

Nondestructive evaluation of formability in cold rolled steel sheets using electromagnetic acoustic transducer for shear horizontal plate wave

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Nondestructive evaluation of formability (\bar{r} -value) in cold-rolled steel sheet with an electromagnetic acoustic transducer (EMAT) for the fundamental shear horizontal plate wave (SH₀-wave) has been developed. First, the principle of nondestructive \bar{r} -value measurement is described. Next the characteristics of the magnetostrictive type EMAT and the Lorenz force type EMAT for the SH₀-wave were evaluated to permit an optimum sensor for nondestructive measurement. Based on the results, the system with the magnetostrictive type EMAT was fabricated and the capability for measuring \bar{r} -values was evaluated using many samples. The system was confirmed to measure \bar{r} -values with an accuracy of $1\sigma = 0.065$ nondestructively.

Keywords: Formability, Cold-rolled steel sheets, Shear horizontal plate wave, Ultrasonic velocity, Electromagnetic acoustic transducer

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1. INTRODUCTION

Cold-rolled steel sheets are polycrystalline metals and have a slightly plastic anisotropic character, which originates from the preferred orientation of the crystallites or texture. The characteristics of these sheets can be effectively controlled by this texture. For instance, steel sheets for the outer panels of automobiles and refrigerators have characteristics which prevent damage during press forming through control of this texture. This type of steel sheet has good formability. W. T. Lankford¹⁾ has proposed that the plastic strain ratio is defined as the ratio of the width (W_b , W_a) and the thickness (T_b , T_a) in characterizing the formability of cold rolled steel sheet as shown in Fig. 1, which is called the r -value.

$$r = \ln(W_b/W_a) / \ln(T_b/T_a) \quad (1)$$

where W_b , W_a , T_b , and T_a are the width and thick-

ness before and after deformation of the tensile specimen, respectively. The r -value is measured using specimens taken in three directions (0°, 45° and 90° relative to the rolling direction), whose values are called r_0 , r_{45} and r_{90} .

The averaged r -value (\bar{r} -value) defined in Eq. (2) is used as a general estimation index for good formability. This test is destructive and allows only localized estimation.

$$\bar{r} = (r_0 + 2 \times r_{45} + r_{90}) / 4 \quad (2)$$

On the other hand, a method for evaluation of the \bar{r} -value by utilizing the correlation between the ultrasonic velocity and the texture has been researched.^{2,3)}

We could apply one or several modes of an ultrasonic wave for the \bar{r} -value measurement of cold rolled steel sheets, for example, a longitudinal wave, a transverse wave, a fundamental symmetrical Lamb wave and a fundamental shear horizontal plate

wave (SH-wave). In each case, there are any weak points and some strong points. This paper describes the case of using the SH₀-wave which means that the vibration occurs in the steel plane (perpendicular to the propagation direction), as shown in Fig. 2.

For practical measurements, non-contacting transducers are required and the EMATs are suitable for this purpose. When the EMATs are used for ferromagnetic materials, the magnetostriction becomes important, especially in the low magnetic field region. In the case of the magnetostrictive EMATs for the SH₀-wave, the EMATs have a simple structure in comparison to Lorenz force type EMATs

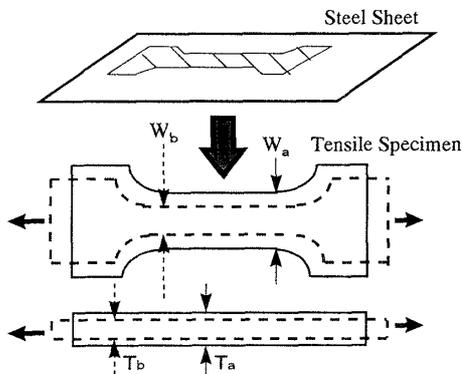


Fig. 1 Definition of Lankford value (r-value).

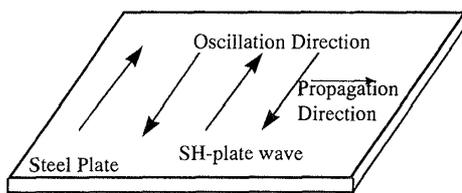


Fig. 2 Definition Shear horizontal plate wave.

