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Analysis of domain wall dynamics based on skewness of magnetic Barkhausen noise for applied stress determination

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ABSTRACT

Skewness of Magnetic Barkhausen Noise (MBN) signal is used as a new feature for applied stress determination. After experimental studies, skewness presents its ability for measuring applied tensile stress compared with conventional feature, meanwhile, a non-linear behavior of this new feature and an independence of the excitation conditions under compressive stress are found and discussed. Effective damping during domain wall motion influencing the asymmetric shape of the MBN statistical distribution function is discussed under compressive and tensile stress variation. Domain wall (DW) energy and distance between pinning edges of the DW are considered altering the characteristic relaxation time, which is the reason for the non-linear phenomenon of skewness.

1. Introduction

Magnetic Barkhausen Noise (MBN) has been proved as an effective technique to measure residual stress (RS) as well as applied stress (AS) on ferromagnetic materials. Micro-magnetic structure of material decides the shape and size of magnetic domains, and then dominates the behavior of domain wall (DW) motion, i.e. its dynamics, which influences Barkhausen noise significantly, thus MBN method attracts numerous researchers. In a dynamical changing (time-varying) magnetic field, DW movement is affected by the structure of the domains itself and by lattice defects in material microstructure, such as inclusions, dislocations, grain boundaries, second phase precipitates and applied or residual stress [1–5]. MBN signal are therefore widely utilized for the characterization of material microstructure under applied field. Furthermore, in many published research works, the root mean square (RMS) value of MBN signals is considered as a function of the applied magnetic field, residual and applied stress, surface hardness and hardening-depth, etc. [1–5]. However, this feature depends on excitation parameters obviously, such as applied magnetic field amplitude and frequency [3–6].

Recent research on magnetic domains focus on nano-scale mechanisms and their potential consequences on magnetic memory [7], logic devices [8,9] and DW dynamics, including effective mass and eddy current-damping effect [10–12]. For example, behavior of DW dynamics are considered as responses to its characteristic relaxation. Zapperi [12] et al. have studied material characteristic relaxation time and verified that it is a signature of negative effective mass of the DW in a ferromagnetic slice (thin sheet). Skewness of the shape of magnetic Barkhausen jump distribution was proposed to track the characteristic of DW dynamics behavior in an applied field. This method reveals a relationship between the electromagnetic signal on the macro-scale and material relaxation time on the micro-scale for sheet specimen. It is well known that all magnetic moment are exchange-coupled to their neighbors. Hence any change in the wall position by motion will be dampened by the adjacent domain. Previous study has shown that damping mechanisms in the adiabatic regime was affected by applied stress [11]. Therefore, skewness of the MBN signal distribution was proposed as a new feature for microstructure characterization and applied stress determination of carburized En36 steel, which had case-depth and double peak MBN shapes, and was demonstrated more sensitive than RMS and peak position [13].

In the here presented paper, skewness is proposed as a signature for applied stress detection on soft steel. Q235 steel specimens (Chemical composition see Table 1) were investigated under compressive and tensile applied-stress of variable amplitude to evaluate the effectiveness of this new feature for soft steel with single peak MBN shape. Subsequently, non-linear behavior

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Table 1
Chemical composition (wt%) of the Q235 steel used in this study.

C	Si	Mn	S	P	Cr	Ni	Cu
≤ 0.22	≤ 0.3	0.30–0.70	≤ 0.045	≤ 0.045	≤ 0.30	≤ 0.30	≤ 0.30

and excitation independence are presented and discussed. Domain wall energy and pinning edges distance, influenced by applied stress, affect the characteristic relaxation frequency, which is considered the dominant variable to govern skewness of MBN signal distribution.

2. Experimental setup

In this experiment, Q235 steel is selected as a sample to evaluate how applied stress affects MBN signal feature. This soft material can provide significant Barkhausen noise under low applied stress, which contributes to remarkable changes in the MBN signal distribution. The chemical composition of the Q235 steel is illustrated in Table 1.

As shown in Fig. 1, a Q235 steel bar (660 mm × 30 mm × 5 mm, L × W × D) is subjected to four-point bending. The vertical press makes compressive stress on the top surface of the specimen and tensile stress on the opposite surface. On the basis of structural mechanics the compressive stress can be expressed as $\sigma_{max} = \frac{3Fd}{S}$, where s is the cross sectional area of the bar, and F is the applied force. The applied stress was limited to be within the range 0–150 MPa to avoid macro-plastic deformation (the yielding point of Q235 is about 200 MPa and influenced by the specimen dimension).

