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On-line Measuring Technique for Plastic Strain Ratio ($\bar{r}$ Value) of Cold-Rolled Steel Sheet

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Abstract:

As a nondestructive evaluation method using ultrasonic waves, a new technique has been developed for the on-line measurement of the plastic strain ratio ($\bar{r}$ value) of cold-rolled steel sheet by a resonance electromagnetic-acoustic method. Conventionally, the plastic strain ratio ($\bar{r}$ value) of cold-rolled steel sheet is measured on specimens cut from the sheet. The new technique evaluates the $\bar{r}$ value of the sheet continuously and on-line by measuring the thickness resonance frequencies of three types of waves propagated in the sheet using an electromagnetic-acoustic transducer (EMAT). The EMAT technique has high measurement accuracy, is capable of noncontact measurement with a compact sensor, and can be installed in the field. It is also less subject to disturbance, such as sheet vibration, temperature and tension. A resonance electromagnetic-acoustic measurement system is already installed on a continuous annealing line and is contributing to the quality stabilization of cold-rolled steel sheet products.

1. Introduction

Press formability, or the ability to be formed without fracturing, is as important as yield strength and other mechanical strength in defining the properties of cold-rolled steel sheet to be press formed into the outer panels of automobiles and electrical appliances. Generally, the r value is used as a formability index of steel sheet when subjected to deep drawing deformation. As its average r value in the rolling plane or $\bar{r}$ value increases, the steel sheet is improved in deep drawability and becomes less susceptible to fracturing during press forming. At present, the $\bar{r}$ value is measured by the tensile test method (**Fig. 1**) or by nondestructive methods such as the intrinsic vibration method, and is used for the quality control of products. These conventional methods call for specimen preparation, take much time and labor, and are capable of evaluating only localized portions of the product.

Work has been conducted on the research and development of techniques for nondestructively and rapidly determining the $\bar{r}$ value of steel sheet product using ultrasonic waves without specimen

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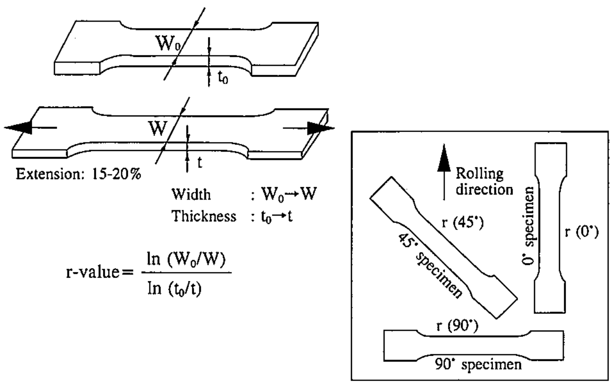

$$\bar{r}=\frac{r(0^\circ)+2r(45^\circ)+r(90^\circ)}{4}$$

Fig. 1 Measurement of $\bar{r}$ value by tensile test method.

preparation[1-3]. The authors theoretically clarified that the in-plane average Young's modulus $\bar{E}$ of steel sheet could be measured in-situ by propagating multiple ultrasonic waves in the sheet and measuring their sound velocity anisotropy. They indicated that the $\bar{r}$ value could be determined with high accuracy from the strong correlation between the $\bar{E}$ value and $\bar{r}$ value. Furthermore, they established a technique for measuring the $\bar{r}$ value with high accuracy by using the resonance electromagnetic-acoustic method, and showed that the new technique could be used for the on-line measurement of the $\bar{r}$ value[4-5].

This article describes the principle and method of measuring the $\bar{r}$ value, the results of performance evaluation, and the application of the new method to the on-line measurement of the $\bar{r}$ value of moving steel sheet.

2. Principle of Measurement

2.1 Evaluation of product of Young's modulus and $\bar{r}$ value by ultrasonic measurement

Annealed cold-rolled steel sheet can be considered an aggregate of cubic single crystals of iron. With no uniform orientation distribution with respect to the material axis, this sheet develops what is called a texture. The evolution of the texture exerts a great effect on the plastic properties of the steel sheet and strongly governs its $\bar{r}$ value as well.