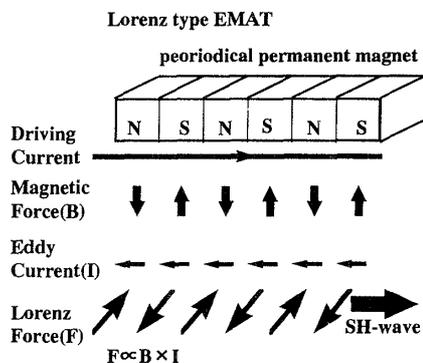


Fig. 3 Composition of Lorenz force type electromagnetic transducer for Shear horizontal plate wave.

which use the periodic permanent magnet geometry as shown in Fig. 3. The Lorenz force type of EMAT having a sufficiently strong magnetic field, which could detect the received signal with a high signal-to-noise ratio, is very difficult to fabricate.

In this paper, the principle of the \bar{r} -value measurement using the fundamental SH₀-plate wave, the driving mechanism for the sensor used in this measuring system and the outline of this system are described. The experimental results of the performance of both type of EMATs are then described. Finally, the evaluation results for the \bar{r} -value using the magnetostrictive type EMAT are presented.

2. PRINCIPLE OF \bar{r} -VALUE MEASUREMENT USING ULTRASONIC VELOCITY

The \bar{r} -value of cold rolled steel sheets is high for sheets with many {1 1 1} crystallographic planes and few {1 0 0} crystallographic planes lying parallel to the rolling direction. On the other hand, the ultrasonic velocity shows changes in accordance with the texture as shown in Fig. 4. Therefore, the \bar{r} -value can be estimated from the changes in ultrasonic velocity. This paper presents the application of the SH₀-mode plate wave to cold rolled steel sheets.

The texture is described quantitatively using the crystallite orientation distribution function (CODF). The CODF, $W(\xi, \psi, \phi)$, is a probability density function and defines how the crystallites are oriented as a whole in the bulk of a polycrystal. The independent variables (θ, ψ, ϕ) are three Euler angles defining the correlation of two Cartesian coordinate systems, one being fixed to a crystallite and the other to the specimen of a rolled sheet. In analogy to Fourier expansion, CODF is expanded in terms of generalized spherical harmonics⁴⁾;

$$W(\xi, \phi, \psi) = \sum_0^\infty \sum_{m=-l}^l \sum_{n=-l}^l W_{lmn} Z_{lmn}(\xi) \exp(-im\psi) \cdot \exp(-in\phi) \quad (3)$$

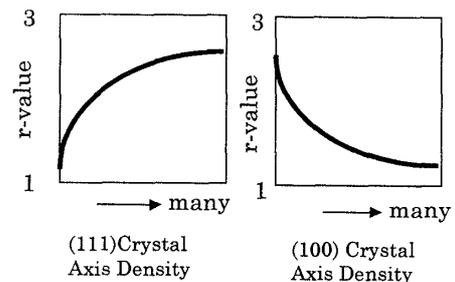


Fig. 4 Principle of \bar{r} -value measurement using ultrasonic velocity.

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$$W_{lmn} = - \int_0^{2\pi} \int_0^{2\pi} \int_{-1}^{+1} W(\xi, \psi, \phi) Z_{lmn}(\xi) \exp(im\phi) \cdot \exp(in\phi) d\xi d\psi d\phi \quad (4)$$

where $Z_{lmn}(\xi)$ is the generalized Legendre function of $\xi = \cos \theta$. The expansion coefficients, W_{lmn} , are called orientation distribution coefficients (ODCs). For orthotropic texture and cubic crystallites, some ODCs vanish and many others are mutually dependent. The independent ODCs are $W_{000} = 1/(4\sqrt{2} \cdot \pi^2)$, W_{4m0} ($m=0, 2, 4$), etc. The CODF is used to weight the orientation dependent monocrystal quantities and integrate them over the total range of Euler angles in order to obtain the macroscopic counterparts for a textured metal. The basic ODCs, W_{000} , determine the isotropic property. All other ODCs contribute to the anisotropy.

