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Monte Carlo Simulation for Barkhausen Noise

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***Abstract*—In this paper, a new method is proposed for analysis of Barkhausen noise, which is expected to be useful for nondestructive evaluations for iron-based materials, using Monte Carlo simulation. The results show typical properties of Barkhausen noise such as temperature dependence and grain size dependence are well reproduced by this method.**

***Index Terms*—Fatigue, magnetization processes, Monte Carlo method, nondestructive testing.**

I. Introduction

BARKHAUSEN NOISE (BN) is well known to be sensitive for states such as grain size or residual stress in magnetic materials [1]. Therefore, BN is expected as a useful way of nondestructive evaluations (NDE) and many researchers have studied BN for iron-based materials [1]–[9]. The mechanism of BN, however, has not been clearly understood, especially for the relations between BN and micromagnetic states such as grain size, residual stress, dislocations, voids, and so on. But the microscopic study for them is important for making NDE using BN fit for practical use because of quantitative analysis for fatigue.

The difficulty of analysis for BN seems to be in dealing with the dynamic magnetic processes including discontinuous hysteresis curve. For example, the Preisach model, which is well used for magnetic hysteresis analysis, consists of continuous hysteresis curves, hence it is not suitable for BN originally. Therefore, we attempted a new analytical method for BN using Monte Carlo (MC) simulation. We will show this method can reproduce several typical properties of experimental results for BN in this paper.

Fig. 1 shows an experimental setup that we use for measurement of BN. BN is detected by a pickup coil for applied magnetic field formed into a triangle wave (frequency $= 15$ Hz) between -1 and $+1$ A which are current flowing through an electromagnet. Fig. 2 shows a typical result of BN at room temperature (RT; 300 K) for SS400, which is a steel with a soft magnetic property. BN appears as an induced voltage ($V_{\rm BN}$) of a pickup coil as shown in Fig. 2(b) with the current for each applied magnetic field in Fig. 2(a). In Fig. 2(b), $V_{\rm BN}$ contains a fluctuation with a triangle wave frequency (15 Hz) depending on a relative position of pickup coil from the magnetic yoke to apply magnetic field, although a high pass filter with a threshold frequency of 100 Hz is inserted in the electrical circuit. Therefore, we deal with a first differentiation of $V_{\rm BN}$; $dV_{\rm BN}/dt$ for analysis as shown in Fig. 2(c), because BN is discrete and it can be approximately regarded as δ function, then the first differentiation remains the information of the original function. On the other hand, the differentiation of the fluctuation is suppressed because of the gradual changes. The result of $dV_{\rm BN}/dt$ at liquid nitrogen temperature (LNT; 77 K) is also shown in Fig. 2(d). We can see some typical properties of BN as follows. The noise intensities show the maximum around at both "A" and "B" (pointed by the arrows in this figure) which locate at the currents just after zero fields ("b" and "d"), and BN decreases

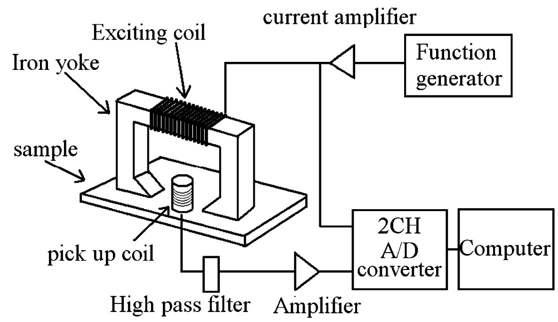

Fig. 1. Schematic view of experimental setup for measuring BN.

