Technical Report

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Non-destructive Inspection Technique Supporting Product Quality

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Abstract

If a flaw in a steel material triggers a structural failure, a serious accident or disaster may result. Non-destructive inspection (NDI) plays an important role in quality assurance for customers and quality control for improving manufacturing processes. This paper presents unique NDI technologies developed by Nippon Steel & Sumitomo Metal Corporation such as phased-array ultrasonic flaw detection, electromagnetic ultrasonic testing, and electromagnetic testing using the rotating field, the inspection methods developed to meet the requirements for high-speed and stable testing of all products, and quantitative measurement of material quality, and that respond to user requirements for higher quality.

1. Introduction

Nippon Steel & Sumitomo Metal Corporation manufactures steel sheets, plates, bars, rods, pipes and parts, which are used for vehicles, ships, aircraft, plants, drilling and transport of oil and gas, etc. If there are flaws in these products that cause structural failure, a serious accident or disaster may result, which means that the company must develop products free from flaws in their intended use, guarantee to their users to that effect, or provide users with safety and security together with the products. An important way to enhance manufacturing performance in this sense is to check the product quality at key stages in production processes, control it accordingly, and should a quality problem be found, identify the cause and take measures to remove it.

Non-destructive inspection (NDI) plays a very important role in the quality control and assurance of the company's products. The computer hardware and software applicable to material inspection have advanced remarkably over the last few years, and against this background, Nippon Steel & Sumitomo Metal has developed high-speed processing methods for measuring and inspecting numerous steel products stably, and new technologies to measure material properties as well as to detect flaws. By so doing, the company has adequately responded to increasingly stricter customer requirements, and actually applied them commercially in addition to conventional standard flaw detection methods. This paper presents some typical examples of such new inspection technologies.

2. High-speed Ultrasonic Inspection Applying Phased Array Technique

The manufacturing technology of high-performance ultrasonic array probes underwent remarkable advances in the late 1990s and thereafter, and as a consequence, phased array technology and its industrial application have also advanced. In the early days of the technology, it was capable of electronic scanning by electronically switching drive elements, ultrasonic beam steering at a specific angle by slightly differentiating the drive timing of individual elements, focusing of the ultrasonic beam upon a desired point, and the combination of these methods (see **Fig. 1**). The advantages of applying the array probe include high-speed scanning by reducing the load of the probes' mechanical scanning, and higher resolution at a desired material position by transmitting an ultrasonic beam of a desired shape and energy distribution by one array probe. Nippon Steel & Sumitomo Metal has developed a high-accuracy and high-speed ultrasonic inspection system for the girth weld joints of gas pipes (see **Fig. 2**) and the welded seams of UOE pipes (see **Fig. 3**) applying the phased array technique.[1, 2)]

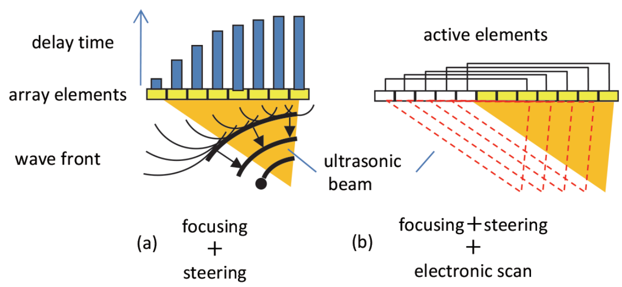

Fig. 1 Phased array ultrasonic testing technique

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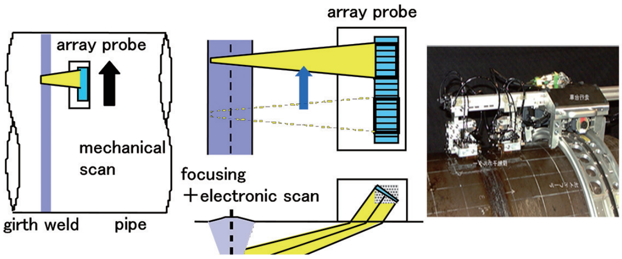

