Development of Concave and Convex Roll Defect Inspection Technology for Steel Sheets by Magnetic Flux Leakage Testing Method

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Abstract. Concave and convex roll defects on thin steel sheets cause problems as they can be seen clearly after the sheets are painted in the customer’s manufacturing process. In the steel production line, these defects are usually invisible since their height or depth is as small as the normal surface roughness of steel sheets. Therefore, they can only be detected by human inspection after grinding the steel surface with a grindstone. However, since it is necessary to stop the traveling steel sheet for this type of human inspection, and this reduces the productivity of the line, realization of automatic inspection equipment had been desired.

Against this background, we found that Magnetic Flux Leakage Testing (MFLT) is effective for detecting these kinds of roll defects. The MFLT method can detect not only magnetic flux caused by the shape of the defects, but also magnetic flux caused by defect strain. As a result of an examination of the application of this MFLT method to an on-line detector for roll defects, we completed the installation of automatic inspection equipment at the continuous annealing line at West Japan Works (Fukuyama District) of JFE Steel Corp.

The sensor head of this equipment consists of 100ch Hall elements arranged at a 1mm pitch in the width direction and an electromagnet which magnetizes the steel sheet in the width direction. This device inspects an area of 100mm in the width direction and 24m in the length direction of the steel sheet in one inspection. Because roll defects occur at the same position in the width direction and at the roll periodic pitch over the full length of the steel sheet, the sensor head inspects the sheet from one sheet edge toward the other edge, repeating the process of inspection, movement, and inspection. Moreover, because the magnetic leakage signal from the roll defect is very weak, we applied synchronous addition processing corresponding to the length of the roll defect periodical pitch to the MFLT method and found that the signal-to-noise ratio can be improved about 3 times by this technique.

This equipment has been operating smoothly since its installation in 2010, and has contributed to improved productivity by reducing the frequency of human surface inspections, which are accompanied by line stops.

1. Introduction
In the production process of steel sheets, periodic defects referred to as roll marks sometimes occur. These roll marks are formed when foreign material adhering to a roll in the production line or unevenness produced on the roll itself when foreign material bites into the roll are
transferred to a steel sheet. Once a periodic defect occurs, it occurs successively until the affected roll is exchanged or the process is improved. Therefore, it is extremely important for yield improvement to discover periodic defects at an early stage and to take measures against those defects. The outline size of these defects is a few millimeters to ten-odd millimeters, but their unevenness is very small, being on the order of several micrometers. For this reason, it is usually impossible to discover these defects by visual observation, as their unevenness is as small as the normal surface roughness of steel sheets. However, when a steel sheet with roll marks is painted in the customer’s manufacturing process and the surface roughness is coated by paint and becomes smooth, the defects appear clearly, causing problems in the appearance of the product.

To detect this type of defect, human surface inspection is conducted after stopping the traveling steel sheet and grinding the sheet surface with a grindstone during the production operation. As shown in Fig. 1., the roll mark becomes visible after grinding the steel sheet surface because the convex part of the defect is flattened and the reflection rate of the defective part increases. However, since it is necessary to stop the traveling steel sheet for this type of human inspection, and this reduces the productivity of the line, realization of automatic inspection equipment had been desired.

Against this background, we judged that an optical method cannot be applied as an on-line roll mark detector because the unevenness of the roll mark is almost equivalent to the normal roughness of the steel sheet surface, and examined the possibility of applying Magnetic Flux Leakage Testing (MFLT) as an alternative to the optical method. As a result, we completed the installation of automatic inspection equipment at the continuous annealing line (CAL) at West Japan Works (Fukuyama District) of JFE Steel Corp.

![Fig. 1. Human inspection after grinding steel surface using grindstone](image)

2. Examination of application of MFLT method

Although there was an example of a report regarding an internal inclusion detector by the MFLT method for thin steel sheets in the past, the purpose of that device was to detect internal inclusions in steel sheets for cans with thicknesses of 0.2 to 0.4mm [1]. However, the targets of human inspection after grinding the steel sheet surface are not only steel sheets for cans, but also include cold-rolled steel sheets and surface-treated steel sheets, the thicknesses of which exceed 1mm. Therefore, examination of the application of the MFLT method for the detection of roll marks having an unevenness of several micrometers on steel sheets with a thickness of 1mm was not adequate, since the inspection capability of that method was regarded as insufficient from the viewpoint of the conventional common sense.