The second order elastic constants, \bar{C}_{ij} , of polycrystalline materials are obtained by integrating the products of elastic constants (C_{ij}) in the monocrystal and CODFs in any direction over the total range of Euler angles.

$$\bar{C}_{ij} = \int_0^{2\pi} \int_0^{2\pi} \int_{-1}^{+1} W(\xi, \psi, \phi) C_{ij}(\xi) \exp(im\phi) \cdot \exp(in\phi) d\xi d\psi d\phi \quad (5)$$

The ultrasonic velocity is calculated from these elastic constants.⁵⁾

Fundamental shear horizontal plate (SH₀) wave velocity is given by :

$$V_{SH_0}(\gamma) = \sqrt{\mu/\rho} (1 + (2\sqrt{2}c\pi^2/35\mu)(W_{400} - \sqrt{70}W_{440} \cos 4\gamma)) \quad (6)$$

where c denotes the elastic anisotropy inherent in a cubic monocrystal, μ is called the Lamé Constant and the elastic constant in the case without texture, ρ is the density of the steel, and the angle γ measures the propagation direction from the rolling direction. We could judge that the velocity of the SH₀-mode plate wave does not depend on the plate thickness from Eq. (6).

By analogy, the fundamental symmetrical Lamb (S₀) wave velocity is given by :

$$V_{S_0}(\gamma) = V_0 \sqrt{1 - \Delta} + (c/\rho V_0)(s_0 W_{400} + s_2 W_{420} \cos 2\gamma + s_4 W_{440} \cos 4\gamma) \quad (7)$$

where c denotes the elastic anisotropy inherent in a cubic monocrystal, V_0 is the ultrasonic velocity in the case without texture, s_0 , s_2 and s_4 are functions of Poisson's ratio, and Δ is the correction term for the velocity decrease due to the finite thickness/wavelength ratio. We have to consider the velocity

Table 1 Relation between W_{lmn} and \bar{r} -value.

	W_{400}	W_{420}	W_{440}
(1 1 1)[1 1 0]	-0.0209	0	0
(1 1 1)[1 1 2]	-0.0209	0	0
(1 1 0)[0 0 1]	-0.0078	-0.0246	0.014
(1 0 0)[0 1 1]	0.0313	0	-0.0187
(1 0 0)[0 0 1]	0.0313	0	0.0187

compensation for the plate thickness because the velocity depends on the plate thickness. The feature of the SH₀-wave is a positive point in the case of evaluating the velocity in the cold rolled steel sheets.

On the other hand, the correlation between \bar{r} -value and W_{lmn} was studied.²⁾ Table 1 describes the results of the calculation of W_{lmn} in the case of single crystal and shows that single crystal having (1 1 1) crystal plane indicates the large negative value of W_{400} and (1 0 0) crystal plane indicates the large positive value. This results supports W_{400} has good correlation with \bar{r} -value.

Equation (8) calculated from Eq. (6) shows that the \bar{r} -value is estimated from the ultrasonic SH₀ wave velocity at $\theta=0^\circ$, 45° relative to the rolling direction ;

$$W_{400} \propto (V_{SH_0}(0) + V_{SH_0}(45))/2 \quad (8)$$

Equation (9) calculated from Eq. (7) shows that the \bar{r} -value is estimated from the SH₀ wave velocity at $\theta=0^\circ$, 45° and 90° relative to the rolling direction ;

$$W_{400} \propto (V_{S_0}(0) + 2 \times V_{S_0}(45) + V_{S_0}(90))/4 \quad (9)$$

Comparing Eq. (8) and Eq. (9), we could evaluate the \bar{r} -value using a low cost sensor system with 2 pairs of sensors in the case of SH₀-wave: one pair means a transmitter and a receiver. We need 3 pair of sensors in the case of the S₀ mode Lamb wave.

3. TEXTURE AND \bar{r} -VALUE

The main crystal axis density in the test pieces which ranged in thickness from 0.3 mm to 1.5 mm was investigated by X-ray diffraction and the \bar{r} -value in the same test pieces was measured by tensile testing. The results are shown in Fig. 5. We could confirm the following facts,

1. There is a strong positive correlation between the (1 1 1) crystal axis density and the \bar{r} -value; the coefficient of correlation is 0.98.
2. There is a strong negative correlation between the (1 0 0) crystal axis density and the \bar{r} -value; the

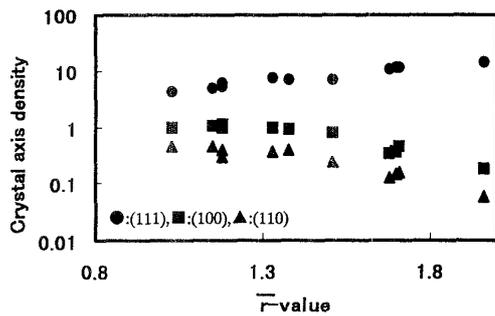


Fig. 5 Relation between texture and \bar{r} -value.

coefficient of correlation is -0.95 .