Fig. 2 Ultrasonic testing system for girth weld joints

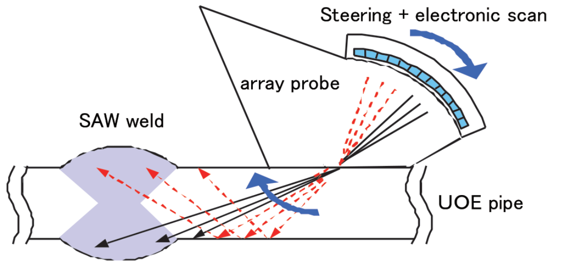

Fig. 3 Ultrasonic testing of UOE pipe seams using array probe

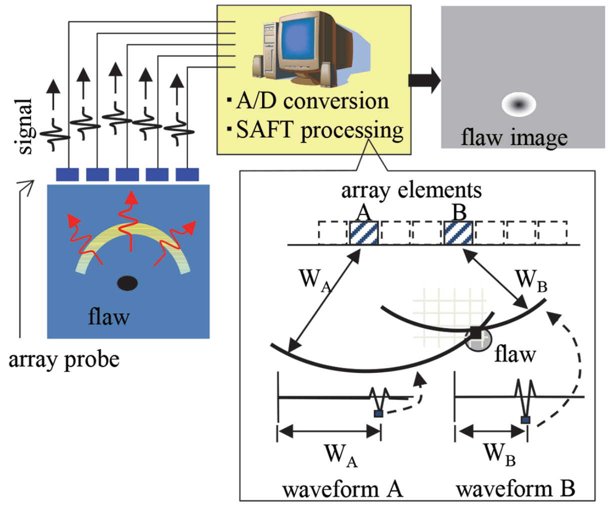

Fig. 4 Synthetic aperture focusing technique

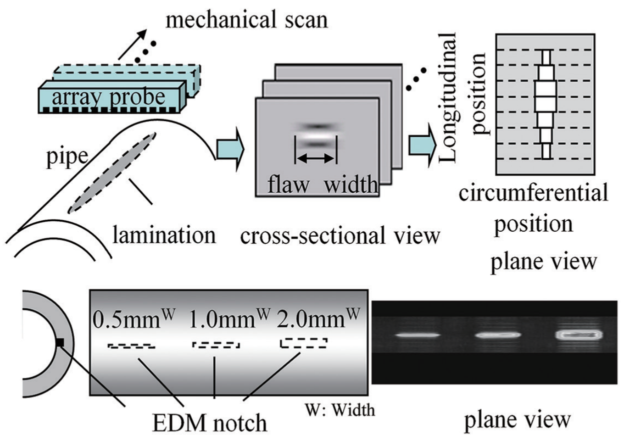

Fig. 5 Quantitative evaluation of lamination

3. Flaw Detection Applying Synthetic Aperture Focusing Technique

Phased array ultrasonic inspection consists of beam control based on time control delay of beam transmission and arithmetic processing of signal waves captured by the elements. Devices for specific applications such as field programmable gate arrays (FPGA) capable of high-speed and economical signal processing began to be used for ultrasonic array inspection equipment in the 2010s, which made it possible to process signals at a higher speed and in more complicated ways than before. A typical example is the synthetic aperture focusing technique (SAFT): it is a signal processing method used in the field of radar for compiling received radio signals into a high-resolution image. The elements of an array probe are very small, and the directivity of their beams is wide, and as a consequence, the amplitude and the phase (travelling time) of the detected reflection waves received by an element contain information of the size and position of reflection sources (or flaws) in the searched zone.

By the technique, the positions of reflection sources are inferred from the waveforms received by two or more elements of an array probe, the values of amplitude are summed for the respective positions, and based on these, a brightness image of the reflection sources is composed (see **Fig. 4**). Because this processing is equivalent to focusing on every reflection source in the searched zone, and an array probe can be regarded as a large aperture sensor, a high focusing effect is realized in the entire search zone, and an image of a high spatial resolution is obtained. Applying this technique, Nippon Steel & Sumitomo Metal has developed a method for quantitatively evaluating the lamination flaws of seamless pipes,[3] whereby synthetic aperture focusing is performed at every position during the mechanical shifting of the probe in the length direction of a pipe, the width of each flaw is calculated from a series of sectional images continuously compiled, and the area of a flaw is defined based on the pitch and cumulative width of the flaw in the axle direction. Flaws can also be seen in the plan view (see **Fig. 5**).