Since roll marks are caused when an uneven area on a roll is transferred to a steel sheet as mentioned above, we presume that strain remains with residual stress in the steel sheet when the unevenness is transferred, and the point where the strain occurs is different from the sound area in terms of the magnetic property of magnetic permeability and so on. Therefore, we assumed that roll marks can be detected by detecting the leakage magnetic...
flux caused by strain in addition to detecting that caused by the unevenness of the defective area, and examined the relationship between strain and leakage magnetic flux.

First, we prepared samples which included roll marks having unevenness of about 4µm, which occurred in a CAL, and measured the residual stress of each sample from the diffraction pattern acquired by irradiating these roll marks with X rays.

Next, we measured the signal levels of the roll marks and the noise levels by the MFLT method. Fig. 2. shows the configuration of the off-line sensor used in these tests. The interval between the two magnetic poles of the electromagnet is 120mm, the distance between the steel sheet sample and the electromagnet is 6mm and the horizontal component of magnetic flux density in the center between the two magnetic poles is set to 60mT at a height of 0.5mm from the sample. We used a Hall element as the magnetic sensor and set the gap between the sensor and the sample, that is to say, lift-off, to 1mm and measured the vertical component of the magnetic field. Here, for the direction of magnetization of the steel sheet, we adopted transverse magnetization, as the results of a sample test showed that this direction has higher detection sensitivity for defects extending thinly in the length direction.

Fig. 2. Configuration of off-line sensor

Fig. 3. shows an example of a cross-sectional shape of a roll mark sample extracted from the CAL as measured by a laser distance meter. Fig. 4. shows the result of the same line as shown in Fig. 3. when tested by the MFLT method. The range of the defect signal using the MFLT method is broader than that of the defect measured by the laser distance meter because the leakage magnetic flux is broader than the size of the defect.

Fig. 3. Example of a cross-sectional shape

As shown in Fig. 4., the peak-to-peak voltage of the defect is defined as S (Signal), and the peak-to-peak voltage in the sound area except at the defect is defined as N (Noise). The value of S divided by N is defined as S/N.
Fig. 5. is a graph which expresses the relationship between the strain measured by a X-ray technique and the S/N ratio measured by the MFLT method for the CAL samples including roll marks with unevenness of about 4μm. A high correlation between the strain amount and the leakage magnetic flux signal was confirmed, suggesting the possibility of detection of roll marks by using the MFLT method in spite of minute roll mark unevenness of about 4μm, even though the S/N ratio of one sample was less than 1.5.

![Fig. 5. Relationship between strain and S/N ratio by MFLT method](image)

3. Improvement of detection performance by utilizing periodicity of roll marks

Since the possibility of detecting roll marks by using the MFLT method was confirmed as described above, we installed an on-line testing apparatus in the inspection line after the CAL and evaluated its detection performance. Fig. 6. shows a schematic of the on-line testing sensor head. The sensor head consists of 100ch Hall elements arranged at a 1mm pitch in the width direction, an electromagnet which magnetizes the steel sheet in the width direction, a sensor box which contains these elements and touch rolls which touch the surface of the steel sheet. Lift-off is 1mm. The analog signals of the 100ch Hall elements, corresponding to the detection range of 100mm, are input to a processing PC after A/D conversion at a 0.1mm sampling pitch in the length direction.

![Fig. 6. Schematic of on-line testing sensor head](image)

The experimental method is as follows. First, steel sheet coils are inspected by grinding with a grindstone at the CAL, and if roll marks are found, the coil is conveyed to the inspection line. Next, the on-line testing sensor head is moved toward the position of the
roll marks in the width direction based on the information from the CAL inspector before traveling of the coil is started. Then, the sensor head is lowered until its touch rolls touch the surface of the coil, and traveling of the coil is started. Data on natural roll marks were collected by repeating this series of operations.