The texture is also closely related to the elastic properties of the steel sheet. The degree of preferred orientation of crystals that determines the texture is expressed by the orientation distribution coefficient that gives the probability of crystals orientation in a given direction. When the specimen is a polycrystalline specimen with the same orthorhombic symmetry exhibited by cold-rolled steel sheet, the three low-order orientation distribution coefficients W_{400}, W_{420} and W_{440} have an important meaning. The secondary elastic constants of steel sheet can all be described by the orientation distribution coefficients W_{400}, W_{420} and W_{440} and the three moduli of elasticity C^0_{11}, C^0_{12} and C^0_{44} of iron single crystals[6]. Since C^0_{11}, C^0_{12} and C^0_{44} are considered physical constants, W_{400}, W_{420} and W_{440} eventually govern the elastic properties as well as Young's modulus of steel sheet.

Texture also affects the ultrasonic waves that propagate in steel sheet, and the ultrasonic waves exhibit velocity anisotropy following anisotropy due to the texture.

The authors used the five types of ultrasonic waves shown in **Fig. 2**, i.e., the longitudinal waves U_{ZZ} propagated in the thickness direction (Z direction), transverse waves U_{ZX} propagated in the thickness direction and polarized in the rolling direction (X direction), transverse waves U_{ZY} propagated in the thickness direction and polarized in the transverse direction (Y direction), and plate waves SH_0 propagated in two directions. They clarified that W_{400}, W_{420} and W_{440} could be obtained from the thickness resonance frequency ratios K_1 and K_2 of the first three types of ultrasonic waves and from the sound velocity ratio K_3 of the last two types of ultrasonic waves.

That is,

$$K_1=\frac{mf_{ZXn}}{nf_{ZXn}},\quad K_2=\frac{mf_{ZXn}}{nf_{ZZm}},\quad K_3=\frac{V_{SH_0}(45^\circ)}{V_{SH_0}(0^\circ)} \quad \cdots\cdots(1)$$

where m and n are arbitrary orders; f_{ZZm} is the m-th order thickness resonance frequency of the longitudinal waves U_{ZZ}; f_{ZYn} is the n-th order thickness resonance frequency of the transverse waves U_{ZY} polarized in the transverse direction; f_{ZXn} is the n-th thickness resonance frequency of the transverse waves U_{ZX} polarized in the rolling direction; and $V_{SH_0}(0°)$ and $V_{SH_0}(45°)$ are the sound velocities of the plate waves SH_0 propagated in the rolling direction and at 45° to the rolling direction, respectively. If

$$K_P=\frac{K_1^2+K_2^2}{K_1^2+K_2^2+1},\quad K_M=\frac{K_1^2-K_2^2}{K_1^2+K_2^2+1}$$

then,

$$W_{400}=\frac{7}{16\sqrt{2}\pi^2}\left(\frac{5C^0_{44}+C^0}{C^0}\right)\left[1-\left(\frac{5C^0_{11}+10C^0_{44}}{2C^0+10C^0_{44}}\right)K_P\right] \quad \cdots\cdots(2)$$

$$W_{420}=\frac{-7}{16\sqrt{2}\pi^2}\left(\frac{5C^0_{44}+C^0}{C^0}\right)\left(\frac{5C^0_{11}+10C^0_{44}}{2C^0+10C^0_{44}}\right)K_M \quad \cdots\cdots(3)$$

$$W_{440}=\frac{7}{8\sqrt{35}\pi^2}\left(\frac{5C^0_{44}+C^0}{C^0}+\frac{4\sqrt{2}\pi^2W_{400}}{7}\right)\left(1-\frac{1}{K_3}\right) \quad \cdots\cdots(4)$$

where $C^0 = C^0_{11} - C^0_{12} - 2C^0_{44}$.

