ORIGINAL ARTICLE

Caution to Apply Magnetic Barkhausen Noise Method to Nondestructive Evaluation of Plastic Deformation in Some Ferromagnetic Materials

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Abstract

Magnetic Barkhausen Noise (MBN) method is known as an effective nondestructive evaluation (NDE) method for evaluation of residual stress in ferromagnetic materials. Some studies on the feasibility of the MBN method for NDE of residual strains were also conducted and found applicable. However, these studies are mainly focused on the state of residual strains which were introduced through a one-cycle-loading process. In practice, however, structures may suffer from an unpredictable and complicated loading history, i.e., the final state of plastic strain may be induced by several times of large loads. Whether the loading history has influences on MBN signals or not is of great importance for the practical application of the MBN method. In this paper, several ferromagnetic specimens with the same final state of residual strain but of different loading history were fabricated and inspected by using a MBN testing system. The experimental results reveal that the loading history has a significant influence on the detected MBN signals especially for a residual strain in range less than 1%, which doubts the feasibility to apply the MBN method simply in the practical environment. In addition, micro-observations on the magnetic domain structures of the plastic damaged specimens were also carried out to clarify the influence mechanism of loading history on the MBN signals.

Keywords: Plastic damage, Deformation history, MBN method, Ferromagnetic materials

1 Introduction

Non-destructive evaluation (NDE) is an important and synthetical technology to ensure the integrity of modern critical structural systems [1–3]. Magnetic Barkhausen Noise (MBN) method is one of the important NDE methods for evaluation of residual stress in ferromagnetic materials [4–10]. The feasibility of MBN for NDE of plastic deformations has also been studied recently [11–17]. For instance, Stefanita et al. [15] investigated the different effect of elastic and plastic deformation on the MBN

signals. Blaow et al. [16] studied the MBN signal changes due to a bending deformation in low alloy steels. Noris et al. [17] explored a magnetic noise scan technique to evaluate the deformation distribution in the surface of a carbon steel plate. Authors also conducted researches to use integrated magnetic method for NDE of several ferromagnetic materials [18, 19]. However, the experiments of these studies are mainly focused on the final state of the residual strains which were introduced to the specimen by one giant load. In practical case, the target structure to be inspected may has a complicated loading history, i.e., the plastic strain was introduced by several times of large loads. To clarify whether the loading histories have significant influences on the MBN signals is also important to apply the MBN method in practical environment.

In this paper, MBN measurements were conducted for specimens with plastic strains of different loading

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histories. Specimens with plastic damages were fabricated with use of a Reduced-Activation Ferritic/Martensite (RAFM) steel [20], a typical ferromagnetic material considered as an important candidate structural material for the nuclear fusion reactors. The plastic deformations were introduced with both the one cycle tensile loading and multiple cycle loading process. The correlation of the loading history and the corresponding MBN signals was investigated via a MBN testing system developed by authors. In addition, magnetic powder-pattern observations were also carried out to investigate the reason why MBN signals is influenced by the loading history. A discussion is given based on the observed magnetic domain structures to explain the influence mechanism from micro defect point of view.

2 NDE Experiments

2.1 Methods and Experimental Systems

The Barkhausen effect is found at 1919 that the irreversible movement of the magnetic domain walls in a ferromagnetic material causes stochastic pulsed electromagnetic signals. This phenomenon is then proved due to the pinning effect of micro material structure, such as the grain boundaries, dislocations, and micro defects [21–25]. As plastic deformation cause micro defects in material, it gives a possibility to evaluate the plastic strain by using the MBN signals from principle point of view.

In this study, a MBN testing system developed by authors as shown in Figures 1 and 2 was used to measure the MBN signals. An electromagnet driving by a sinusoidal current is applied to magnetize the material in order to generate MBN signals. In practice, the sinusoidal wave of 1 Hz frequency and 0.8 V amplitude was generated by using a function generator and magnified 10 times with a power amplifier. The currents drive a group of excitation

