Barkhausen noise measurement system using a three-pole probe

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Abstract

In the present study, a three-pole probe is proposed for measurement of Barkhausen noise (BN). A system was constructed for forming a magnetic field using a three-pole probe and succeeded in forming rotating magnetic fields of the same amplitude in all directions and arbitrary orientated stationary alternating magnetic fields. Furthermore, a BN measurement system was constructed and used to measure the BN of a grain-oriented electrical steel sheet. The results show that the BN exhibits a large output in the direction of the easy magnetization axis of the specimen, and it is demonstrated that the BN measurement result using the rotating magnetic field formed by the three-pole probe is reliable.

Keywords

Three-pole probe, Barkhausen noise, Rotating magnetic field, Grain-oriented electrical steel, Easy magnetization axis

1. Introduction

A significant proportion of chemical and oil refinery plants are fabricated using steel components. However, these components are easily damaged when subjected to high stresses. Therefore, to ensure plant safety, it is necessary to evaluate the stress conditions of the components, identify locations where the stresses are large, and evaluate the remaining life accordingly.

Stress measurement is usually performed using X-ray diffraction, but it is necessary to handle the X-rays with care, and the apparatus is expensive. In addition, etching of the test location is usually required before the analysis can be performed, and the depth of the stress measurement for steel samples is limited to approximately 10 μm beyond the sample surface [1]. An alternative stress measurement technique is to utilize Barkhausen noise (BN). Studies have confirmed that BN behavior is related to stress. Pérez-Benitez et al. [2] and Anglada-Rivera et al. [3] showed that the BN of 1000 commercial steel and 1005 commercial steel, respectively, increases in proportion to stress and decreases after reaching a maximum value. Blaow et al. [4] demonstrated that there is a correlation between BN and compressive residual strain due to bending in magnetically hard martensite.

Stress measurement using BN is safer and simpler than X-ray diffraction, and it allows for deeper probing into the sample. However, it is necessary to measure the BN in all directions to determine the stress conditions in all directions. That is, it is necessary to form a magnetic field that is uniform in all directions. There are two approaches for this. The first, proposed by Krause et al. [5], is to physically rotate the magnetizer in all directions and the second is to electronically rotate the magnetic field with a multipolar probe. Multipolar probes that can generate magnetic fields in all directions within 10 seconds have been developed by a research group at Queen's University [6,7], which used a four-pole probe with feedback. The contact conditions between the surface of the test position and the magnetizer are very important to evaluate stress conditions using BN measurements, but it is difficult to make good contact with a four-pole probe. However, it is easier with a three-pole magnetizer. Fukuoka et al. [8] have succeeded in generating magnetic fields in all directions with a three-pole magnetizer for magnetic-particle testing. Therefore, in this study, we attempted to construct a BN measurement system using a three-pole magnetizer.

2. Three-pole Magnetization System for BN Measurement

Figures 1(a) and (b) show the three-pole magnetizer used in this study. The magnetizer consisted of a disk and three poles (#1, #2, and #3), and was manufactured from ferrite. The disk had a diameter of 35.6 mm and a thickness of 2.5 mm, and formed part of the magnetic circuit. The poles were cylindrical with a diameter of 4.5 mm, and the ends were polished into a hemispherical shape to ensure grounding. Each magnetic pole had a coil with 278 turns and was adhered to the disk body such that the spatial angle between poles was 120°.

In the three-pole magnetizer, excitation currents with different phases can be directed to the three magnetic poles, and these excitation currents are represented as sine waves with different amplitude and phases, as follows:

$$\begin{aligned} I_1 &= A_1 \sin(\theta_1) \\ I_2 &= A_2 \sin(\theta_2) \\ I_3 &= A_3 \sin(\theta_3) \end{aligned} \tag{1}$$

where I_1 , I_2 and I_3 are the magnetizing currents for each magnetic pole, A_1 , A_2 and A_3 are the amplitudes of the magnetic fields generated by each magnetic pole, and θ_1 , θ_2 and θ_3 are the phases of the magnetizing currents of each magnetic pole.

Since the magnetic field strength is proportional to the amplitude of the magnetizing current of the coils, the magnetic field generated from each magnetic pole can be expressed as in Eq. (2), with the coefficients k_1 , k_2 and k_3 indicating the strength of the relationship between the magnetic field and the magnetizing current for each magnetic pole.

$$\begin{aligned} H_1 &= k_1 A_1 \sin(\theta_1) \\ H_2 &= k_2 A_2 \sin(\theta_2) \\ H_3 &= k_3 A_3 \sin(\theta_3) \end{aligned} \tag{2}$$

As shown in Figure 1(a), in the configuration of the three-pole magnetizer used, magnetic pole #1 is located at 90° from the x axis, while magnetic poles #2 and #3 are located at 330° and 210° from the x axis, respectively.