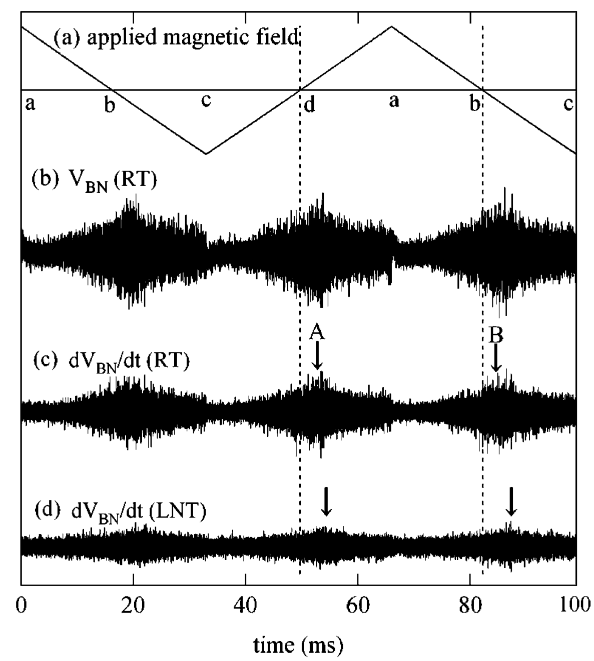

Fig. 2. Experimental results of BN for SS400 at room temperature (RT) and liquid nitrogen temperature (LNT). The intensities of $V_{\rm BN}$ and $dV_{\rm BN}/dt$ are given relatively. In this study, relative comparison between experiments and calculations is meaningful.

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around at the turning current points of "c" and "a." It is apparent that the average BN intensity decreases with the lowering temperatures. Furthermore, "A" and "B" field points are influenced by the ambient temperatures. Namely, these fields at LNT are delayed more than those at RT. It may be attributed to the change in the pinning forces for magnetic domain shifts accompanied with thermal spin fluctuations.

The above properties are reproduced by MC simulation as shown in the following sections.

II. Numerical Method

We use a simple spin Hamiltonian of a spin system describing magnetism for simplicity as follows:

$$H = -\sum_{i,j} J_{ij} S_i S_j + B \sum_i S_i. \tag{1}$$

Here S_i denotes the spin state of ith cell, and J_{ij} stands for the effective exchange energy between ith and jth spins. B represents an applied magnetic field. Now the first summation of (1) runs over the nearest neighbor cells with a constant exchange energy J. In the conventional Monte Carlo method, after an initial spin arrangement is first set, the local Hamiltonian of a focused spin is calculated including thermal fluctuation effects. Then a new arrangement is decided by comparison with the energy of other states of this spin. This cycle is ordinarily repeated until getting a stable state [10]–[16]. But now we stopped the repeating before getting a stable state because of dealing with pseudodynamic processes for BN. One MC step (1 MCS) means scanning up to the total cell number of times and 1000 MCS was carried out for one applied magnetic field. Under the constant field condition, the total spin is in an unequilibrium state and going to an equilibrium state with progressing MC steps. The applied magnetic field is given as a step function of MC steps. The step width is taken to be 0.001 and the field changes as a triangle wave between -0.1 and $+0.1$, overall.

As for a typical spin system, a single cubic lattice system composed of $31^3 = 29791$ spin cells ($0 \le x \le 30, 0 \le y \le 30$, $0 \le z \le 30$), was prepared for simplicity, although the real α-iron takes the b.c.c. lattice. The single cubic lattice has each side length (L) of 30, given by using one lattice constant as the unit.

Fig. 3 shows an example of a calculation result for magnetization M in (b) and the second differentiation of the magnetization d^2M/dt^2 in (c) under applied magnetic field formed as a pseudotriangle wave in (a). As shown in the upper circle, the triangle wave is constructed from numerous tiny steps. One step is held for 1000 MCS. In a few steps as shown in the lower circle, magnetization has discrete changes, although it has a tendency to decrease in this region on the whole. Here, it is worthwhile to note that the data obtained in the regions less than 1000 MCS are usually renounced because of the data in the meaningless nonequilibrium state. On the contrary, the data elucidate the nonequilibrium state in the steps less than 1000 MCS especially in the transient applied fields. The second derivative of the magnetization including the discrete change with respect to time; d^2M/dt^2

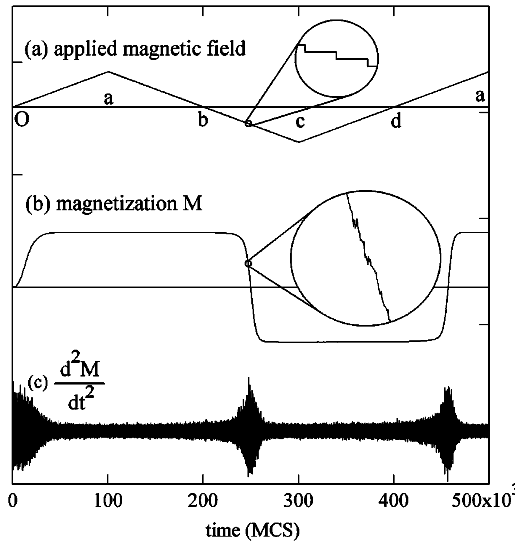

Fig. 3. Example of a calculation result for (b) magnetization M and (c) the second differentiation of the magnetization d^2M/dt^2 under (a) applied magnetic field formed as a pseudotriangle wave.