As already described, the nine elastic moduli C_{ij} and Young's modulus $E(\theta)$ in the θ direction in the rolling plane can be expressed by the above-mentioned W_{400}, W_{420} and W_{440}, and C^0_{11}, C^0_{12} and C^0_{44}. This means that the Young's modulus $E(\theta)$ can be

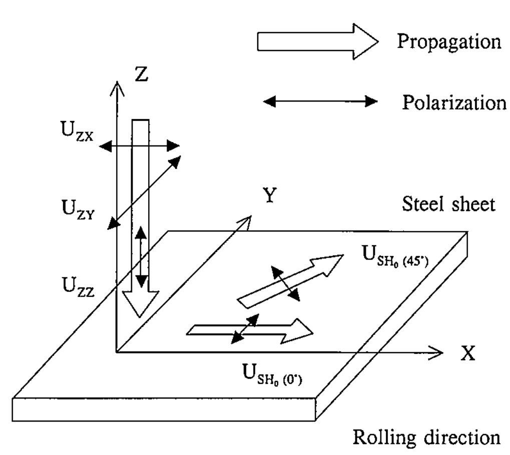

Fig. 2 Five types of ultrasonic waves propagated in cold-rolled steel sheet

calculated from the variables K_P, K_M and K_3 determined by the ultrasonic measurements and from the three elastic moduli of iron single crystals.

$$E(\theta) = Func_1 (W_{400}, W_{420}, W_{440}, C^0_{11}, C^0_{12}, C^0_{44}, \theta) = Func_2 (K_p, K_M, K_3, C^0_{11}, C^0_{12}, C^0_{44}, \theta) \quad \cdots\cdots(5)$$

Of the ultrasonic measurements, the sound velocity ratio K_3 of the plate waves SH_0 propagated in the two directions is important when obtaining the Young's modulus $E(\theta)$ in each direction, but does not appreciably affect the average in-plane Young's modulus $\bar{E} = [E(0°) + 2E(45°) + E(90°)]/4$.

When errors were evaluated by keeping K_3 constant over the ranges of K_1, K_2 and K_3 obtained by measuring many steel sheet samples, the change in $\bar{E}$ was found to be very small, or about 0.05 GPa at most.

Thus,

$$\bar{E} = Func_3 (K_p, K_M, C^0_{11}, C^0_{12}, C^0_{44}) \quad \cdots\cdots(6)$$

A strong correlation is known to exist between the average r value in the rolling plane ($\bar{r} = [r(0°) + 2r(45°) + r(90°)]/4$) and the average in-plane Young's modulus $\bar{E}$[7]. If the average Young's modulus $\bar{E}$ is obtained as noted above, the $\bar{r}$ value can be calculated by an empirical formula such as the quadratic equation $\bar{r} = a\bar{E}^2 + b\bar{E} + c$, where a, b and c are appropriate coefficients.

From what has been discussed above, it can be seen that the average Young's modulus $\bar{E}$ and the $\bar{r}$ value can be obtained by eliminating the sound velocity measurement of the plate waves SH_0 related to K_3 and measuring the thickness resonance frequencies of the ultrasonic waves propagated in the thickness direction.

3. Measuring Method

3.1 Resonance electromagnetic-acoustic method

First, the principle of the generation and detection of the three types of ultrasonic waves propagated in the thickness direction of cold-rolled steel sheet is described by referring to **Fig. 3**.

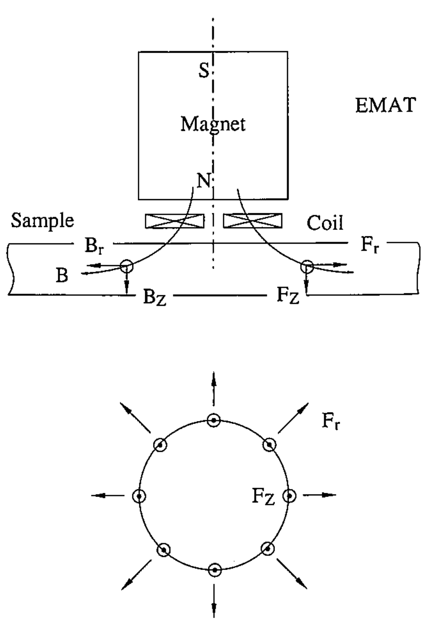

Fig. 3 Generation and detection of ultrasonic waves by electromagnetic-acoustic transducer (EMAT)

The electromagnetic-acoustic transducer (EMAT) used in the resonance electromagnetic-acoustic method consists of an electromagnet with a flat circular coil placed below it. When the transducer is placed near a cold-rolled steel sheet, the electromagnet generates a magnetic field in the sheet. The magnetic field consists of the component B_Z normal to the surface of the sheet and the component B_r parallel to and radially distributed on the surface of the sheet.