Therefore, the x and y components of the resultant magnetic field generated from the three-pole probe are given at the

center of the three-pole magnetizer by

$$H_{Rx} = H_{1x} + H_{2x} + H_{3x}$$

$$= k_1 A_1 \sin(\theta_1) \cos 90^\circ + k_2 A_2 \sin(\theta_2) \cos 330^\circ + k_3 A_3 \sin(\theta_3) \cos 210^\circ \quad (3)$$

$$H_{Ry} = H_{1y} + H_{2y} + H_{3y}$$

$$= k_1 A_1 \sin(\theta_1) \sin 90^\circ + k_2 A_2 \sin(\theta_2) \sin 330^\circ + k_3 A_3 \sin(\theta_3) \sin 210^\circ \quad (4)$$

where H_{1x} , H_{2x} , H_{3x} and H_{1y} , H_{2y} , H_{3y} are x and y components of the magnetic field generated from each magnetic pole, respectively. The first subscript indicates the number of the magnetic pole. The strength (H_R) and the angle (ϕ) of the resultant magnetic field are given by the following equations.

$$H_R = \sqrt{H_{Rx}^2 + H_{Ry}^2} \quad (5)$$

$$\phi = \begin{cases} \arctan\left(\frac{H_{Ry}}{H_{Rx}}\right) & (H_{Rx} > 0, H_{Ry} > 0) \\ 90^\circ & (H_{Rx} = 0, H_{Ry} > 0) \\ \arctan\left(\frac{H_{Ry}}{H_{Rx}}\right) + 180^\circ & (H_{Rx} < 0, H_{Ry} > 0) \\ \arctan\left(\frac{H_{Ry}}{H_{Rx}}\right) + 180^\circ & (H_{Rx} < 0, H_{Ry} < 0) \\ 270^\circ & (H_{Rx} = 0, H_{Ry} < 0) \\ \arctan\left(\frac{H_{Ry}}{H_{Rx}}\right) & (H_{Rx} > 0, H_{Ry} < 0) \end{cases} \quad (6)$$

It is assumed that A_1 , A_2 and A_3 and k_1 , k_2 and k_3 are set to the same value, and are defined as A and k . As for the phase of the magnetizing current, θ_2 and θ_3 are set to $\theta_1 - 120^\circ$ and $\theta_1 - 240^\circ$. When θ_1 is 90° , by using Eqs. (3) and (4), H_{Rx} and H_{Ry} are calculated to be 0 and $3Ak/2$. Then, as shown in Figure 2, H_R and ϕ are calculated to be $3Ak/2$ and 90° using Eq. (5) and (6). Since θ_1 moves from 0° to 360° during the measurement, the rotating magnetic field with uniform amplitude $3Ak/2$ in all directions can be obtained through similar calculations by using Eqs. (3) to (6).

Moreover, when A_1 , A_2 and θ_1 , θ_2 are set to the same value, and A_3 is 0, the resultant orientated stationary alternating magnetic field in the 30° and 210° directions can be obtained using Eqs. (3) to (6), as shown in Figure 3. In the figure, the solid, dot and bold arrows indicate the magnetic fields generated by magnetic poles #1, #2 and

the resultant magnetic field, respectively, and the black and gray indicate that θ_1 is 90° and 210° , respectively.

3. Experimental Results and Discussion

3.1 Experimental Procedure for Magnetic Field Measurement

Figure 4 shows a rotating magnetic field-generating system using a three-pole magnetizer. The amplitudes and phases of the three magnetizing currents were controlled and were generated by two synchronized function generators each with two channels. The amplitudes of the three currents were amplified by three power amplifiers. The amplitude and the phase of the currents flowing to each magnetic pole were adjusted between 0 and 200 mAp-p (0 and 1 Vp-p), and 0° to 360° , respectively. The frequencies of the three currents were all 10 Hz. The Hall probe has two Hall elements with active areas of $0.05 \text{ mm} \times 0.05 \text{ mm}$, which were installed orthogonally on the tip of the probe. The rotating magnetic field formed at the center of the three-pole magnetizer was measured with the Hall probe and the gauss meter, and is displayed on the x - y axis.