In addition, an on-line ultrasonic inspection system for round bars has been developed, whereby a spreading beam is transmitted by delay time control, and synthetic aperture focusing is applied at receipt of the signals (see **Fig. 6**).[4] Conventionally, ultrasonic flaw detection of round bars was conducted by combining internal inspection using a normal beam and surface and sub-surface layer inspection using angle beams, but more recently, higher sensitivity has been required for higher material quality, and high-speed inspection for higher production efficiency. The rotating probe method for the conventional “one normal beam channel + two angle beam channels” (part (a) of Fig. 6) was replaced by the phased array method by electronic scanning (part (b)), thus satisfying the requirement for higher sensitivity. To meet the requirement for high-speed inspection, however, electronic switching of beam transmission and signal reception in quick cycles is necessary, but this is difficult because of “ghost echo”, a physical phenomenon intrinsic to ultrasonic inspection. By the developed method (part (c)), on the other hand, a widely spreading beam is transmitted to cover the areas of the normal and angle beams, and the signal-to-noise ratio is enhanced by the synthetic aperture focusing, which solved the above problem. This realizes high-speed inspection by decreasing the number of times of beam transmission and reception necessary for covering a sectional area.

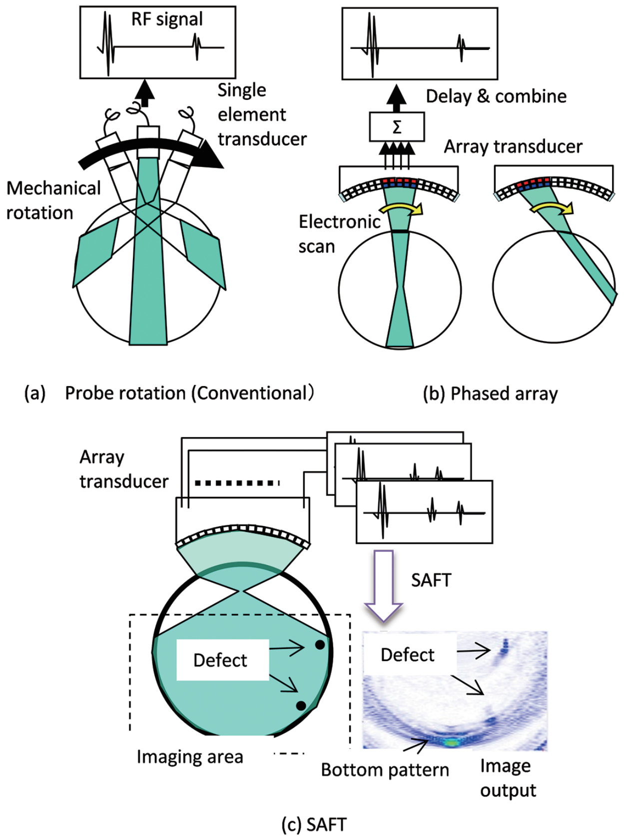

Fig. 6 Ultrasonic testing technique for cylindrical products

4. Noncontact Ultrasonic Transmission and Reception

If it is possible to transmit and receive ultrasonic waves without contacting the object to be inspected, ultrasonic flaw detection will be applicable to objects in high temperature, of complicated shapes, or in rapid movement, with which it is difficult to supply a contact medium, and such a method will be greatly advantageous for the steel industry.

Typical methods for noncontact ultrasonic transmission and reception include the laser ultrasonic technique and the electromagnetic ultrasonic transducer (EMAT) technique. By the former, the distance between the transmitter and the object can be comparatively large, but the transmission is significantly affected by the change in reflectance of the object due to surface scale and the atmosphere of the light path, and the transmission/reception sensitivity is not always high. In addition, the optical devices such as the laser oscillator and interferometer are expensive. By the latter, although the equipment consists of electric circuits, coils and magnets, and is more economical than that of the former, eddy currents and magnetostriction induced in the object are used for the ultrasonic transmission and reception, and the sensitivity is low, and the distance between the sensor and the object is several millimeters at the maximum.