When a high-frequency current is applied to the circular coil, the eddy current I_ϕ is generated in the sheet. The interaction between I_ϕ and B_Z generates the electromagnetic force F_r parallel with and radially distributed on the surface of the sheet. The interaction between I_ϕ and B_r simultaneously generates the electromagnetic force F_Z normal to the surface of the sheet. The electromagnetic force F_r can be divided into the component F_X parallel with the rolling direction (X) and the component F_Y parallel with the transverse direction (Y). In the sheet, F_Z generates the longitudinal waves U_{ZZ} propagated in the thickness direction (Z), F_X generates the transverse waves U_{ZX} polarized in the rolling direction and propagated in the thickness direction, and F_Y generates the transverse waves U_{ZY} polarized in the transverse direction and propagated in the thickness direction. The ultrasonic waves thus generated are detected in a reverse physical process. In this way, the three modes of ultrasonic waves can be simultaneously generated and detected by one electromagnetic-acoustic transducer.

Next, the method of measuring the thickness resonance frequencies is described. The ultrasonic waves are generated according to the principle described above. When a high-frequency current is applied to the circular coil, standing waves are generated in the thickness direction of the cold-rolled steel sheet if the frequency of the high-frequency current satisfies the following equation:

$$f_{ZZm} = \frac{m}{2d} V_{ZZ}, \quad f_{ZYn} = \frac{n}{2d} V_{ZY}, \quad f_{ZXn} = \frac{n}{2d} V_{ZX} \quad \cdots\cdots(7)$$

The thickness resonance frequencies expressed by Eq. (7) can be obtained if the ultrasonic waves are repeatedly generated and detected according to the above-mentioned process while changing the frequency of the high-frequency current applied to the circular coil and the frequencies at which the detected signals become maximum are recorded. This method of measuring the thickness resonance frequencies with the electromagnetic-acoustic transducer (EMAT) is termed the resonance electromagnetic-acoustic method.

In Eq. (7), d denotes the thickness of the steel sheet. The resonance frequencies to be measured change with the sheet thickness as well as with the sound velocity. Since this method to measure the $\bar{r}$ value actually uses the resonance frequency ratio as expressed by Eq. (1), the change in the sheet thickness has no effect on the evaluation of the $\bar{r}$ value.

The configuration of the resonance electromagnetic-acoustic measurement system is shown in **Fig. 4**. The measurement system consists of the transducer (EMAT), oscillator, power amplifier, wide-band amplifier, bandpass filter, A/D converter, microcomputer and several other components.

An example of an ultrasonic resonance spectrum measured with the new system is shown in **Fig. 5**. Each of the three ultrasonic wave types has multiple resonance peaks. The resonance peaks of the same type of ultrasonic wave are spaced at the same distance. The resonance frequency of the longitudinal waves can be determined from the fact that the resonance peak interval of the longitudinal waves is about twice that of the transverse waves. The