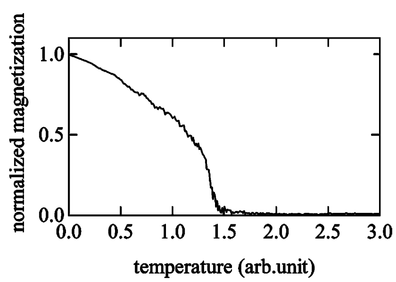

Fig. 4. Temperature dependence of magnetization for a single lattice cubic system composed of 31^3 spin cells.

was calculated to compare with experimental data of $dV_{\rm BN}/dt$.

The simulations were carried out by using the super-computer, ORIGIN 2000 in the Institute of Fluid Science, Tohoku University. 1 MCS took about 0.3 s and the total CPU time was 99 900 s for a typical calculation.

III. Results and Discussion

Fig. 4 shows the temperature dependence of magnetization in zero external magnetic field under the initial condition of the random spin arrangements corresponding to the paramagnetic state at high temperatures. The calculated result was found to obey well the Curie–Weiss law; therefore, the Curie temperature was estimated at about $T_C = 1.5$. Hereafter, we use this value as the criterion for the temperature.

Fig. 5(a) shows the temperature dependence of the second derivative of the magnetization (d^2M/dt^2) accompanied with applied magnetic field formed as a pseudotriangle wave for the temperature from $T = 0.05$ $((1/30)T_C)$ to $T = 2.0$ $((4/3)\ T_C)$. In the region of higher temperatures than T_C ($T = 1.5,\ 2.0$), each d^2M/dt^2 shows only a large constant noise and it does not show any particular peak. In the lower temperatures than T_C, the constant noise decreases as temperature goes down. And then noise peaks are revealed in

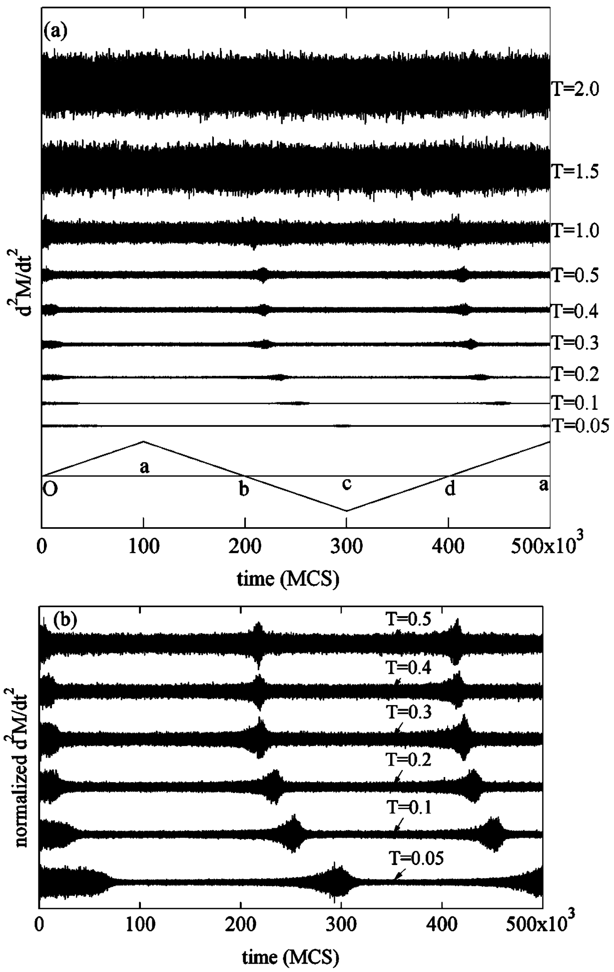

Fig. 5. (a) Temperature dependence of d^2M/dt^2 accompanied with applied magnetic field formed as a pseudotriangle wave for the temperature from $T = 0.05$ $((1/30)\ T_C)$ to $T = 2.0$ $((4/3)\ T_C)$. (b) Normalized d^2M/dt^2 for the temperature from $T = 0.05$ to $T = 0.5$.