When the inspection object is a steel sheet, however, it is possible to compensate for the low sensitivity of the laser ultrasonic technique by measuring the sound velocity of the zero-group-velocity lamb waves in the sheet with respect to the frequency range.[5)] We have applied this to the quality measurement of the phase transformation ratio, Poisson's ratio, etc. of sheets and reported the results.[6)] The application of the above to the stress measurement of steel sheets is presented below.

4.1 Measurement principle

When a pulse beam from a YAG laser oscillator is concentrated through a lens and irradiated onto the surface of a steel sheet, ultrasonic waves are emitted from the sheet owing to ablation due to the reaction to instantaneous evaporation of the metal, thermal elasticity resulting from rapid thermal expansion and contraction, etc. When the power density of the laser beam at the sheet surface is high, the ablation effect is strong and the amplitude of the ultrasonic waves is large, but a laser mark remains on the surface and the application of this method is largely restricted. In the case of ultrasonic excitation by thermal elasticity, in contrast, the power density required for ultrasonic emission is comparatively small, and no laser mark remains, although the sensitivity is somewhat lower.

As an example of measurement using ultrasonic waves due to ablation, there is a report of a test in which the S_1-mode frequency and the A_2-mode frequency of zero-group-velocity (hereinafter expressed as S_1f and A_2f, respectively) of lamb waves in a sheet were measured, and from those values, Poisson's ratio, the sound velocity of transversal waves and the same of longitudinal waves were calculated.[5)] In addition, S_1f and A_2f are expressed theoretically as follows:

$$S_1 f = \beta_1 \cdot \frac{V_L}{2d} \tag{1}$$

$$A_2 f = \beta_2 \cdot \frac{3V_S}{2d} \tag{2}$$

here, β_1 and β_2 are coefficients in the form of functions of Poisson's ratio, V_L is the sound velocity of longitudinal waves, V_S is the same of transversal waves, and d is the sheet thickness.

When stress is imposed on a sheet, its elasticity changes, albeit very slightly, and the sound velocity of ultrasonic waves also changes. This sound velocity change due to stress is called the acoustoelastic phenomenon, and is expressed as:[7)]

$$\Delta V = C_A \cdot V_0 \cdot \sigma \tag{3}$$

here, ΔV is the sound velocity change, C_A the acoustoelastic coefficient, V_0 initial sound velocity, and σ the imposed stress. It is presumed from equations (1) to (3) that, when stress is imposed on a steel sheet, the sound velocities of longitudinal and transversal waves change, and as a consequence, the measured values of S_1f and A_2f also change.

Through the study of ultrasonic excitation in the thermoelasticity range where no irradiation marks remain on the surfaces of steel sheets, when the pulse energy density is decreased so as not to cause irradiation marks, S_1f can be measured, but A_2f cannot. Therefore, we studied the possibility of stress measurement using S_1f only.

4.2 Stress measurement

4.2.1 Test equipment and condition

Figure 7 shows a schematic diagram of the test equipment to measure stress imposed on a thin steel sheet. The generation laser was a pulse oscillating YAG laser with a wavelength of 1 064 nm and an energy density of 1.8 mJ/mm^2, and the detection laser is a continuously oscillating YAG laser with a wavelength of 52 nm and a power output of 1 W.

A laser beam was irradiated from the generation laser to the surface of the specimen sheet, and longitudinal, transversal and lamb ultrasonic waves were generated in it. A commercially available laser interferometer was used to receive the ultrasonic signals.[8)]

Figure 8 shows the configuration of the laser interferometer; different from a Fabry-Perot interferometer, multiple reflection in the resonator is not used, and thanks to this, it is comparatively small