3. There is a strong negative correlation between the (1 1 0) crystal axis density and the \bar{r} -value; the coefficient of correlation is -0.95 .

These results confirmed that the evaluation of texture by the SH_0 -wave velocity leads to the evaluation of the \bar{r} -value in cold rolled steel sheets.

4. DEVELOPMENT OF EMAT FOR \bar{r} -VALUE MEASUREMENT

Some features of the measurement principle using the SH_0 -wave were described. However, we have to consider some problems in the actual velocity measurement of the SH_0 -wave. Generally, sensors for determining \bar{r} -value of cold rolled steel sheets non-destructively must satisfy the requirements;

(1) The SH_0 -wave must be transmitted and received without contact media for accurate measurement of the velocity (In this paper, the transit time was measured in place of velocity).

(2) A signal amplitude with a high S/N ratio at a thickness of 2 mm must be obtained. However, it was very difficult to fabricate a sensor to satisfy these requirements. Because the sensor does not need a couplant, an electromagnetic acoustic transducer (EMAT) using the Lorentz force has been studied by many researchers. However, a permanent magnet having a complicated composition is required, and this leads to insufficient detectability. When the EMATs are used for ferromagnetic materials, the magnetostriction becomes important, especially in the low magnetic field region as shown in Fig. 6. This is due to the fact that, in the case of the magnetostrictive type EMATs, the required magnetizing current for optimum transduction efficiency is much less than 1/10 in comparison to the Lorentz force type EMATs, and the EMATs have a simple structure in comparison to the Lorentz force type

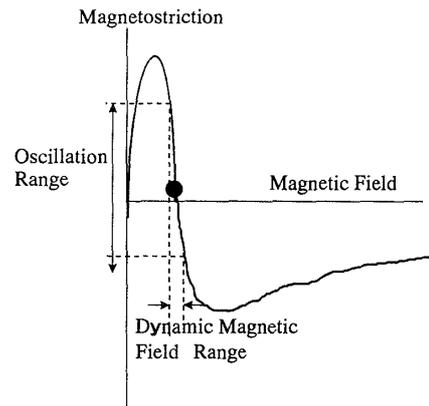


Fig. 6 Relation between magnetostriction and magnetic field.

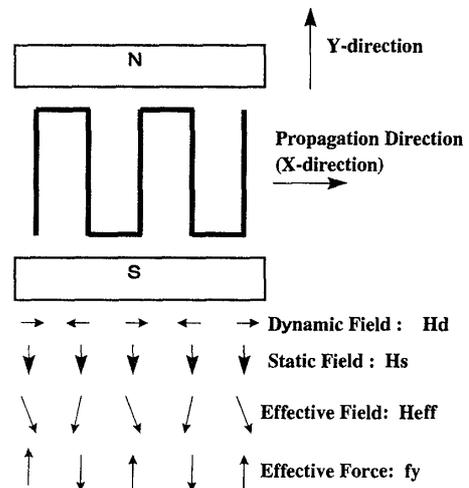


Fig. 7 Composition of magnetostrictive type electromagnetic transducer for Shear horizontal plate wave (magnetostrictive type SH -EMAT).

EMATs which use a periodic permanent magnet geometry.^{6,7)}

As shown in Fig. 7, magnetostrictive type EMATs for the SH_0 -wave consist of a meandering coil and an electromagnet which applies the magnetic field orthogonally in the propagation direction of the SH_0 mode surface wave. When the RF current drives the coil, the dynamic field, H_d , occurs in a direction vertical to the static magnetic field. The pitch of the coil wire coincides with the half wavelength. Figure 7 also shows the distribution of the effective magnetic field H_{eff} , which is the sum of the static field, H_s , and the dynamic field, H_d , and that of the resulting magnetostriction, E_m , in their instantaneous direction in the ferromagnetic materials. Under dynamic conditions, this deformation may be