Figure 2 A photography of the MBN experimental system
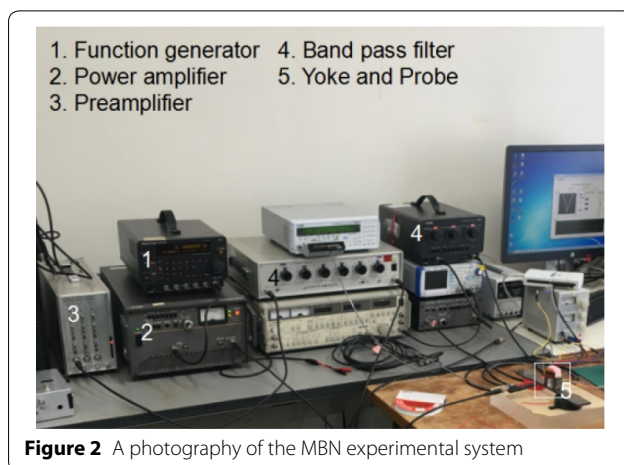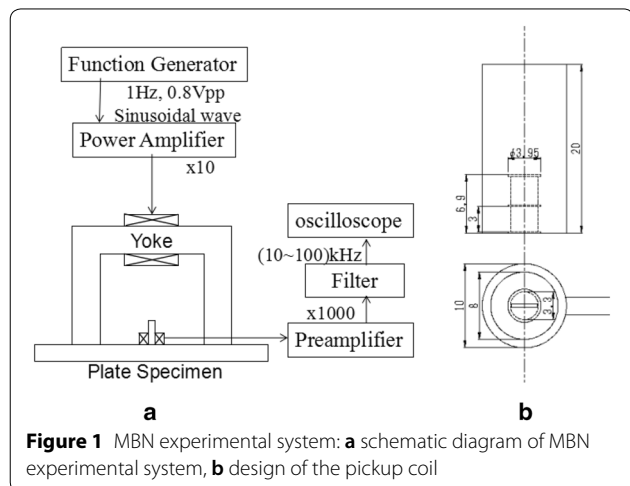
coils wounded on the legs of the U shaped permalloy yoke, which was set near by the inspection target material. The MBN signals were measured by using the pickup coil of an eddy current testing probe setting between the yoke legs and of 0.5 mm liftoff. Since the MBN energy mainly lies around a frequency of 50 kHz for the RAFM steel, a band pass filter was applied to reduce the influence of low and high frequency noise. The frequency range was set as 10 kHz to 100 kHz. Finally, the pickup signals of the coil were magnified by 1000 times with a signal amplifier and digitized through an oscilloscope with a sampling frequency of 10 MHz. The block diagram as well as the design of the ECT probe are shown in Figure 1. Figure 2 presents a photography of the MBN experimental system.

Typical MBN signals of specimens is illustrated in Figure 3. There is a background noise with the average value of about 0.018 V behind the MBN signals. A threshold of 0.02 V is selected to cut the background noise in measured MBN signals. As shown in Figure 3, the MBN signals in this study is narrow and sharp and the peak value of MBN signals changes significantly with plastic deformation.
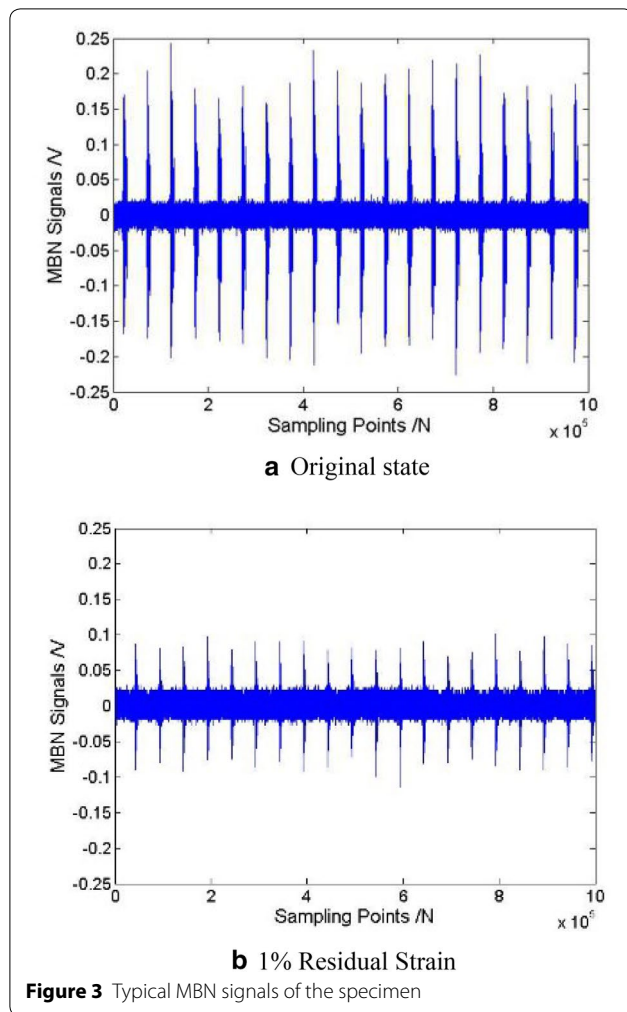
Since there is a rap in the peak value of MBN signals, the feature parameter of the MBN signals is chosen as the root mean square (RMS) of signals defined by