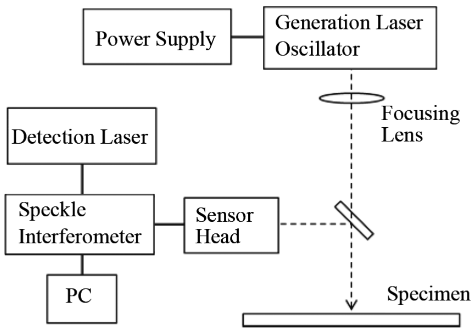

Fig. 7 Schematic diagram of the stress measurement system

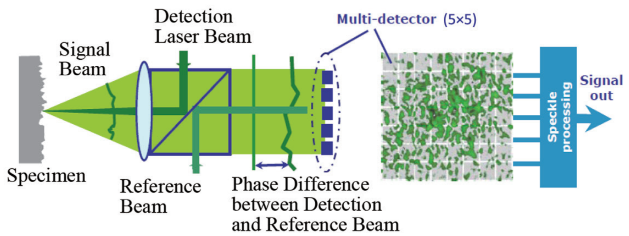

Fig. 8 Principle of ultrasonic stress measurement with interferometer

and very robust against vibration and other disturbances. It has a 5 × 5 multi-detector, which is capable of detecting ultrasonic waves in feeble and diffused reflection (speckle light) from a rough surface. In the present test, the frequency $S_1 f$ was calculated by sending the signals captured by the laser interferometer to the AD converter board of the PC and applying frequency analysis (fast Fourier transformation, FFT). The stress was applied to the specimen sheet of JIS SS400, 250 × 70 × 1.0 mm in size, using a four-point bender.

4.2.2 Test result

Figure 9 shows the measurement result without applying stress, and **Fig. 10** the same with a tensile stress of 15 MPa. The two graphs show that the frequency peak of $S_1 f$ was divided into two when tensile stress is imposed on the specimen. The value of $S_1 f$ was 2.65 MHz without the stress, and the two peaks $S_1 f_1$ and $S_1 f_2$ under the stress were 2.66 and 2.74 MHz, respectively. It is presumed from the above that, when stress was imposed, the difference in the sound velocity of longitudinal waves in different propagation directions increased owing to the tensile stress, and plural peaks of $S_1 f$ appeared according to equation (1).

It is clear that the distance between the two frequency peaks increases with the higher tensile stress imposed on the specimen as shown in **Fig. 11**; here, $S_1 f_1 < S_1 f_2$, $\Delta S_1 f_1 = S_1 f_2 - S_1 f_1$, and the separation of the two peaks is expressed as $\Delta S_1 f / S_1 f_1$.

When the amount of stress imposed on a specimen is unknown, we consider it possible to obtain the amount of stress by the following steps: applying known stresses to another specimen, determining the relationship between the separation of the two frequency peaks $\Delta S_1 f / S_1 f_1$ and the amount of stress imposed, drawing a curve of the relationship as a calibration curve, and referring to it when the value of $\Delta S_1 f / S_1 f_1$ is measured on the specimen in question.

4.3 Material quality measurement by laser ultrasonic

Stress measurement of thin steel sheets using an ultrasonic laser is shown in this sub-section. It has been possible to compensate for the disadvantage of low sensitivity of ultrasonic laser measurement and detect signals at a high signal to noise ratio by using the sound velocity of lamb waves in the zero-group-velocity mode. In addition

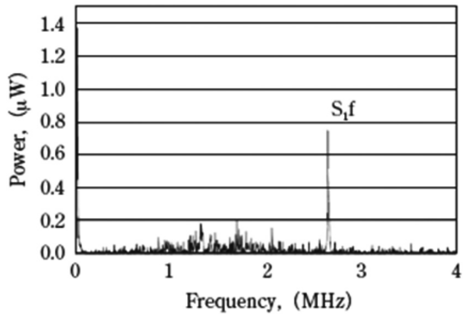

Fig. 9 Power spectrum of the output signal from a sample without stress

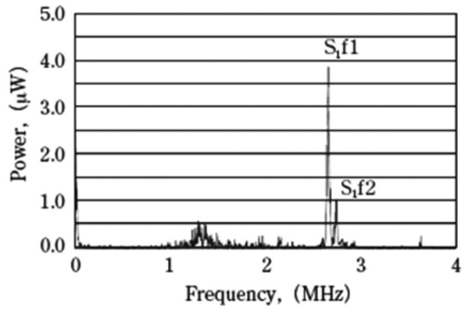

Fig. 10 Power spectrum of the output signal from a sample with stress (15 MPa)

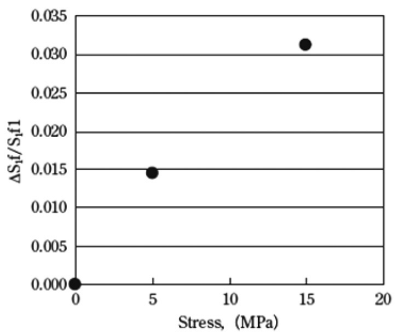

Fig. 11 Relationship between the stress and the parameter $\Delta S_1 f / S_1 f_1$

to stress measurement, this method will be effective also for the non-destructive measurement of crystal grain size, phase transformation ratio, mechanical properties, etc. of sheet products, and its application to material quality measurement will require further exploration.