As examples of detection of roll marks, Fig. 7.(a) and Fig. 8.(a) show 2-dimensional images from the signals of the 100ch Hall elements. In Fig. 7.(a) and Fig. 8.(a), whiter plotted points indicate higher signal levels of the point in the positive direction, and blacker plotted points indicate higher signal levels in the negative direction. Fig. 7.(b) and Fig. 8.(b) show the signal waveforms at the point of the dashed arrow in the lower image of Fig. 7.(a) and Fig. 8.(a). Here, Fig. 7. shows the result for a relatively large roll mark, and Fig. 8. shows the result for a relatively small roll mark. Although the roll mark shown in Fig. 7. can be detected easily, the one shown in Fig. 8. is very difficult to detect on-line in this state, as its S/N ratio (1.8) is too small.

![2D images by MFLT method](image1)

(a) 2D images by MFLT method

![Leakage magnetic flux signal along dashed arrow in (a)](image2)

(b) Leakage magnetic flux signal along dashed arrow in (a)

**Fig. 7.** Example of on-line test result

Since roll marks are caused when unevenness on a roll is transferred to a steel sheet, they occur at the roll periodic pitch over the length of the steel sheet. Therefore, we considered improvement of the S/N ratio by using this periodicity to obtain S/N>3, which is needed in on-line inspection. As shown in the upper 2-dimensional images in Fig. 7.(a) and Fig. 8.(a), the leakage magnetic flux signals from roll marks are observed twice in one period apart from each other. We found that the 2-dimensional distribution of both defect signals had a similar pattern. Focusing on this feature, we developed a method of improving the S/N ratio by utilizing a correlation operation for the 2-dimensional distribution of the leakage magnetic flux signal.

The method of detecting periodic defects will be explained with reference to Fig. 9. below. Fig. 9. shows a 2-dimensional map in which the vertical represents the width direction and the horizontal represents the moving direction of the steel sheet. First, Areas 1 to 5, whose respective sizes (l x h) are as large as a roll mark, are set at the same position in the width direction and at the interval d in the length direction.
A correlation value $R_{12}(d)$ is calculated between Area 1 and Area 2 by Eq. (1). Similarly, Eq. (2) is calculated, and the correlation values $R_{13}(d)$, $R_{14}(d)$ and $R_{15}(d)$ are obtained at the parts corresponding to Area 1 and Area 3, Area 1 and Area 4 and Area 1 and Area 5. Next, Eq. (3) is calculated, and the value $R(d)$ is obtained by adding the correlation values $R_{12}(d)$, $R_{13}(d)$, $R_{14}(d)$ and $R_{15}(d)$. $R(d)$ is the similarity evaluation index.

\[
R_{12}(d) = \sum_{i=1}^{h} \sum_{j=1}^{l} x(i, j) \times x(i, j + d) \quad (1)
\]

\[
R_{13}(d) = \sum_{i=1}^{h} \sum_{j=1}^{l} x(i, j) \times x(i, j + 2d) \quad (2)
\]

\[
R_{14}(d) = \sum_{i=1}^{h} \sum_{j=1}^{l} x(i, j) \times x(i, j + 3d)
\]

\[
R_{15}(d) = \sum_{i=1}^{h} \sum_{j=1}^{l} x(i, j) \times x(i, j + 4d)
\]

\[
R(d) = R_{12}(d) + R_{13}(d) + R_{14}(d) + R_{15}(d) \quad (3)
\]
The distance d as a base value between the areas whose correlation values were calculated is then changed to d+Δ. The change range of d is adjusted to the range where periodic defects may be generated, namely, the range of the circumference of the roll where defects can occur, and the value R(d+Δ) is calculated according to each distance d+Δ set in the same manner. Here, Δ is a fixed number smaller than the length l in the length direction of a given area.

If there is a roll mark in Area 1, the value R(d) becomes maximum when the distance d corresponds to the period of the defects.