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} X_i^2},\tag{1}$$

where n is the total number of sampling points and X_i is the signal amplitude at ith sampling point.

2.2 Experimental Procedure

To investigate the influence of loading history on the MBN signals, 13 plate specimens of 5 mm thickness were

Figure 1 MBN experimental system: **a** schematic diagram of MBN experimental system, **b** design of the pickup coil

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a Original state

b 1% Residual Strain

Figure 3 Typical MBN signals of the specimen

fabricated at first with a typical RAFM steel [26]. Heat treatments are carried out to the specimens to release the initial residual stress. before Plastic strains were introduced to some specimens with a one-cycle-tensile-loading process (hereafter, denoting as No-History specimens) by using a MTS tensile testing machine at a strain rate of 0.3 mm/min. The levels of residual plastic strains introduced to the No-History specimens are 0%, 0.1%, 0.3%, 0.5%, 1%, 2%, 3%, 5%, 7% and 10% respectively. The strain of specimens was monitored by using a strain gauge mounted on the surface of specimen during the loading and unloading process. The MBN signals were measured offline after the specimens were unloaded from the test machine.

In addition to the No-History specimens, plastic deformation was introduced to other specimens (History specimens hereafter) through a multiple tensile loading process. In practice, a specimen without residual strain was loaded to the first target strain at first and unloaded for MBN measurement. The same specimen was then

reloaded for the next target strain and unloaded for MBN measurement again. The process was repeated until the maximum target residual strain was reached. The loading procedure for each loading step was exactly the same with that for the No-History specimens. The MBN signals of 3 history specimens were measured with target residual strains listed in Table 1. The measured MBN signal results are compared with those of the No-History specimens to investigate the influences of the loading history on the MBN signals.
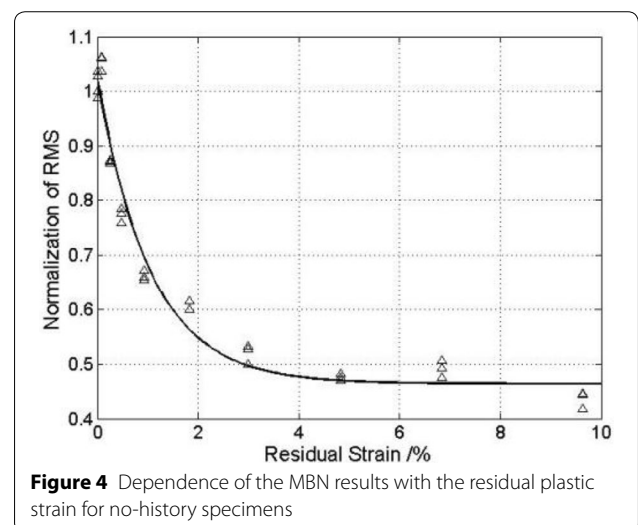
3 Experimental Results
3.1 Results for the No-History Specimens
The MBN results of the No-History specimens are presented in Figure 4. In the figure, the signal values were normalized with the measured value of the virgin state specimen.