5. Omnidirectional Flaw Detection Applying Electromagnetism

5.1 Background to development

While electromagnetic flaw detection (eddy current flaw detection and magnetic flux leakage testing) has been effectively employed to detect flaws of steel pipes stretching in the longitudinal and circumference directions, Nippon Steel & Sumitomo Metal has pursued a new technique for detecting flaws stretching in any direction with high accuracy.

5.2 Superimposed magnetic field rotation technique (SMaRT)[9, 10]

The AC magnetic flaw detection method is widely used for detecting small surface flaws. **Figure 12** shows the relationship between the orientation of an AC magnetic field applied by a sensor (sensor directionality) and the change in the amplitude of flaw signals depending on the direction in which it stretches. The signal amplitude is largest when the magnetic field and the flaw length cross at right angles, and it tends to decrease as the crossing angle decreases. It is also possible to maximize the SN ratio of a flaw stretching in a specific direction by setting the sensor directionality perpendicular to the flaw length direction, and at the same time, applying a bias magnetic field parallel to the flaw length as shown in **Fig. 13**. This is because the parallel bias magnetic field best suppresses the noise (μ noise) caused by uneven magnetic permeability of the material.

The superimposed magnetic field rotation technique (SMaRT) shown in **Fig. 14** has been devised to realize the condition of Fig. 13 for flaws stretching in any direction. A bias magnetic field is formed by setting two electromagnets such that their magnetization directions are perpendicular to each other, and applying alternating currents to them in the same frequency fr but differentiating the phases by 90 degrees from each other. A rotating field is formed and the condition of Fig. 14 is maintained by providing, directly above the detection coil, two air-cored coils at right angles so that their magnetization directions are perpendicular to each other, and applying to them two AC currents that are generated by amplitude modulation of a high-frequency current, 50 to 100 times fr in frequency, in sine waves of the same frequency fr but that differ in phase by 90 degrees from each other.

5.3 Laboratory test result

We confirmed the following through a laboratory test. By combining the magnetizing method given in Fig. 14 with a signal processing method, it is possible to detect flaws stretching in any direction with the same sensitivity (see **Fig. 15**). We can also define the stretching direction of a flaw with an accuracy of ±15°. In addition, the μ noise of carbon steel pipes, which are ferromagnetic, is decreased to below 70% by applying a bias field, which improves the SN ratio of flaw signals (see **Fig. 16**). The SMaRT remains a technique still under development, and we intend to make it commercially viable as soon as possible. In that event, the technique will improve the electromagnetic flaw detection of steel pipes to the level of identifying flaws stretching in any direction, contributing to the quality improvement of the product.

6. Conclusion

This paper introduced examples of the unique technical developments of Nippon Steel & Sumitomo Metal in the field of non-destructive inspection supporting the quality of its products. To create a safer and more secure society, material inspection technology is required to meet the need for the ever increasing high level of quality. Presently, increasingly higher and complicated information proc-

