Ding S, Tian G, Dobmann G, Wang P.

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Journal of Magnetism and Magnetic Materials 2017, 421, 225-229

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DOI link to article:

<https://doi.org/10.1016/j.jmmm.2016.08.030>

Date deposited:

13/12/2017

Embargo release date:

08 August 2017

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Analysis of Domain Wall Dynamics based on Applied Stress Measurements on Q235 Steel

Using Magnetic Barkhausen Noise

Song Ding^{1,3*}, GuiYun Tian^{1,2}, Gerd Dobmann¹, Ping Wang¹

¹School of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 210016, China

²School of Electrical and Electronic Engineering, Merz Court, University of Newcastle upon Tyne, Newcastle, NE1 7RU, UK

³School of Electronic Engineering and Control Science, Nanjing Tech University, Nanjing, Jiangsu, 211816, China

Abstract: This paper reports on the determination of applied stress using Magnetic Barkhausen Noise (MBN). Effective damping in Barkhausen noise influencing the asymmetric shape of the MBN statistical distribution function is discussed under compressive and tensile strain variation. After experimental studies, the skewness of MBN distribution profile is presented as a new feature for applied stress characterization. A non-linear behaviour of this signature and an independence of the excitation conditions have been found and is discussed. Domain wall (DW) energy, characteristic relaxation time and distance between pinning edges of the DW are considered as the reason of the phenomenon. Skewness presents its robustness to excitation parameters and ability for measuring applied stress.

Keywords: applied stress, Magnetic Barkhausen Noise, skewness, wall energy, characteristic relaxation time

1. INTRODUCTION

Magnetic Barkhausen Noise (MBN) has been proved as technology to measure residual stress (RS) as well as applied stress (AS) on ferromagnetic materials. The ability to analyze due to MBN micro-magnetically the microstructure attracts numerous researchers because it decides the shape and size of the domains, thus the behavior of DW motion, i.e. its dynamic, are dominated. In a dynamical changing (time-varying) magnetic field, DW movement is affected by magnetic structure of the domains itself and by lattice defects in the microstructure, such as inclusions, dislocations, grain boundaries, second phase precipitates and applied or residual stress [1-5]. MBN signals are therefore widely utilized for the characterization of material microstructure under applied field. Furthermore, in many previously published research work, the root mean square values (RMS) of the MBN signals as function of the applied magnetic field are measured and as the most popular feature, the maximum of this value, obtained during a half-period of excitation is selected. This value is then discussed in a variety of papers, as a feature to characterize residual or applied stress, surface hardness and/or hardening-depth, etc. However, obviously this feature depends on excitation parameters, such as magnetic field amplitude and frequency [3-6].

Recent research on magnetic domains have focused 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 provides to reveal 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, following the interpretation of the analysis of Zapperi et al. [12], skewness of the MBN signal distribution is proposed as a new feature for microstructure characterisation of bulk material.

In the here presented paper, skewness is proposed as a new feature for applied stress detection. Q235 steel specimens (composition see table 1) were investigated under compressive and tensile applied-stress of variable amplitude to evaluate the effectiveness of this new feature. DW dynamics are discussed subsequently to explain the ambiguity in the skewness behavior as function of stress in the upper stress regime, and how, wall energy and viscous damping, affect the characteristic relaxation frequency, which is the dominant variable to govern skewness of MBN signal distribution.

* Tel: +86 13951898115

E-mail: dingsong@njtech.edu.cn

2. EXPERIMENTAL SETUP

In this experiment Q235 steel was selected 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.

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

As shown in Fig.1, a Q235 steel bar (660×30×5mm, L×W×D) was subjected to four-point bending. The vertical press made 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

Fig.1 Schematic for compressive stress loading and MBN signal detection

Fig.2 Example of MBN signal

and F is the applied force. The applied stress was limited to be within the range 0~150MPa to avoid macro-plastic deformation (the yielding point of Q235 is about 200MPa and influenced by the specimen dimension).