It can be seen from Figure 4 that the relationship between the MBN signals and the residual plastic strains has downward tendency. The RMS values of MBN signals decrease with the increasing residual strains. The decrease of MBN signals is more dramatic in range from 0.1% to 1% residual strain but the downtrend becomes smoothly for larger plastic strains. Despite the signal rising a little at 0.1% residual state, the global tendency of

Table 1 Target residual strain for history specimens

No	Target residual strains
1	0%, 0.1%, 0.3%, 0.5%, 1%
2	0%, 1%, 2%, 3%, 5%, 7%, 10%
3	0%, 0.1%, 0.3%, 0.5%, 1%, 2%, 3%, 5%, 7%, 10%

Figure 4 Dependence of the MBN results with the residual plastic strain for no-history specimens

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MBN signals shown in Figure 4 has an exponential down-trend. The results prove that it is feasible to evaluate the plastic deformation of No-History specimens by using the MBN method.
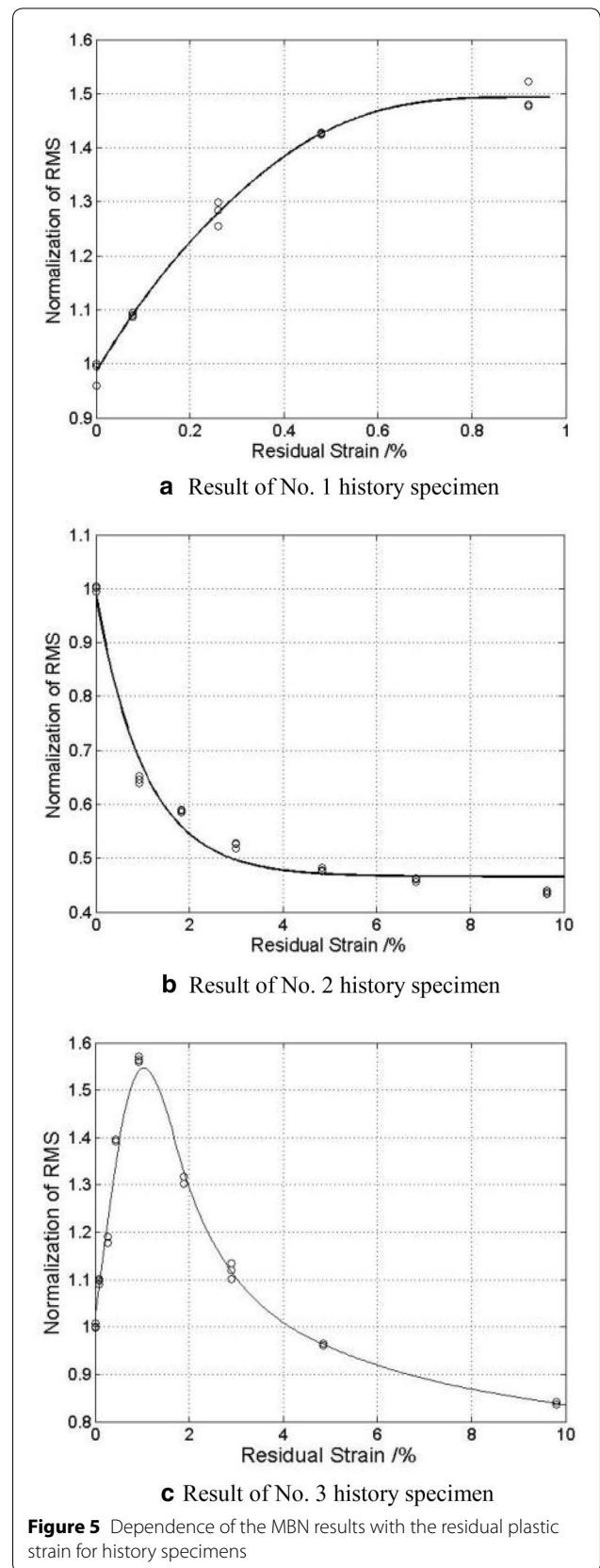
3.2 Results for the History Specimens

Figure 5 gives the MBN experimental results of History specimens. Specifically, Figure 5a is the results for specimen No. 1 of loading histories shown in Table 1. Figure 5b is for specimen with loading history of only large plastic strain (specimen No. 2 with loading history) while Figure 5c is the results for specimen No. 3 of loading history.