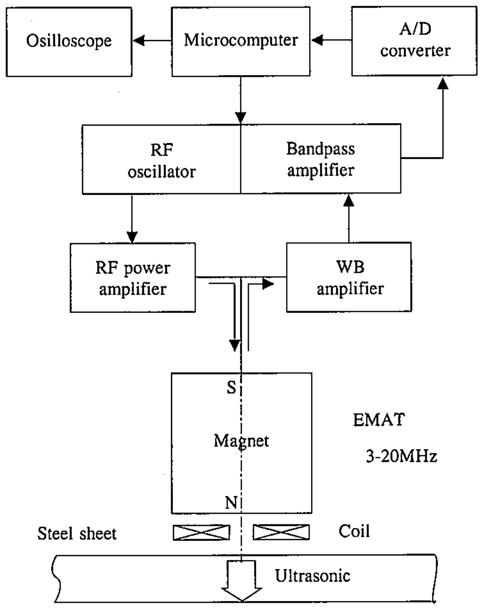

Fig. 4 Configuration of resonance electromagnetic-acoustic measurement system

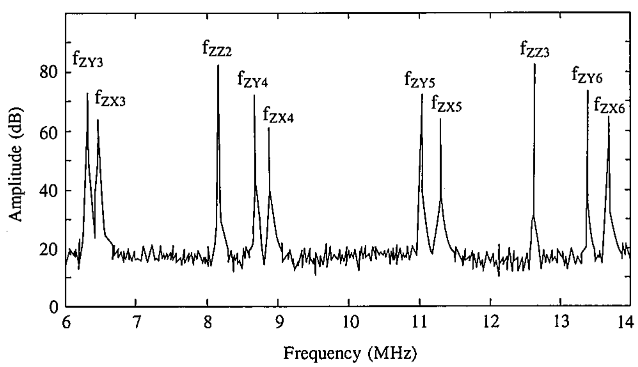

Fig. 5 Ultrasonic resonance spectrum

resonance frequencies of the two types of transverse waves can be determined from the relation $f_{ZY} < f_{ZX}$.

From the resonance frequencies f_{ZZ}, f_{ZY} and f_{ZX} measured by the system, the $\bar{r}$ value can be obtained as shown in the previous chapter.

The features of this measurement method can be summarized as follows:

1) The $\bar{r}$ value of steel sheet can be measured nondestructively in a noncontacting manner.

2) The sensor is very compact (80 mm in diameter and 60 mm in height) and can be easily installed on-line.

3) The thickness resonance frequency ratio is the quantity to be measured and can be stably measured with high accuracy with relative freedom from the effects of sheet thickness variation and other factors.

4. Performance Evaluation Experiments

The following experiments were conducted to confirm the accuracy of $\bar{r}$ value measurements made on steel sheet using the resonance electromagnetic-acoustic method, and to investigate the effects of various factors such as sheet temperature, tension and running speed in preparation for the on-line application of the resonance electromagnetic-acoustic method.

4.1 Evaluation of measurement accuracy with steel sheet samples

Experiments to verify the measurement accuracy were conducted with 134 steel sheet samples, ranging from carbon steel samples with low $\bar{r}$ values of 0.9 to 1.2 to extra-deep-drawing steel samples with excellent formability and very high $\bar{r}$ values of 1.8 to 2.2.

Fig. 6 shows the correlation between the average Young's modulus $\bar{E}$ measured by the resonance electromagnetic-acoustic method and the $\bar{r}$ value measured by the conventional tensile test method using specimens cut from the samples. From this figure, a strong correlation can be seen between the two sets of values. An experimental formula (quadratic equation) common to the sheet steels studied and intended for use in estimating the $\bar{r}$ value from the average Young's modulus $\bar{E}$ measured by the resonance electromagnetic-acoustic method was derived by the method of least squares from the results shown in **Fig. 6**. When the $\bar{r}$ value was estimated again by the quadratic equation, a very small measurement error has obtained (standard deviation $\sigma < 0.04$), verifying the high measurement accuracy of the resonance electromagnetic-acoustic method.

4.2 Effect of the gap (lift-off) between the steel sheet and sensor on sensitivity

One excellent feature of the resonance electromagnetic-acoustic method used to measure the $\bar{r}$ value of cold-rolled steel sheet is that the $\bar{r}$ value of the sheet can be measured by the sensor in a completely noncontacting condition. The effect of the gap (also termed lift-off) between the sheet and the sensor on the sensitivity of the sensor was investigated, and the maximum permissible gap was confirmed.

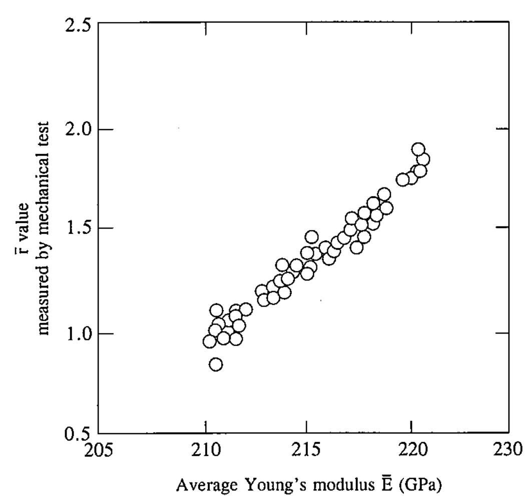

Fig. 6 Correlation between average Young's modulus measured by EMAT and $\bar{r}$ value measured by tensile test

