MAGNETIC FLUX LEAKAGE INSPECTION FOR MOVING STEEL SHEET

Goo Hwa Kim and Zhong Soo Lim
Research Institute of Industrial Science and Technology,
P.O. Box 135, Pohang, Kyungpook, 790-600, Korea

Eui-Wan Lee
Department of Physics, Kyungpook National University,
1370 Sankyuk-Dong, Pook-Gu, Teagu, 701-702, Korea

INTRODUCTION

Nondestructive magnetic methods are widely using to inspect the surface defects in steel products such as the billets, wire rods and tubes. In the case of thin steel sheet, we can classify the defects of steel sheet to the surface defects and the internal defects. On the other hand the surface defects can be detected by the optic methods, inspecting the internal defects, such as the nonmetallic inclusions that cause cracking of 2-piece steel can during the flanging process, is quite difficult.

To find nonmetallic inclusions in a steel sheet that is moving fast, the magnetic flux leakage (MFL) test is a powerful method because of its speed and capability of detection and of immediate analysis of defect signals. The detection of defects with high speed by the magnetic method means that the conducting material moves within the magnetic field so that the induced currents are produced in the conducting material. The induced field is generated near the test specimen by the induced currents. In the case of high-speed defect detection of products using the MFL method, the magnetic field distribution near the magnetizing unit will be changed according to the relative speed of the magnetizer and the specimen. The magnetic sensor fixed to the magnetizing unit reads out total magnetic field by the superposition of MFL, stray field and induced magnetic field. Therefore the investigation of the changes of magnetic field near the sensor, with the variation of inspection parameters, is important in order to operate the magnetic sensors properly and to classify the defects.

Even though some studies [1-4] were carried out to identify the changes of MFL signals according to the relative speed of electromagnet and test specimen, extensive experimental results and corresponding theoretical analyses have not been reported until now. Previously conducted studies explained the changes of MFL without much attention to the induced field.

In this paper, we will study the MFL and the induced field from the sheet with defects moving at high speed.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18
Edited by Thompson and Chimenti, Kluwer Academic/Plenum Publishers, 1999

THEORETICAL BACKGROUND

When the steel sheet is moving with a velocity (v) relative to the electromagnet, the changing flux induces a current within the steel sheet by electromotive force. Considering the Galilean invariance, the Faraday's law, and the Coulomb gauge, the Ampere's law for the moving coordinate system can be written in the form of

$$\nabla \times \mathbf{H} = \mathbf{J}_s - \sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \mathbf{v} \times \mathbf{B} . \tag{1}$$

If the steel sheet is magnetized by applying a direct current to the coil of electromagnet, the second term of the right hand side of (1) will disappear.

When inspecting a defect located in or on the moving steel sheet by MFL method, the induced current flow within the sheet near the electromagnet poles as illustrated in Fig. 1. In this case, magnetic flux lines are formed through the steel sheet parallel to the sheet except just near the electromagnet poles. Only the magnetic field perpendicular to the moving direction of the sheet generates the induced currents so that current loop pairs (C1 and C2, C3 and C4) are induced by approaching and receding of the sheet to each pole (N- and S- pole). The total sum of induced current loop generates an induced field above the moving sheet between the electromagnet poles.

The perpendicular components of magnetic flux near the defect do not induce a magnetic field by which that component is in the moving coordinate system. Thus the total field is a superposition of the stray field from the electromagnet, the induced field from the moving sheet, and the leakage field from defects.

EXPERIMENTS

To investigate the dependence of MFL and induced field on the speed of the specimen, we constructed an inspection system, which could change the speed of a steel sheet up to 18 m/s.