3.2 Results of Magnetic Field Measurement

Figure 5 shows the magnetic fields formed by the three-pole magnetizer used in this study. Figure 5(a) indicates a circular magnetic field with approximately constant amplitude, which denotes that a rotating magnetic field was formed. Figure 5(b) shows an orientated stationary alternating magnetic field, which means that an orientated stationary alternating magnetic field can be created in any direction by adjusting the amplitudes and the phases of the magnetizing currents to each pole. These results show that we have succeeded in generating a circular rotating magnetic field and an arbitrary orientated stationary alternating magnetic field by adjusting the amplitude and phases of the magnetizing currents.

3.3 Experimental Procedure of BN Measurement with a Three-pole Probe

BN measurement was performed with the rotating magnetic field. A detection coil having an air core coil with 824 windings of 0.05 mm copper wire was prepared. The outer and inner diameter of the detection coil was 3 mm and 1 mm, and the thickness of the detection coil was 1 mm. The detection coil was installed at the center of the

three-pole magnetizer so that the surface of the detection coil contacted the surface at the test position. A band-pass filter designed for 4 to 220 kHz was applied to the signal and signals between -1 and 1 mV were removed as background noise. The Barkhausen energy E_{BN} ($\text{mV}^2 \text{s}$) (Eq. (7)) was used to characterize the BN because previous studies [9-11] indicated that this is an effective parameter for evaluating material condition. E_{BN} was calculated from BN output $BN(V)$ with two peaks measured in 0.1 second, and the average E_{BN} was calculated as the average value of 10 measurements.

$$E_{BN} = \int BN(V)^2 dt \quad (7)$$

where $BN(V)$ is the measured signal.

3.4 Results of BN Measurement

A grain-oriented electrical steel test piece with easy magnetization axis in the rolling direction due to Goss orientation was used. This test piece was selected because the effectiveness of the measurement system can be determined from the results of the BN measurement in the easy magnetization axis direction. If it can be measured properly, the BN should show a large output in the easy magnetization axis direction. The test piece had a length of 50 mm, a width of 50 mm, and a thickness of 0.2 mm. First, the 0° direction of the rotating magnetic field was set to coincide with the direction of the easy magnetization axis of the test piece. Next, the 90° direction of the rotating magnetic field was set to coincide with the direction of the easy magnetization axis of the test piece.

Figure 6 shows polar plots of E_{BN} of the grain-oriented electrical steel test piece in the magnetization direction of the rotating magnetic field formed by the three-pole magnetizer. The polar plots show the average of 10 measurements, and the average value of E_{BN} calculated from the four signals was divided into twelve and plotted every 30° . When the 0° direction of the rotating magnetic field is set to coincide with the easy magnetization axis of the test piece, E_{BN} of the 0° direction of the rotating magnetic field is larger than that of any other direction. When the 90° direction of the rotating magnetic field is set to coincide with the direction of the easy magnetization axis of the test piece, E_{BN} of the 90° direction of the rotating magnetic field is larger than that of any other direction. Both E_{BN} peaks coincide with the directions of the easy magnetization axis, because BN increases in the easy magnetization axis direction. In addition, the amplitudes of both E_{BN} are approximately equal.

However, the difference in the E_{BN} pattern between the 0° and 90° directions is because each pole has a characteristic originated from its physical tilt of the pole with respect to the sample surface, the strength of magnetic field and its angular position in the probe. In addition, it might be difficult for the change in the magnetic domain configuration of a grain-oriented electrical steel test piece to follow the rotating magnetic field generated by the three-pole magnetizer.

The experimental findings demonstrate that the BN measurement result using the rotating magnetic field formed by the three-pole probe is reliable.

4. Conclusions

A three-pole probe for measurement of BN was proposed, and a BN measurement system using a three-pole probe was constructed. The results of the analysis are as follows:

- A rotating magnetic field with a uniform amplitude in all directions and an arbitrary orientated stationary alternating magnetic field can be created using a three-pole probe.
- The BN shows a large output in the direction of the easy magnetization axis of a specimen of grain-oriented electrical steel sheet, and the peaks of E_{BN} also coincide with the easy magnetization axis. BN measurement in all directions with a rotating magnetic field formed by a three-pole probe is possible using the proposed system.

Acknowledgements

This work was supported by a Grant-in-Aid for Young Scientists (B), JSPS KAKENHI Grant No. 24760593 and Yokohama National University.