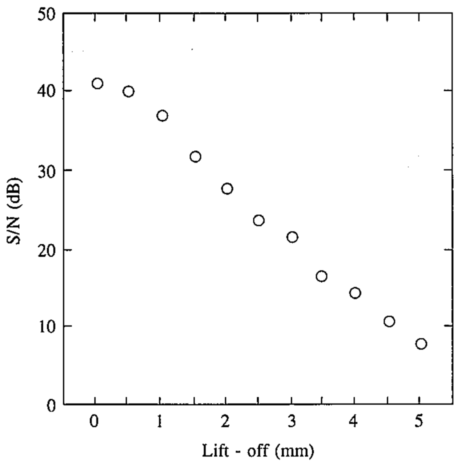

Fig. 7 Effect of lift-off between sensor and steel sheet on sensitivity

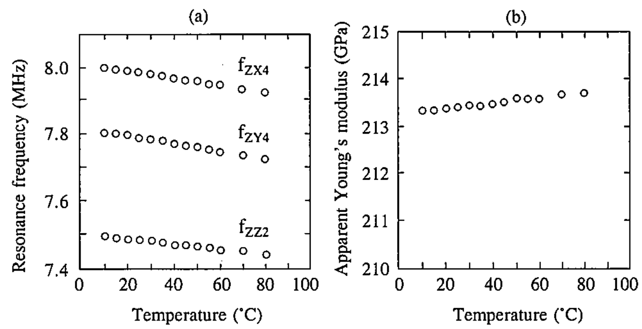

Fig. 8 Effect of steel sheet temperature on resonance frequency and apparent Young's modulus

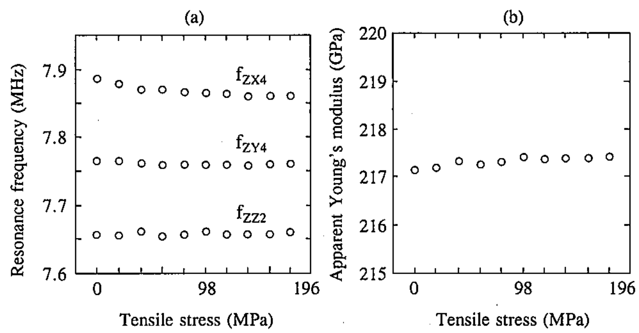

Fig. 9 Effect of steel sheet tension on resonance frequency and apparent Young's modulus

Fig. 7 shows the sensitivity (signal-to-noise ratio or S/N ratio) of the sensor when the gap between the sensor and an 0.8-mm thick steel sheet was increased in 0.5-mm increments from 0 to 5 mm. In this example of measurement, when the gap is up to 3 mm, the S/N ratio is 20 dB or more, indicating that satisfactory measurements can be made. Actually, it was decided to set the gap at 2 mm in consideration of the differences in sensitivity between different sheet steels.

In the resonance electromagnetic-acoustic method, the physical quantity to be measured is the frequency of ultrasonic waves, and the signal intensity of ultrasonic waves is not directly related to the measured values. For example, when the vibration of the sheet during on-line measurement varies with the gap of the sensor, the gap variation does not affect the measured $\bar{r}$ value, and the $\bar{r}$ value need not be compensated for the gap variation.

4.3 Effects of steel sheet temperature and tension on measurement accuracy

The sound velocity of ultrasonic waves traveling in steel sheet is affected by the steel sheet temperature and tension as well as the texture to be evaluated by the measurement of the $\bar{r}$ value. The variations in the sheet temperature and tension also change the resonant frequencies. These variables are considered to act as disturbances, especially during on-line measurement, and to adversely affect the accuracy of measurement. The effects of the steel sheet temperature and tension on the accuracy of measurement were experimentally evaluated.

First, to confirm the effect of steel sheet temperature variation, the sensor and cold-rolled steel sheet were maintained at temperatures of 10 to 80°C in a thermostatic chamber. The resonance frequencies and apparent Young's modulus were measured at each temperature. The results are shown in **Fig. 8**. The decrease in resonance frequency with increasing temperature slightly increases the apparent Young's modulus. The rate of this change is about 0.053 GPa per 10°C and corresponds to an $\bar{r}$ value of only about 0.005.