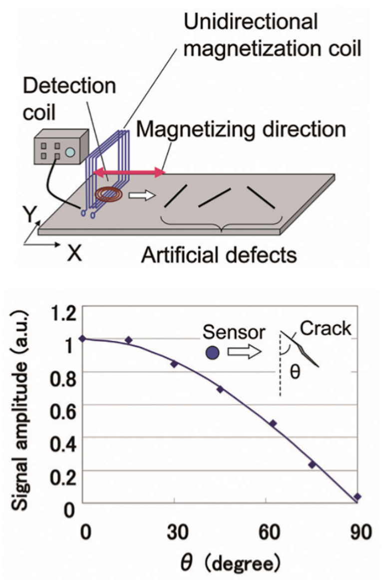

Fig. 12 Relationship between signal amplitude and crack angle

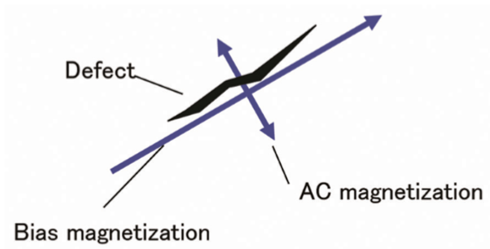

Fig. 13 Optimum AC magnetization and bias magnetization for flaw detection

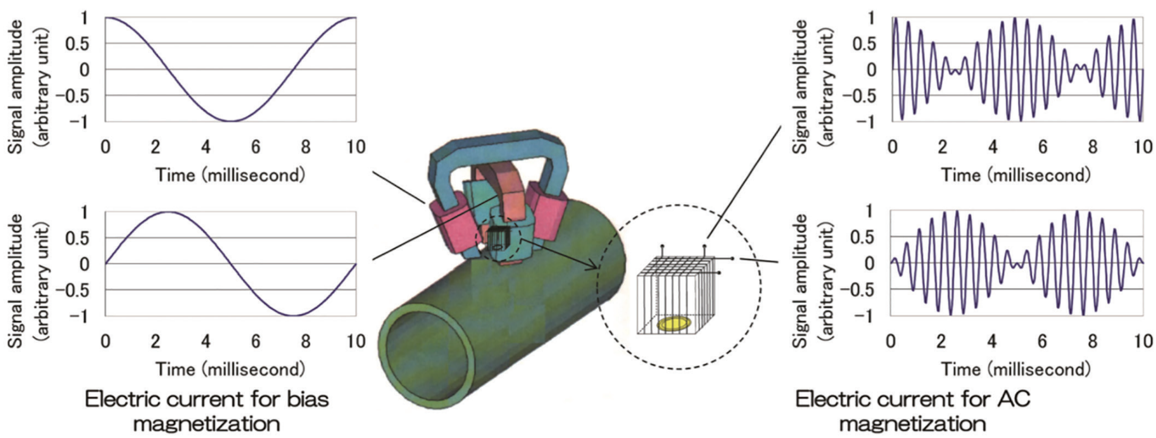

Fig. 14 Schematic configuration of SMaRT device

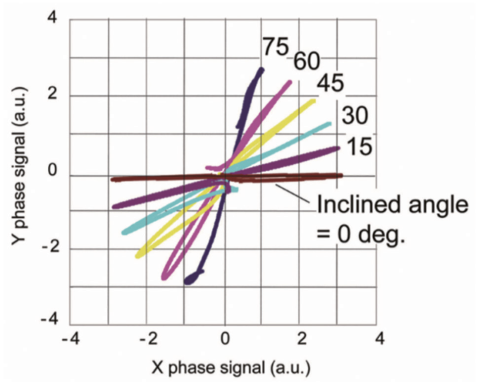

Fig. 15 Relationship between signal wave form and crack angle by SMaRT

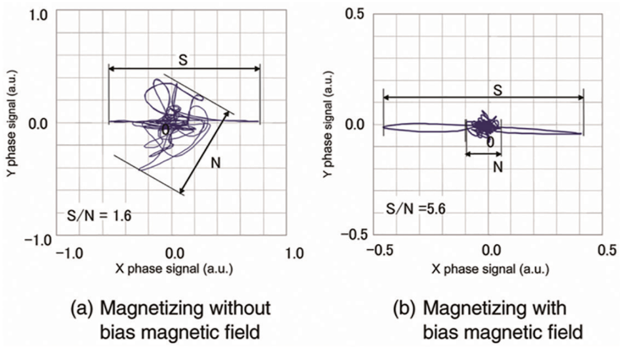

Fig. 16 Improvement of SN ratio (specimen: 0.25%C steel pipe)

essing has been enabled thanks to the advances in computer processing speed, and the application of artificial intelligence to material inspection, which has been trusted to human judgment only, requires further study. Nippon Steel & Sumitomo Metal will continue to take on the challenge of new revolutionary technologies and their practical application to respond to the requirements.

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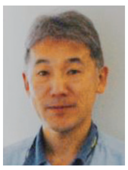
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