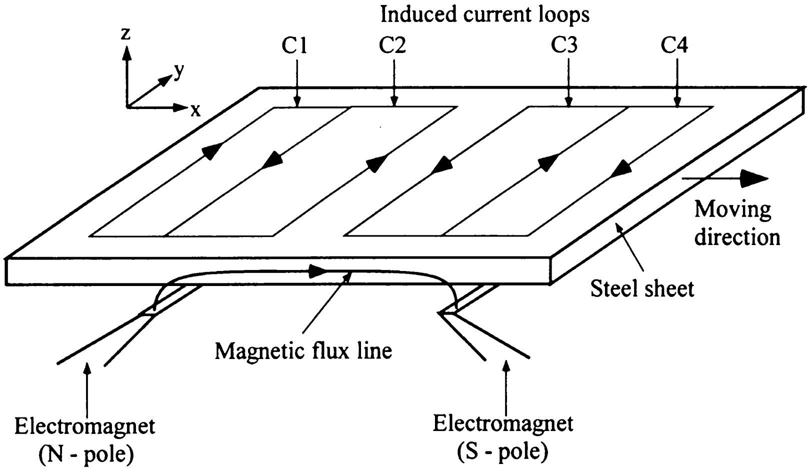

Figure 1. The schematic view of induced current loops in the moving steel sheet

System Construction

The experimental system consisted of a Hall sensor, an electromagnet (yoke), a speed control device, and a data acquisition unit. The pole gap of the electromagnet was 40 mm within which the magnetic sensor was located. The roll was placed on the opposite side of the electromagnet with respect to the steel sheet. 300 turns of copper coil were wound around the electromagnet core that was made of low carbon steel. The magnetic flux density at the surface of electromagnet pole was about 2.5 kG with 10 A magnetizing current. The roll was made of nonmagnetic stainless steel (316L), then a steel sheet was tightly wound around the roll. Control of the rotational speed of the roll was done by an AC motor with an urethane coupler that reduced the vibration of the roll. The speed of the steel sheet could be precisely controlled from 0.5 m/s to 18 m/s, which was determined by reading the pulses from the encoder attached to the shaft of roll.

The specimen used in this study was a cold-rolled thin steel sheet with a thickness of 0.28 mm on which an artificial slot-type defect was fabricated by electro-discharge machining (EDM) with a size of 0.3 mm width, 0.1 mm depth and 30 mm length. Magnetizing direction was perpendicular to the direction of the defect length.

Measurements of Magnetic Field

To analyze the induced field generated by a moving steel sheet within a magnetic field, the changes of the magnetic field according to the speed of steel sheet and to the magnetizing current were measured just above the steel sheet using magnetic sensor with a finite lift-off from the sheet. Since the induced magnetic field is related to the speed of the conducting sheet in a given magnetic field perpendicular to the direction of sheet movement, the induced magnetic field does not change with a fixed rotational speed of roll. This means that the induced field can be obtained by measuring the DC signal of magnetic sensor output. On the other hand, the source of MFL is a localized variation of magnetic permeability due to the defect in the specimen. The spatial expansion region of MFL from a slot-type defect of the size described above was a few millimeters with 2 mm lift-off. This localized MFL was superposed to the induced field in a simple additive manner.

One of the parameters of MFL signals characterizing the leakage field normal to the sheet is the peak-to-peak value. We investigated the dependence of MFL on the magnetizing current and the sheet speed by measuring the peak-to-peak values of the MFL signals. Since the magnetic field strength was varied between the electromagnet poles, the MFL for a given defect with same physical properties was also varied according to its position. The changes of MFL according to the sensor position between the electromagnet poles were measured by moving the sensor along the direction of electromagnet poles.

RESULTS AND DISCUSSION

Induced Field

Between the poles of electromagnet having a pole gap of 40 mm, we measured the magnetic flux densities with fixed parameters: the magnetizing current was 5 A, the lift-off was 2 mm, and the distance from the sheet to the electromagnet poles was 2 mm. Then we measured the magnetic field distribution according to the speed of the steel sheet. The magnetic field distribution without defect according to the sheet speed is a superposition of stray field and induced field as illustrated in Fig. 2.

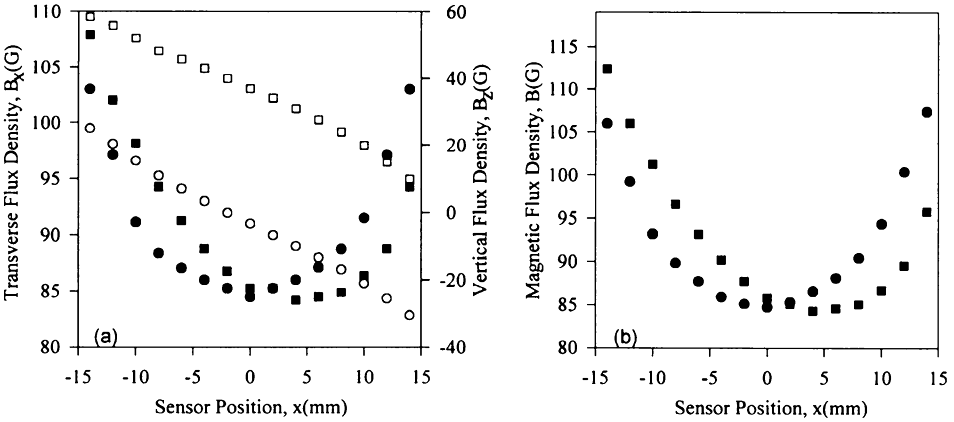

Figure 2. The magnetic flux density distribution between the poles of electromagnet according to the sheet speed. (a) Vertical and transverse component of magnetic flux density to the sheet surface, and (b) calculated magnitude magnetic flux density.