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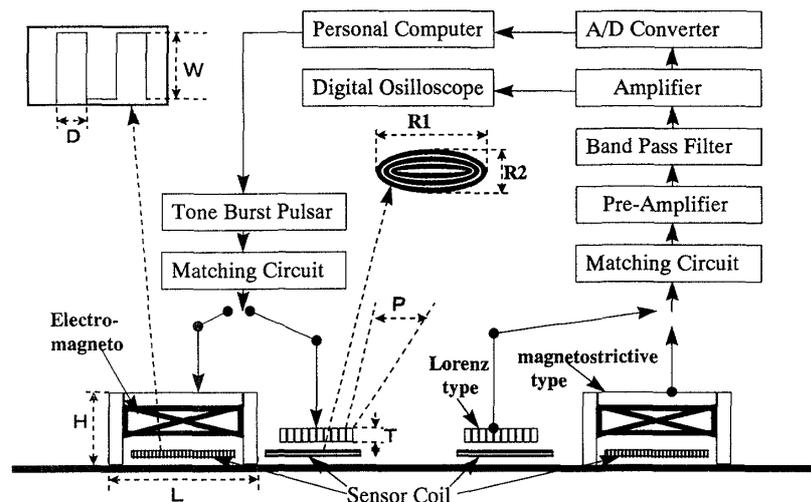


Fig. 8 Block diagram of measurement system.

described by stress σ_{xy} , which coupled with the periodicity induced in the x direction by the meander coil, produces an effective force, f_y (N/m^3), in accordance with the relation

$$f_y = \frac{\partial}{\partial x} \sigma_{xy} \quad (10)$$

This force generates the SH_0 -mode plate wave. The stress varies the magnetic permeability of the ferromagnetic material through the inverse magnetostrictive effect. When the stress of the SH_0 mode plate wave changes the permeability of the steel, it results in a flux density change under the static field. An eddy current is then introduced in the sheet, and the meandering coil detects the magnetic field induced by the eddy current.^{8,9)}

5. EXPERIMENTAL PROCEDURE

Figure 8 shows the block diagram of the experimental setup. Plates of JIS-SS400 low carbon steel, which were from 0.3 mm to 2.0 mm thick, 450 mm wide and 450 mm long, were prepared. For the magnetostrictive type EMAT, the pitch of the meander coil (D) was 6 mm and the width of the meander coil (W) was 25 mm for the SH_0 mode plate wave. The electric resistance of the electromagnet was 10 Ω . The electromagnet consisted of a copper wire of 1 mm diameter wound 1000 times around the magnetic pole, and the magnetic poles (L) were then placed 50 mm apart.

For the Lorenz force type EMAT, a permanent magnet displaced periodically whose pitch (P) was 5 mm and the height (T) was 10 mm. The sensor coil like a pancake, the long diameter was 50 mm and

the short diameter was 20 mm, were used.

A burst wave of 0.3 MHz drives the EMAT to transmit the SH_0 wave into the specimen. The EMATs for the transmitter and receiver were placed at a distance of 200 mm. We could evaluate the \bar{F} -value using the transit time in place of the velocity, if the distance between the EMAT for the receiver and the EMAT for the transmitter were fixed. The transit time was approximately 50 μs to the SH_0 mode plate wave. The received signal was digitized with a resolution of 2.5 ns. Both the amplitude and the phase were measured while varying the magnetizing current (I_H) to the electromagnet.

6. PERFORMANCE OF EMAT FOR SH_0 -WAVE

Figure 9 shows the dependence between the signal amplitude, the phase and the magnetizing current of the magnetostrictive type EMAT for the SH_0 -wave. The test piece was the low carbon steel sheet of 0.3

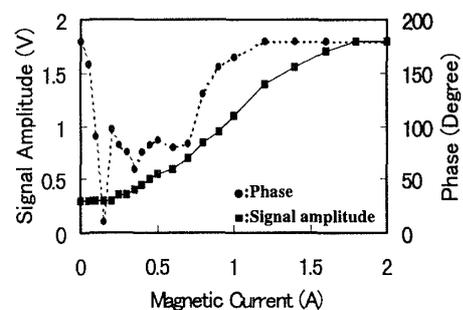


Fig. 9 Relation between signal amplitude, phase of magnetostrictive type SH-EMAT and magnetizing current.

mm thickness. As the magnetizing current (I_H) increases, the amplitude initially increases to the maximum value ($I_H = 1.2$ A), then decreases. As I_H increases, the phase initially decreases to the minimum value ($I_H = 0.2$ A) and increases by 180 degrees at $I_H = 0.7$ A. This result shows that we should use a magnetizing current of 1.2 A. We could observe the received signal with sufficient intensity and measure the transit time accurately because the phase was stable for the variation in the magnetizing current.