Since it is not known in advance where defects exist in a steel sheet when the steel sheet is actually inspected, it is necessary to change the position of Area 1 in the width direction and the length direction gradually and calculate the above value R(d) at these points. A defect which has a period d is judged to exist when the value R(d) exceeds a predetermined threshold level.

Fig. 10. shows the result of an evaluation of the periodicity of the defect shown in Fig. 8. by the correlation operation described above. In Fig. 10., the evaluation index of periodicity R(d) becomes maximum at the length which coincides with the circumference of the roll, i.e., about 1700mm. This agrees with the circumference of the roll on which the defect actually occurred, and shows that the period could be identified by the above method.

Next, the signals of 5 points of the same coordinate in each area from Area 1 to Area 5 are added and averaged. This synchronous addition and averaging processing is conducted
for all the points in the area from Area 1 to Area 5. Finally, a defect is judged to exist when the S/N ratio after synchronous addition and averaging processing exceeds a predetermined threshold level. Fig. 11. shows the results of the synchronous addition and averaging processing of the defect shown in Fig. 8.. The contrast of Fig. 11.(a) is stronger than that of Fig. 8.(a) before synchronous addition and averaging processing, and the S/N ratio of 3.7 is obtained; this value exceeds the S/N ratio of 3.0 needed in on-line inspection. Here, it is expected that the noise level will become $1/\sqrt{5}$ with 5 repetitions of the synchronous addition and averaging processing operation because noise occurs randomly. This means an improvement of two times the original value, and corresponds to the results of the on-line test shown in Fig. 8. and Fig. 11..

4. Configuration of on-line apparatus
Since satisfactory results were obtained in the on-line test, we considered introduction of an on-line inspection apparatus to the CAL. Fig. 12. shows a schematic of the configuration of the on-line apparatus and the image of the inspection method. The sensor head is set above the steel sheet, which is wound around a non-magnetic metal roll to reduce the influence of the vibration of the steel sheet. Two sensor heads are set at each position for top and bottom side inspection.

The sensor head of this equipment consists of an electromagnet which magnetizes the steel sheet in the width direction and 100ch Hall elements arranged at a 1mm pitch in the width direction between 2 magnetic poles, in the same way as the on-line test sensor head, and can inspect an area of 100mm in the width direction. Inspection is conducted as described below.

First, the information on the width and thickness of the steel sheet is received from the process computer. After the top of the steel sheet, namely, the weld point, passes the position of the sensor head, the sensor head is set at the inner side of one edge of the steel sheet by a traverse servomotor, and is set at the height of 1mm from the sheet surface by a progression and regression servomotor. The sensor head then inspects an area of 24m in the
length direction in one inspection. This length corresponds to about 10 times the maximum circumference of the rolls which need to be inspected. We decided to adopt 10 synchronous addition and averaging processing operations in the actual on-line equipment. Next, after the sensor head is retracted, moved 100mm in the width direction and set at a lift-off of 1mm, and inspection is started. Thus, the sensor head inspects the sheet from one edge toward the other edge, repeating the process of inspection, movement, and inspection, because roll marks occur at the same position in the width direction and at the roll periodic pitch over the full length of the steel sheet. Adoption of this sensor head traverse method made it possible to reduce the number of Hall element channels and thereby hold down the cost of the apparatus.

Subsequently, the processing PC in Fig. 12. judges whether roll marks exist or not while the sensor head is moving to the next inspection area. When roll marks are detected, an alarm is sent to the line operator. After the operator confirms the period of the roll marks from the HMI (Human Machine Interface) PC and stops the traveling steel sheet, he inspects the steel sheet surface by grinding it with a grindstone.

5. Conclusion
In the past, roll marks could only be detected by human inspection after grinding the surface of a steel sheet with a grindstone in the steel production processing line. Therefore, we focused on the stress which is caused when a roll mark occurs and developed a detection method using the MFLT method. An off-line sample test was performed to clarify the relationship between leakage magnetic flux and stress. In on-line tests, we devised an algorithm which improves the S/N ratio by using synchronous addition and averaging processing.

This equipment has been operating smoothly since its installation in 2010 and has contributed to improvement of line productivity by reducing the frequency of human surface inspections to 40% in comparison with that before installation.

References