There is a clear rising tendency of MBN signals with the residual plastic strains in Figure 5a which is total different with the results of the No-History specimens shown in Figure 4. However, comparing the results shown in Figures 4 and 5b, it can be found that not only the tendency but also the values of the RMS are nearly the same between the History and the No-History specimens with same residual strains. This means that, there is no history effect if the first loaded plastic strain is large. In Figure 5c, the MBN signals of specimen No. 3 of loading history is almost the same with those shown in Figure 5a, which reveals a good repeatability of the experiments. However, compared with the results shown in Figure 5b, the results of Figure 5c are very different, i.e., the relationship between the plastic strain and MBN signal is greatly influenced by the small plastic strain loaded before, that means a big influence of loading history. The results reveal that if the first residual plastic strain is less than 1%, the deformation history has clear influence on the detected MBN signals even the final residual strain is of a relative large value. While if the first residual plastic strain is over 1%, the plastic deformation history only has limited effect on the MBN signals. However, as structures always suffer from unpredictable and complex damage histories in practice, loading history causes uncertainty in plastic strain results when evaluated by using the MBN method for the RAFM steel.
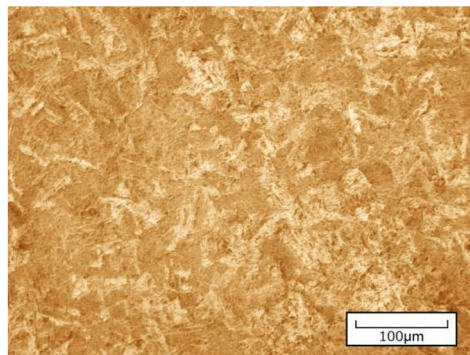
4 Magnetic Powder-Pattern Observation
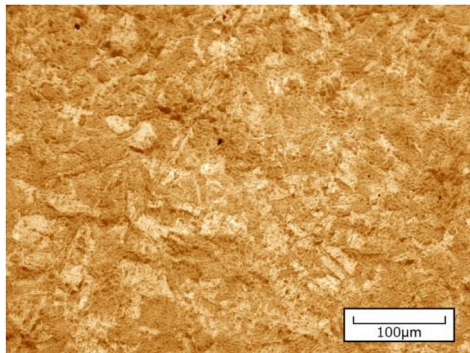
4.1 Methods and Observation Results

To investigate the reason of the phenomena found in experiments, the evolution of magnetic domain structures is observed in view that the MBN signals are closely related to the movement of magnetic domain wall. The powder-pattern method is used for observation of the domain structures. No-History samples of 0%, 1%, 10% and History sample with 1% residual strain are cut from the damaged specimens and observed with the magnetic powder-pattern method. No-History samples of 0% and
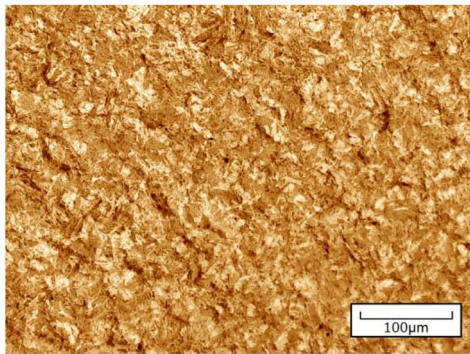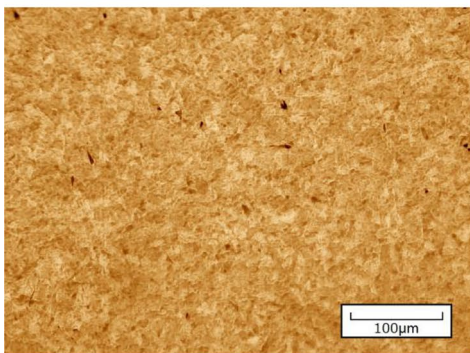

a Result of No. 1 history specimen

b Result of No. 2 history specimen

c Result of No. 3 history specimen

Figure 5 Dependence of the MBN results with the residual plastic strain for history specimens

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a 0% No-history Sample

b 1% No-history Sample

c 10% No-history Sample

d 1% History Sample

Figure 6 Magnetic Powder-pattern images for no-history and history sample of different plastic deformation (200 times)

10% plastic residual strain are selected to investigate the influence of plastic deformation on domain structures while No-History and History samples of 1% are used to investigate the influence of plastic deformation history on the domain structures. In practice, specimens are first cut into small samples of 8 mm by 10 mm by 4.5 mm size with the side of 4.5 mm being the thickness direction, and then the samples are polished employing sand papers and etched through silica suspension. The magnetic colloid liquid A-07 is taken as the magnetic particle suspension for the powder-pattern method.