The flux density normal to the sheet (open symbols in Fig. 2. (a)) was decreased gradually (not linearly) as the position of the sensor increased, and vice versa. For a finite speed of the steel sheet (12.56 m/s, square symbols in Fig. 2. (a)), the normal components of flux density near the center region of the electromagnet poles were increased. If the direction of the sheet movement changed, they were decreased. The induced field generated by the induced current loops caused these changes of the flux density. The transverse flux density (filled symbols in Fig. 2. (a)) showed a shift to the direction of the sheet movement as the speed of the sheet increased. This was caused by the induced currents along the poles of the electromagnet that contained induced current loops. The stray field was the field when the speed of sheet (v) was zero as in the Fig. 2 with circle symbols. As shown in Fig. 2. (b), the field distributions between the poles of the electromagnet and just above the sheet were distorted to the direction of sheet movement. As a result, the distortions of the field distributions between the poles were the effect of superposition of the stray field and the induced field.

The dependence of the vertical component of the induced field on the sheet speed, as shown in Fig. 3 (a), was constant in the center region of electromagnet poles. In that region, the vertical induced field was linearly increased as the sheet speed was increased. The previous numerical prediction [4] illustrated quite different results from our results. The wide flat region reveals that the induced field caused by the sum of the induced current loops in Fig. 1. The distribution of the horizontal induced fields was also affected by the changes of sheet speed especially near the poles. Fig. 3. (b) shows the dependence of the horizontal induced field on the sheet speed. The movement of the steel sheet does not generate the horizontal component of the induced field at the center between the electromagnet poles. This was the result of cancellation of the induced current in the center region. As the sensor was approached to the electromagnet poles, the absolute values of the horizontal induced field were increased nonlinearly. All of the performance of induced field is well coincide with the cause of Lorentz force.

MFL According to the Sheet Speed:

The MFL from the slot-type defect was measured by varying the speed of the steel sheet from 0.5 m/s to 18 m/s, as shown in Fig. 4. The magnetic sensor was located at the center between the poles of the electromagnet with lift-off of 2 mm. Even though the sheet

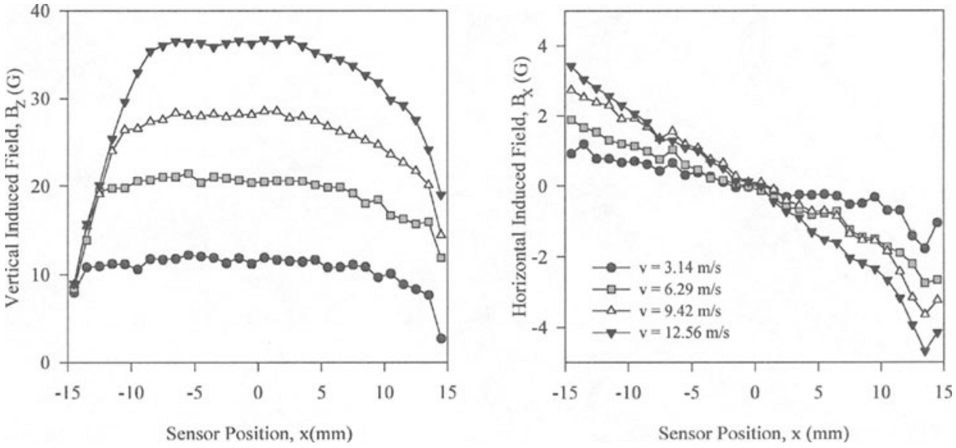

Figure 3. The changes of induced field according to the speed of sheet.

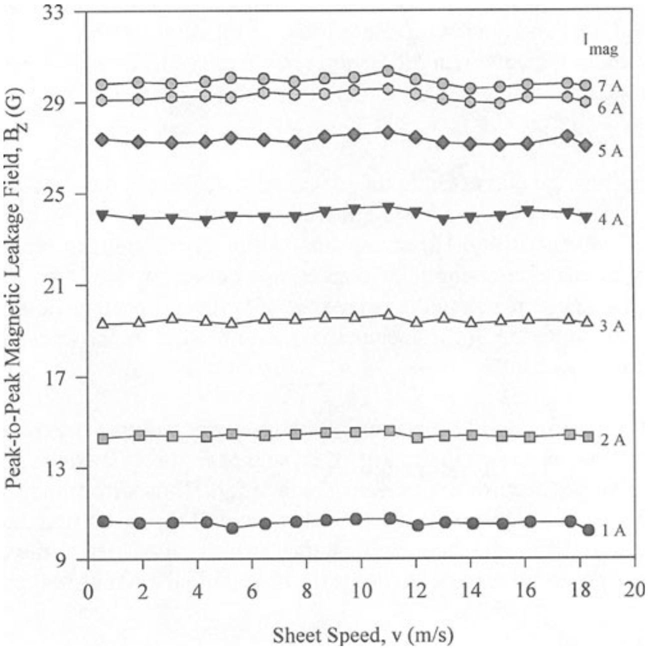

Figure 4. The MFL from the slot-type defect with varying the speed of steel sheet.

