJ*, **6**(1993)2, 505, (in Japanese)
12) I. N. Ermolov: NDT Int., December (1976), 275–280