Next, to confirm the effect of steel sheet tension variation, JIS No. 5 specimens were machined from cold-rolled steel sheet in parallel with the rolling direction, subjected to a tensile stress of 176.4 MPa in the elastic range, and measured for resonance frequency. The apparent Young's modulus $\bar{E}$ was then evaluated. The results are shown in **Fig. 9**. The increase in the tensile stress slightly increases the apparent Young's modulus. The rate of this change is about 0.015 GPa per 10 MPa of tensile stress and corresponds to an $\bar{r}$ value of only about 0.001. This means that the steel sheet tension has a very small effect on the accuracy of measurement under a normal steel sheet tension of 20 MPa or less.

The above-mentioned results show that although the variations in the steel sheet temperature and tension change the measured values of resonance frequencies and the apparent Young's modulus $\bar{E}$ and the $\bar{r}$ value, these changes in the apparent Young's modulus $\bar{E}$ and the $\bar{r}$ value are small enough to be practically ignored without compensation. When the Young's modulus $\bar{E}$ and the $\bar{r}$ value of cold-rolled steel sheet are measured by the resonance electromagnetic-acoustic method, the ratios of the resonance frequencies are used rather than the resonance frequencies themselves. This is considered to contribute to the stabilization of measurements.

4.4 Effect of sheet running speed

To confirm the applicability of the resonance electromagnetic-acoustic method to moving steel sheet, 8.5 m of cold-rolled steel sheet was connected to form a ring and then measured to determine the $\bar{r}$ value at a running speed of 0 to 2.0 m/s using a rotating test apparatus. The test results confirmed that the electromagnetic-acoustic transducer (EMAT) is capable of measuring the $\bar{r}$ value of

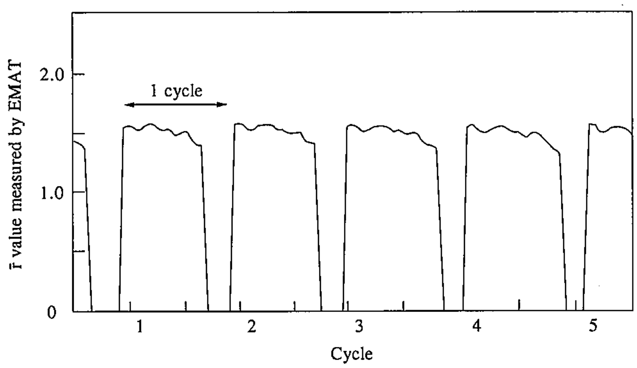

Fig. 10 r̄ value measured by rotating test apparatus

moving sheet with the same degree of accuracy that it obtains when measuring the r̄ value of still sheet. **Fig. 10** shows the r̄ value of the sheet measured for five cycles. The r̄ value is measured with good reproducibility. Next, the r̄ value of the sheet was repeatedly measured in the same position while switching the running speed from 0 to 0.33, 0.67 and 1.0 m/s. At each speed, the difference from the r̄ value of the still sheet fell within ±0.004, and the repeatability of measurements was $\sigma < 0.002$. These results confirm the excellent reproducibility of EMAT measurements.

5. On-Line Application and Evaluation

As indicated by the experimental results presented in the previous chapter, the resonance electromagnetic-acoustic method is less susceptible to various disturbances presumed to occur during on-line measurement and is expected to stably measure the r̄ value of cold-rolled steel sheet. A resonance electromagnetic-acoustic measurement system was installed on the No. 2 continuous annealing line at Nippon Steel's Kimitsu Works. The layout of the system is shown in **Fig. 11**, and its specifications are given in **Table 1**.