Agilent 33250A provided different frequency excitation wave forms which were amplified by a bi-polar power amplifier, Newtons 4th LPA05B. The output of the power amplifier was fed to the coil wound the magnetic yoke (made of ferrite core) to drives the applied field. The frequency of the magnetic excitation was selected variable from 2 to 10Hz and the current was ~0.8A in its peak maximum (corresponding to a maximum tangential magnetic field $H_{max}=7000$ A/m). The MBN signal was detected using a pick-up air-coil (with 1500 turns of 0.07mm 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].

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:

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

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

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

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 2Hz excitation, L is about 200ms, less than a quarter of the driving period. However, L changes to 35ms, near half of the driving period, when the excitation frequency increases to 10Hz.

With different compressive stress values, the skewness and the RMS¹ value of MBN signal were calculated and compared for estimating the effect of excitation parameters. All these features were normalized by dividing the values with the one obtained from 0MPa stress.

3.1 Effect of compressive stress on skewness

With different applied compressive stress, skewness of MBN distributions and RMS can be obtained by calculation and can be compared. The normalized features with scatter-bars, representing the repeatability, are presented in Fig.3. In fact, both of these features have been averaged taking into account the MBN information received in 20 individual excitation periods. Figure3 reveals three facts:

- Normalized skewness has better sensitivity than RMS when the compressive stress is below 75MPa.
- The scatter in skewness data is slightly smaller than in RMS.
- Normalized RMS decreases linearly with compressive stress, whereas skewness has an ambiguous behavior, which will be discussed in chapter 3.4.

Fig.3 Normalized skewness and Root Mean Square (RMS) of MBN signal distributions

According the basic understanding of stress interaction with DW [1, 2], compressive stress aligns the magnetic domains perpendicular to stress direction and makes the magnetization process difficult, when excitation is in stress direction. In our experiment we have observed too the well-known fact, that the peak position in the time scale of the MBN distribution increased monotonously with increasing compressive stress; the same is with the peak position in RMS. It is also in line with the standard inertia theory describing the resistance of material mass when movement start or when movement temporarily is stopped and has to start again. A slightly higher driving force has to be applied, to overcome the effect [12]. As a whole, applied compressive stress does not only delay the peak position, but also decrease the

¹ $RMS(x(t)) = (\int_0^T x^2(t)dt)/T$, where T is an appropriate chosen integration interval.

peak value of MBN signal, which both make the MBN profile tend to a negative skewness. Thus, it is easy to accept that skewness shows better sensitivity than RMS on measuring applied compressive stress.

3.2 Effect of tensile stress on skewness

The MBN signal were measured also to understand the effect of applied tensile stress. The relationship between MBN signal features and tensile stress is presented in Figure 4. Skewness and RMS again were normalized on the maximum value. Both features were averaged after collecting individual BN distributions in 20 different exciting periods. The symbol positions in Fig. 4 indicate the average value.

Fig.4 Normalized RMS and Skewness depend on applied tensile stress

From figure 4, skewness rises with the increase of tensile stress. RMS is calculated for comparison which shows the same tendency as skewness. Obviously, skewness curve is more sensitive - i.e. has a higher dynamic - to the applied tensile stress than RMS curve, which has been also presented in previous research [13]. It is considered that applied tensile stress not only decreases exchange energy, it make the Barkhausen jump easy to be performed. So the MBN profile peak becomes higher and left-shifted [1, 2]. As main result we see:

- The normalized skewness shows better sensitivity to applied tensile stress compared with the normalized RMS value.
- The fitting curve of the RMS values remains linear from 0 to 150MPa, while the skewness curve keep this characteristic below 120MPa only. Distinct nonlinearity and scatter appears when the applied tensile stress above 120MPa for skewness curve.
- The scatter in the RMS curve becomes larger above 90MPa applied stress.

3.3 Effect of wall energy and pinning edge distance on skewness

In Figure 3, skewness presents its sensitivity and linearity to compressive stress below 75MPa, and then rises reversely with the applied compressive stress increasing up to 150MPa. The increase of domain wall energy, which has been mentioned in 3.1, can be used to explain the decrease of skewness with low compressive stress. However, it cannot explain the reverse increase of skewness when compressive stress is above 75MPa in this experiment. The same phenomenon has been presented in Beck's [11] study, where the effective damping reversed when the applied stress was above 50MPa.