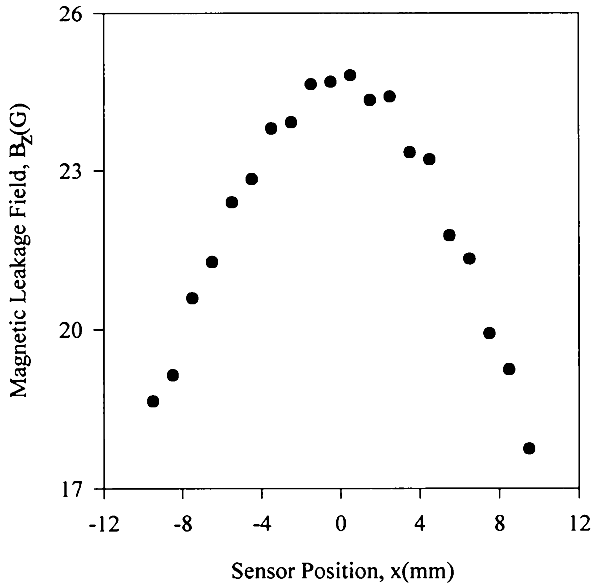

Figure 5. The MFL according to the variation of the sensor position in the direction of electromagnet poles

speed was varied up to 18 m/s, the MFL preserved its values with just a small variation. The MFL is a physical quantity, which depends on the magnetic property of the steel sheet, the shape of the defect and the magnetizing force. While the speed of sheet changed, the shape of defect and the magnetizing force did not change. The magnetic property of the steel sheet also did not change, even though the specimen moved with a finite speed against the electromagnet.

Some studies [3,4] claimed that the magnetic flux lines in the specimen should be distorted in the direction of the specimen movement in the case of a thick specimen and a constant magnetic permeability. This means that the magnetic field strength should change as the specimen moves even though the magnetizing current is fixed. According to their results, moving the specimen should change the MFL. This is quite different from our results without consideration of the specimen conditions such as the thickness and the magnetic permeability.

The MFL according to the variation of the sensor position in the direction of the electromagnet poles was shown in the Fig. 5. Because the sheet is wound around the roll, the lift-off also changes according to the sensor position. Thus we compensated that by measuring the MFL according to the lift-off. This trend of the result was undefended even though the sheet speed was changed. By this, the sensor was posited at the center between the electromagnet poles when we inspect the defects using the MFL method.

CONCLUSIONS

This study was carried out in order to investigate the effect of the specimen speed on the MFL signals and the induced field for developing the automatic inspection system of NMI. A slot-type defect with 30 mm length, 0.3 mm width and 0.15 mm depth was machined on 0.28 mm thick steel sheet by EDM.

The movement of the steel sheet changes the distribution of flux density that was distorted to the moving direction of sheet between the poles of an electromagnet by superposition of stray field and induced field. Induced magnetic field was proportional to the speed of the sheet. A vertical induced field was generated with a uniform value in the center region of the yoke by the movement of the sheet and a horizontal induced field was increased as the magnetic sensor approached to the poles of the yoke.

MFL was quite similar values, even though the speed of the sheet changed. This means that the magnetic properties of the sheet were not affected when the steel sheet was moving within the magnetic field. After all the magnetic flux density within the poles of electromagnet and above the moving sheet is the value of superposition of induced field that depends on the velocity of sheet and MFL that is independent of sheet velocity. The MFL values have maximum value at the center between the poles in all speed of the sheet.

REFERENCES

1. Y.K. Shin and W. Lord, *Review of Progress in QNDE*, vol. 10A, pp. 921-925, 1991.
2. S. Mandayam, L. Udpa, S. S. Udpa and W. Lord, IEEE Transactions on Magnetics, vol. 32, pp. 1577-1580, 1996.
3. T. Hideya, M. Yashuhiro, Y. Junichi, A. Seigo, N. Katsuyuki and I. Mamoru, Steel and Iron Engineer, vol. 79, pp. 103-108, 1993.
4. Young-Kil Shin, IEEE Transactions on Magnetic, vol. 33, pp. 2127-2130, 1997.