Nomenclature

A_1, A_2, A_3	Amplitude of magnetizing currents for each magnetic pole (A)
E_{BN}	Barkhausen energy ($\text{mV}^2 \text{ s}$)
I_1, I_2, I_3	Magnetizing currents for each magnetic pole (A)
k	Coefficient indicating the strength of the relationship between magnetic field and magnetizing current (m^{-1})
H_R	Amplitude of resultant magnetic field in x - y coordinates (A m^{-1})
H_{Rx}	x component of resultant magnetic field (A m^{-1})
H_{Ry}	y component of resultant magnetic field (A m^{-1})
H_1, H_2, H_3	Magnetic field generated from each magnetic pole (A m^{-1})
H_{1x}, H_{2x}, H_{3x}	x component of magnetic field generated from each magnetic pole (A m^{-1})
H_{1y}, H_{2y}, H_{3y}	y component of magnetic field generated from each magnetic pole (A m^{-1})
ϕ	Angle of resultant magnetic field in x - y coordinates (degrees)
$\theta_1, \theta_2, \theta_3$	Phase of magnetizing currents for each magnetic pole (degrees)

References

1. Residual stress measurement by X-ray diffraction-SAE J784a, (1971), SAE Iron and Steel Technical Committee, Society of Automotive Engineers. Fatigue Design and Evaluation Committee. X-Ray Division, p.62
2. Pèrez-Benitez JA, Padovese LR, CapóSánchez J, Anglada-Rivera J (2003) Investigation of the magnetic Barkhausen noise using elementary signals parameters in 1000 commercial steel. *Journal of Magnetism and Magnetic Materials* 263 (1-2):72-77
3. Anglada-Rivera J, Padovese LR, CapóSánchez J (2001) Magnetic Barkhausen Noise and hysteresis loop in commercial carbon steel: influence of applied tensile stress and grain size. *Journal of Magnetism and Magnetic Materials* 231 (2-3):299-306
4. Blaow M, Evans JT, Shaw BA (2005) Magnetic Barkhausen noise: the influence of microstructure and deformation in bending. *Acta Materialia* 53 (2):279-287
5. Krause TW, Clapham L, Atherton DL (1994) Characterization of the magnetic easy axis in pipeline steel using magnetic Barkhausen noise. *Journal of Applied Physics* 75:7983-7988
6. McNairnay P (2014) Magnetic Barkhausen Noise Measurements Using Tetrapole probe Designs. A thesis submitted to the Department of Physics, Engineering Physics and Astronomy in conformity with the requirements for the degree of Master of applied Science
7. White S, Krause TW, Clapham L (2012) A Multichannel magnetics flux Controller for Periodic Magnetizing Conditions. *IEEE Transactions on Instrumentation and Measurement* 61 (7): 1896-1907
8. Fukuoka K, Kawagoe I, Ozaki T, Iwata M, Kumeta M, Oikawa Y (2015) Development of Magnetic Particle testing Magnetizer for Generation of Uniform Rotating Magnetic Field in Wide Area. *Journal of the Japan Society of Applied Electromagnetics and Mechanics* 23 (1): 118-124
9. Hutanu R, Clapham L, Rogge RB (2005) Intergranular strain correlation with magnetic behavior in steel. *Applied Physics Letters* 86 (16):162503-162503
10. Stefanita CG, Atherton DL, Clapham L (2000) Plastic versus elastic deformation effects on magnetic Barkhausen noise in steel. *Acta Materialia* 48 (13):3545-3551
11. Dhar A, Clapham L, Atherton DL (2001) Influence of uniaxial plastic deformation on magnetic Barkhausen noise

Figure Captions

Fig. 1 Three-pole magnetizer: (a) plan view, (b) side view.

Fig. 2 Magnetic fields generated from each magnetic pole and resultant magnetic fields of the three magnetic fields at the center of the three-pole magnetizer when θ_1 is 90° .

Fig. 3 Magnetic fields generated from each magnetic pole and the resultant magnetic fields at the center of the three-pole magnetizer when θ_1 is 90° and 210° .

Fig. 4 Rotating magnetic field-generating system using a three-pole magnetizer.

Fig. 5 Magnetic fields formed by the three-pole magnetizer: (a) circular rotating magnetic field, (b) orientated stationary alternating magnetic field.

Fig. 6 Polar plots of E_{BN} of the magnetization direction of the rotating magnetic field formed by the three-pole magnetizer.

(a)

(b)

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