We could not change the magnetic current because that Lorenz force type EMAT used a permanent magnet.

Figure 10 shows the dependence of the signal amplitude and lift-off which means the distance from the surface of the sensor to the surface of the thin steel sheet. The plate thickness was 0.5 mm. If we consider the conditions for use of the sensor in a production line, we need performance which detects the receiving signal having a sufficient signal amplitude in the case where the lift-off is 5 mm. Lorenz force type EMAT could not observe the receiving signal in the case where the lift-off was more than 1 mm. We confirmed that this type of

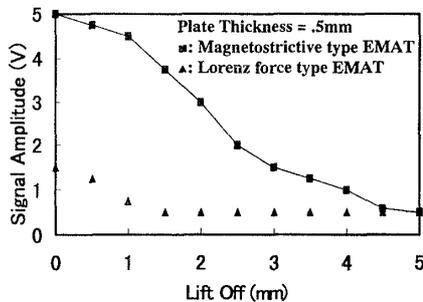


Fig. 10 Relation between signal amplitude of both type EMATs and Lift-off.

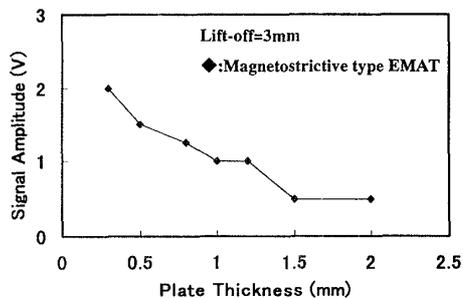


Fig. 11 Relation between signal amplitude of magnetostrictive type SH-EMAT and plate thickness.

EMAT could not be used for this purpose because of the poorer performance. A magnetostrictive type EMAT could observe the receiving signal in the case where the lift-off is less than 5 mm.

Figure 11 shows the dependence of the signal amplitude and plate thickness. The lift-off was 3 mm. If we consider the conditions for industrial use of the sensor, we need performance which detects the receiving signal having a sufficient signal amplitude in the case of thickness ranging from 0.3 mm to 2 mm. A Lorenz force type EMAT could not detect the receiving signal in any thickness range. A magnetostrictive type EMAT could observe the received signal in any thickness range.

We have decided to use the magnetostrictive type EMAT for the transit time measurement of the SH_0 -wave.

7. VELOCITY DEPENDENCE FOR PROPAGATION DIRECTION

Figure 12 shows how the transit time of the SH_0 -wave depends on the propagation direction with respect to the rolling direction using calculated results from Eq. (6) and measured results using the magnetostrictive type EMAT. We used the relation between W_{lmn} and the (1 1 1), (1 1 0) and (1 0 0) crystal planes and adapted the (1 1 1), (1 1 0) and (1 0 0) axis density values in Table 2 to obtain the calculated results. The transit time was increasing as the propagation angle increased from the rolling direction to 45 degrees and was decreasing as the propagation angle increased from 45 degrees to 90 degrees. The rate of the transit time change for 0 degree and 45 degrees was almost 5%. The transit times for 0 degree and 90 degrees were almost the same. The measured results approximately agreed with the calculated results, and the difference was

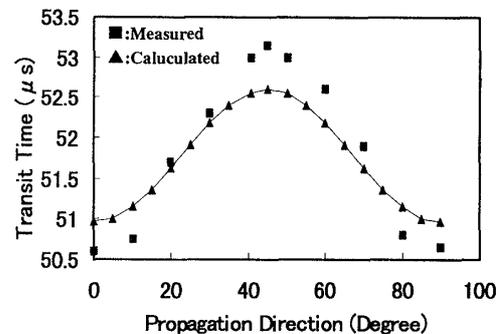


Fig. 12 Transit time dependence of SH-plate wave for propagation direction.

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less than 2%. The difference in both values could be due to the fact that other crystal axis densities except the (1 1 1), (1 1 0) and (1 0 0) crystal axis densities were not considered. These results show that the \bar{r} -value can be effectively evaluated by the transit time of the SH₀-wave using Eq. (6).