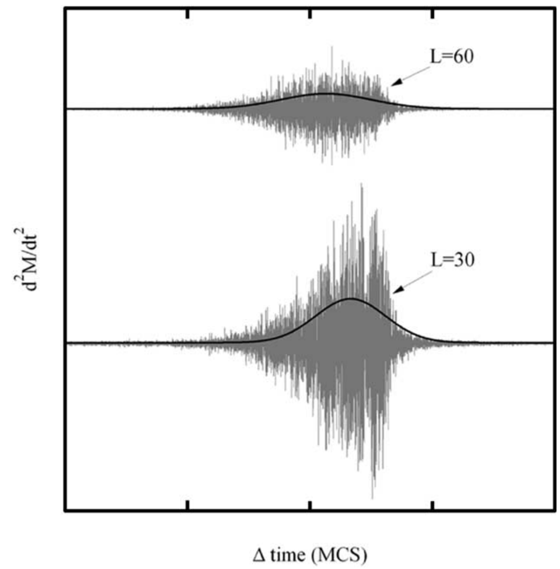

Fig. 6. Normalized d^2M/dt^2s by the number of spin cells at $T = 0.1$ for the spin system with $L = 30$ and 60. Black lines show the Gaussian fitting curve.

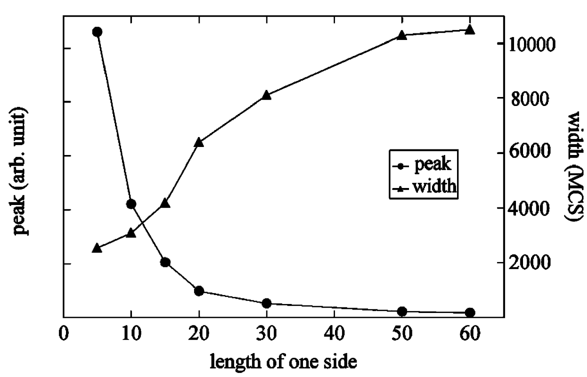

Fig. 7. Grain size dependence of peak intensity and peak width of d^2M/dt^2.

the region of magnetic field between “b” and “c”, or “d” and “a.” The peak intensity decreases with the temperature.

For more exact analysis, d^2M/dt^2 results normalized by the maximum intensity of themselves are also shown in the region of temperatures under T_C in Fig. 5(b). The amplitude peak of d^2M/dt^2 at $T = 0.5$ appears just after the zero magnetic fields (“b” and “d”) and those peaks delay gradually in the lower temperatures. Moreover the deviation of the peak increases as the temperature decreases.

These properties of d^2M/dt^2s well reproduce experimental results of $dV_{\rm BN}/dt$, namely (i) the average noise intensity decrease with temperature; (ii) the peak of the noise at lower temperatures than T_C appears just after the zero magnetic fields; (iii) the peak at lower temperatures delays; and (iv) the peak intensity decreases with temperature. Therefore, we regard d^2M/dt^2 are a simulated $dV_{\rm BN}/dt$, namely calculated BN.

The method was applied to the study of the relation between the grain size (i.e., size of spin system) and the behavior of BN. We prepared various sizes of spin systems arrayed as the single cubic lattice with each side length (L) of 5, 10, 15, 20, 30, 50, and 60. Fig. 6 shows the normalized d^2M/dt^2s by the number of spin cells at $T = 0.1$ for the spin system with $L = 30, 60$ on magnetic processes between “b” and “c” of applied magnetic field in Fig. 5(a). The peak intensity of d^2M/dt^2 per a spin cell for $L = 30$ is larger than one for $L = 60$, namely the assembly of the smaller grain induces the greater BN. The Gaussian fitting curves of the absolute normalized d^2M/dt^2s are also displayed as the black line in Fig. 6. We can see the grain size dependences of the peak intensity and the peak width. Fig. 7 shows the dependence for the spin system with $L = 5, 10, 15, 20, 30, 50, 60$. It is clearly seen that the peak intensity decreases and the peak width increases as one side length of spin system becomes larger. Usually BN is measured as the average intensity of induced voltage of pick up coil [17]. But the calculated result suggests that it is very important to measure raw BN data including the peak intensity and the peak width for evaluation of dynamic magnetic processes.

IV. Conclusion

A new analysis method for BN using Monte Carlo simulation reproduced the properties of experimental typical results of BN. The results of temperature dependence for calculated BN would also be available to recent studies of BN for micromagnetic wires. The grain size dependence of calculated BN suggests that it is very important to measure raw peak features for the detailed analysis of the magnetic state. Moreover, for more exact analysis the peak shape of BN such as asymmetry may be useful. Finally, we can say that the present method has a great potential for analysis tool of BN including other microscopic information such as dislocations and voids.

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