The observation results of powder-pattern method with a magnification of 200 times are shown in Figure 6. The difference in colors of patterns is due to the orientation of magnetic domains. The figures show that the sizes of magnetic domains are in micrometer order. Comparing the results between No-History specimens as shown in Figure 6a and c, one can find that the focused domain orientations become stronger with the increasing plastic deformations. The pattern in Figure 6b has several darker parts between patterns shown in Figure 6a and c. For the pattern shown in Figure 6d, though the total residual strain is the same with the sample for Figure 6b, it has a more cataclastic domain structure with only slightly focused orientations. Comparing the results in Figure 6a and d, it can also be found that small rate of plastic deformations cut the domains into pieces, which indicates that the location of domain walls is related to micro defects such as the dislocations caused by the plastic deformations. According to these experimental results, it can be concluded that plastic deformation has influences on domain structures of materials. To be specific, a large plastic deformation (over 1%) introduced through the one-cycle-loading process may limits the orientation of domains and leads to a unique domain orientation while a small plastic deformation (small than 0.5%) by several loading processes lead to a cataclastic domain structures with weak orientation focusing. The pinning effect to domain wall of the plastic damage is closely connect to the loading histories.

4.2 Discussions

As well known that the MBN signals are accumulated energies released in the irreversible magnetization stage when the domain walls move across the pinning point. The amount of pinning points and the movement of domain walls are keys for the releasing of MBN signals. In case that the movement of domain walls can move across any kinds of pinning points, more accumulation of energy is needed and also more energy will be released from this domain wall movement consequently for pinning defect of big size, which means a stronger MBN signal. However, according to the NDE results, the MBN

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signals decrease as the plastic deformation is enlarged, which means that the movement of domain walls is hindered by the defects of larger geometrical size. Combined with the results of magnetic observations, one can image that some magnetic domains are stuck due to micro defects in the No-History specimens with a residual strains over 1% and form a focused orientation under the influence of these defects.

On the other hand, considering the loading process of History specimens of small residual strains, micro defects are more likely to be formed at new positions instead of to be expanded to large size due to the strain hardening effect [27, 28]. Thus the size of pinning defect in 1% History specimen will be much smaller than that in No-History specimens while the number of these defects are much higher in contrast. However, defects with relatively small size still have the ability divide magnetic domain walls under nature condition, which should be the reason of the cataclastic domain structure in Figure 6d. Since the History specimen with 1% residual strains has the biggest number of pinning defects and these pinning defects are small enough for the domain wall to move across, the History specimen with 1% residual strains has a higher MBN signal. In addition to the MBN results shown in Figure 5c, it can be concluded that the small defects formed under small plastic strain continuously influence the NDE signals when additional plastic strain is introduced. The results indicate that the influence of small plastic deformation history on the evaluation results of MBN methods, which is defined as loading history effect, is not negligible. As most of the ferromagnetic materials have crystal structure which means strain hardening phenomenon occurs during the deformation process, it can be speculated that the loading history effect may applicable for some other materials and reduces the evaluation precision of MBN method in engineering.

5 Conclusions

In this study, the feasibility to use the MBN technique for evaluating plastic strain of complex loading history is investigated through experiments for a ferromagnetic steel.

The experimental results show that the MBN signals are not influenced by the loading process when the first residual plastic strain introduced is over 1%. However, MBN signals are strongly influenced by the loading history when the plastic strain is introduced little by little. Since the deformation history is usually unknown in practice, the MBN method may be not suitable for NDE of plastic deformation under practical conditions for some ferromagnetic materials.

In addition, the influence mechanism of the plastic deformation on the MBN signals is also studied through observing the magnetic domain structures with the magnetic power pattern method. As conclusion, the MBN signals are affected by the loading history because the size and number of the pinning defects in material are closely related to the deformation history of the target material.

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