To obtain MBN signals, the Agilent 33,250 A provided low frequency excitation which is amplified by a bi-polar power amplifier, Newtons 4th LPA05B. The output of the power amplifier is fed to the coil wound the magnetic yoke (made of ferrite core) to drives the applied field. The frequencies of the magnetic excitation are selected variable from 2 to 10 Hz, and the current was about 0.8 A in its peak maximum (corresponding to a maximum tangential magnetic field $H_{\max}$=7000 A/m). The MBN signal, as show in Fig. 2, was detected using a pick-up air-coil (with 1500 turns of 0.07 mm diameter wire) on.

the surface of the bar sample. The MBN signals were amplified (gain has been fixed at 30 dB), band pass filtered (2–40 kHz), and sampled at a 200 kHz frequency by 14-bit data acquisition (DAQ2010) analog-to-digital converter. Synchronously, the excitation voltage was acquired using the second channel [13].

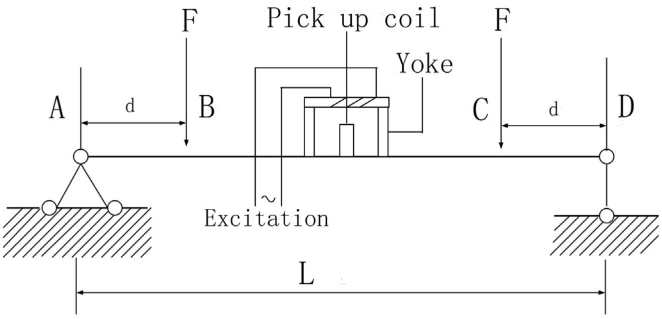

Fig. 1. Schematic for compressive stress loading and MBN signal detection. F is applied at B and C to produce compressive applied stress on the top surface and tensile applied stress on the bottom surface.

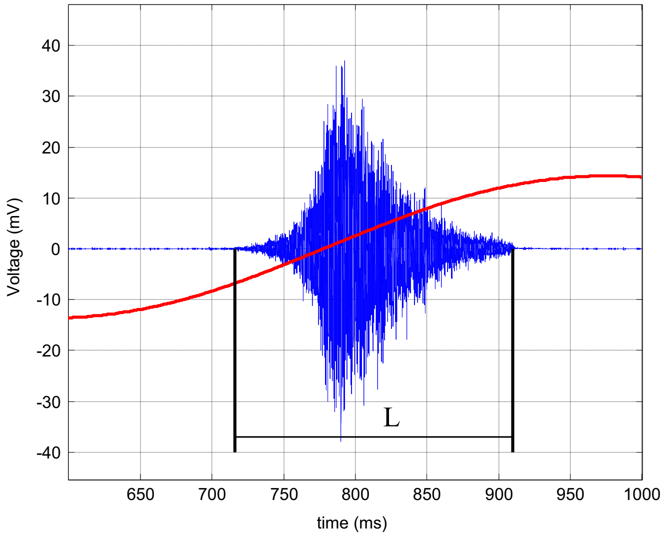

Fig. 2. Example of MBN signal. The red cure is excitation and the blue one is MBN signal. L describes the period of one MBN signal in time domain. The start point is selected when MBN signal profile over a certain threshold, and the cutoff point is selected when MBN signal profile less than the same threshold. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

As mentioned previously, skewness of MBN profile shape is influenced by damping mechanisms. To calculate the MBN signal skewness, equation according to the method mentioned by Zapperi et al. [12] was applied as follows:

$$\mathrm{sk}(\mathrm{L}) = \frac{\frac{1}{L}\int_0^L dt\left\langle v(t, L)\right\rangle (t - \bar{t})^3}{\left[\frac{1}{L}\int_0^L dt\left\langle v(t, L)\right\rangle (t - \bar{t})^2\right]^{3/2}} \tag{1}$$

L is the length of a time-window in which the distribution of events ν (here the BN distribution) in amplitude is larger than a certain threshold which is normally given by the electronic noise in the receiver circuit.

$$\bar{t} = 1/L \int_0^L dt\left\langle v(t, L)\right\rangle t$$

is the so called first moment of the distribution function and defines the mean value at which the distribution is maximal. sk (L) characterizes how skew the distribution is, skew means – the distribution is not symmetric to the mean value. This window length L is clearly influenced by the excitation frequency. For example, with 2 Hz excitation, L is about 200 ms, less than a quarter of the driving period. However, L changes to 35 ms, near half of the driving period, when the excitation frequency increases to 10 Hz.

With different compressive and tensile stress values, the skewness and the RMS[1] value of MBN signal are calculated and compared for estimating the effect of domain wall dynamics and excitation parameters. All these features are normalized by dividing the values with the one obtained from 0 MPa stress.

3.1. Effect of compressive stress on skewness

With different applied compressive stress, skewness of MBN distributions and RMS are obtained by calculation and compared. The normalized features with scatter-bars, representing the

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[1] RMS($x(t)$)= $\int_0^T x^2(t)dt)/T$, where T is an apropriate choosen integration interval.