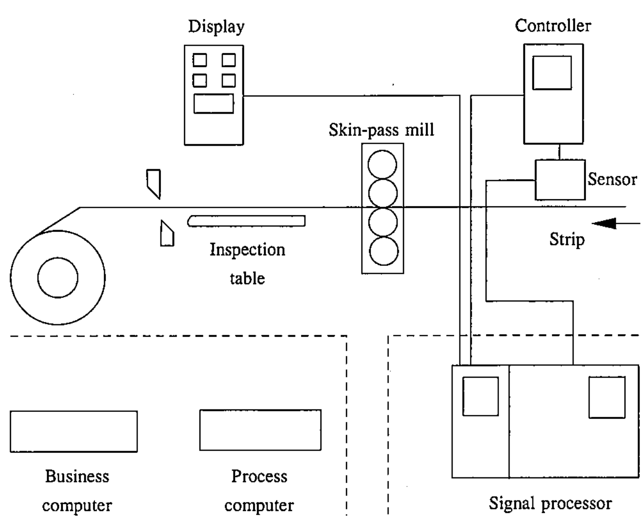

Fig. 11 Layout of resonance electromagnetic-acoustic measurement system

Table 1 Specifications of resonance electromagnetic-acoustic measurement system

r̄ value range	0.9-2.5
Accuracy	δ =0.04
Measurement interval	0.4s
Strip thickness	0.3-2.6mm
Line speed	9.7m/s (max)

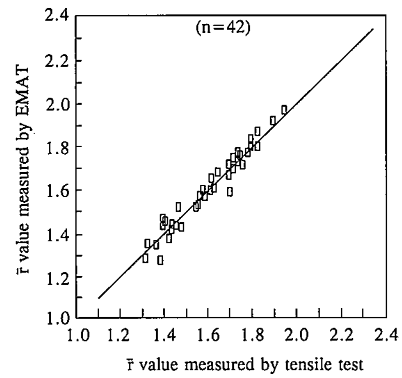

Fig. 12 Correlation between r̄ value measured by EMAT and r̄ value measured by tensile test (deep-drawing steel)

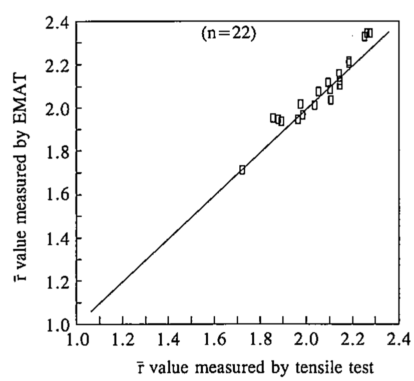

Fig. 13 Correlation between r̄ value measured by EMAT and r̄ value measured by tensile test (extra-deep-drawing steel)

The r̄ values of cold-rolled steel coils were measured over their entire length by the EMAT system. Specimens were then taken from the coils and measured for the r̄ values by the conventional tensile test method. The two sets of the r̄ values measured at the same positions are compared for deep-drawing steel in **Fig. 12** and for extra-deep-drawing steel in **Fig. 13**. It is clear that the resonance electromagnetic-acoustic system can measure the r̄ value of cold-rolled steel sheet on-line with extremely high accuracy.

6. Conclusions

A new technique, termed the resonance electromagnetic-acoustic method, has been developed for determining on-line the average in-plane Young's modulus $\bar{E}$ and the $\bar{r}$ value of cold-rolled steel sheet. The thickness resonance frequencies of three types of ultrasonic waves propagated in cold-rolled steel sheet are measured by the resonance electromagnetic-acoustic method under nondestructive, noncontacting and clean conditions. The average Young's modulus $\bar{E}$ and the $\bar{r}$ value of the sheet are then calculated on-line from the measured thickness resonance frequencies and the three known moduli of elasticity of iron single crystals. The new method is applied to the quality evaluation of cold-rolled steel sheet products.

This highly accurate nondestructive technique of evaluating the mechanical properties of steel sheet directly and on-line is rare and phenomenal. The technique uses a very compact sensor or electromagnetic-acoustic transducer (EMAT) which can be easily installed on steel processing lines. The physical quantity to be measured is not the received signal intensity of ultrasonic waves but their resonance frequency ratios. Due to its lower susceptibility to environmental factors that often interfere during on-line measurement, such as the lift-off between the sensor and steel sheet and the steel sheet temperature and tension, the resonance electromagnetic acoustic method is capable of stably measuring the $\bar{r}$ value of cold-rolled steel sheet.

A resonance electromagnetic-acoustic measurement system was installed on a continuous annealing line and is smoothly operating and contributing to quality stabilization and reliability improvement. This new system is also confirmed to be applicable to coated steel sheet, and is expected to find usage in more steel processing lines and in applications such as process control.

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