8. TEXTURE AND TRANSIT TIME

Figure 13 shows the relationship of the transit time propagating in the rolling direction, the transit time propagating at an angle of 45 degrees to the rolling direction and the averaged transit time of both transit times and the (1 1 1), (1 1 0) and (1 0 0) crystal axis densities obtained destructively using X-ray diffraction, which test pieces were cut from the production line. The SH₀ wave in the sheets with high \bar{r} -values propagates faster than in those with low \bar{r} -values. The velocity decreases by about 4% in the case of \bar{r} -values from 1 to 2. Therefore, the time measurement resolution of the system must be about 0.02% (=10 ns) to measure \bar{r} -values with a target accuracy within $1\sigma=0.07$. Our measuring system has sufficient measuring precision as described above the experimental procedure.

The correlation coefficients with \bar{r} -values were as follows,

1. There is a strong negative correlation between the $T(0)$ and the \bar{r} -value; the coefficient of correlation is -0.94 .
2. There is a negative correlation between the $T(45)$ and the \bar{r} -value; the coefficient of correlation is -0.89 .
3. There is a very strong negative correlation between the averaged transit time and the \bar{r} -value; the coefficient of correlation is -0.98 .

We confirmed that the \bar{r} -value could be evaluated by the transit time of the SH₀-wave, especially by the averaged transit time corresponding to W_{400} .

9. EVALUATION ACCURACY OF \bar{r} -VALUE

Figure 14 shows the relationship of the \bar{r} -value transferred from the averaged transit time, assuming the relation the averaged transit time and the \bar{r} -value have to the straight line whose coefficients A and B were determined by the least squares method.

$$\bar{r} = A \times (T_{SH_0}(0) + T_{SH_0}(45)) / 2 + B \quad (11)$$

It is shown that the correlation coefficient is 0.98 and the measurement accuracy was $1\sigma=0.065$; σ is the

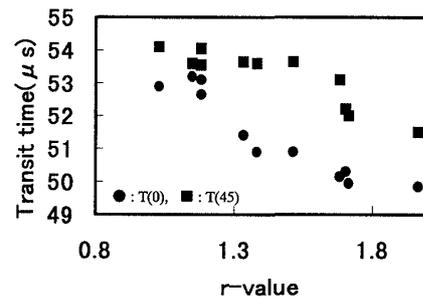


Fig. 13 Relation between texture and transit time of SH-plate wave.

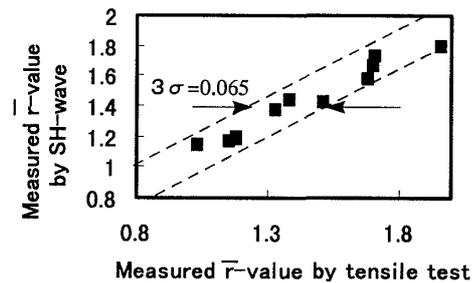


Fig. 14 Relation between measured \bar{r} -value destructively and non-destructively.

standard deviation between the measured \bar{r} -value derived from the averaged transit time and the \bar{r} -value due to tensile testing.

10. CONCLUSIONS

The following information was obtained in the development of an \bar{r} -value evaluation system using the magnetostrictive type EMAT and the Lorenz force type EMAT for the SH₀-mode plate wave.

- (1) The optimum current to the electromagnet was found for the transduction efficiency of the magnetostrictive type EMAT.
- (2) The maximum signal amplitude with the magnetostrictive type EMAT is much bigger than that of the Lorenz force type EMAT.
- (3) The signal amplitude having a signal-to-noise ratio=3 was obtained at the condition of lift-off=3 mm and steel plate thickness=1 mm in the case of the magnetostrictive EMAT for the SH₀-wave. The received signal could not be observed under the same condition in the case of the Lorenz force type EMAT.
- (4) The transit time of the SH₀-mode plate wave, which propagates at 0° and 45° relative to the rolling direction, has good correlation with the \bar{r} -values. Especially, the average transit time has the best

correlation with the \bar{r} -values.

(5) The difference in the \bar{r} -values obtained from the averaged transit time of the SH_0 -mode plate wave and the \bar{r} -values obtained from tensile testing was $1\sigma=0.065$.

Generally, it has been suggested that the SH_0 -wave has some excellent features to for evaluating the formability of cold rolled steel sheets, but there was no sensor satisfying the specifications to measure the velocity industrially. If the magnetostrictive type EMAT were used, the method could be improved considerably.

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