To find an interpretation for these experimental results we consider a simple model that describes the Barkhausen effect in soft ferromagnetic materials on the basis of dynamics of a domain wall according the differential equation (2) [14]

$$m \frac{d^2 x}{dt^2} + \beta \frac{dx}{dt} + \alpha x = 2M_s H_0 e^{j\omega t} \quad (2)$$

where m is the effective mass of domain wall, β is a viscous damping parameter, α is spring constant, M_s is saturation magnetization, H_0 is amplitude of applied field, ω is angular frequency, and x is the domain wall displacement. Considering that domain wall velocity (dx/dt) is proportional to the recorded $v(t)$ and the mass of domain wall $m \rightarrow 0$, equation (2) can be solved. The relaxation frequency ω_0 is expressed as $\omega_0 = \alpha/\beta$. Taking into account a simple model that domain wall is pinned along two edges, the spring constant and domain wall energy are related by $\alpha = 18\sigma_w/d^2$. The relaxation frequency ω_0 is written

$$\omega_0 = 18\sigma_w/[d^2 \times \beta] \quad (3)$$

where σ_w is domain wall energy, and d is the distance between pinning edges [14, 15].

According to current models of damping mechanisms the main damping sources are associated to an eddy current effect β_E and spin relaxation β_R [16, 17]. Beck [11] has discussed that until a critical stress is attained, both the eddy current and spin relaxation contribute to the stress dependence of the domain wall damping. Above the critical stress, as the eddy current damping is stress independent, the main modification of the damping mechanisms is due to spin relaxation. The viscous damping is nearly proportional to applied stress. Our experimental results show that skewness decreases linearly with increase in compressive stress up to 75MPa. It is mainly due to the increasing of viscous damping under compressive stress. When the compressive stress increases above 75MPa, skewness increases, but is not proportional to the applied stress.

Compressive stress has been proved to impede the domain wall motion [5], in other words, it increases the pinning energy of DW. Considering the increase of wall energy, the distance between pinning edges and damping, they affect skewness of MBN shape. Experimental results indicate that the material has elastic deformation below 75MPa. Low applied compressive stress cannot change the distance between pinning edges much. However, this distance can decrease with the increase in the density of dislocations when the compressive stress is large enough [5]. In spite of the increase of viscous damping, from equation (3), we consider that the rise of the domain wall energy and reduction of the distance between the pinning edges can cause the domain wall relaxation frequency increases conversely. As a result, skewness presents its ambiguity when applied compressive stress is increasing above the value of 75MPa. In the same way, domain wall energy σ_w and pinning edge distance d make the characteristic relaxation frequency ω_0 decrease, and the same to skewness, when tensile stress is applied.

3.4 Excitation independence

The previous research has shown that normal features, such as RMS, Peak and others from MBN profile, are influenced by excitation parameters significantly. At low excitation frequencies, 2Hz, 5Hz and 10Hz, skewness of the MBN profile with sinusoidal and triangular excitations are presented in Figure 5.

Fig.5 Normalized skewness with different frequency and wave-shape excitation

Moreover, Figure 5 shows that skewness value of MBN shape is nearly independent to excitation frequency and wave-shape. As a 3rd order statistical parameter, skewness reflects variation of domain wall relaxation frequency, which is mainly decided by the material microstructure and modified by applied stress in this experiment. According to Zapperi's research [12] the relaxation time of a DW is about dozens of nanosecond, we believe that is why skewness is especially insensitive against excitation parameter influences at low frequency applied field.

4. CONCLUSION

In conclusion, this paper presents the result that skewness of the MBN distribution is affected by applied compressive and tensile stress on Q235 steel. Compared to RMS, the most popular feature to utilize MBN signal for stress measurement, skewness shows better sensitivity when the applied stress from -75MPa to +120MPa. The applied compressive stress decrease the peak of MBN signal, and delay the peak position of MBN profile synchronously. On the contrary, the applied tensile stress shifts the peak position to the opposite direction. By considering the definition of skewness, this 3rd statistic feature includes more information of the random process realization. Thus, better sensitivity of this indicator is acceptable.

Furthermore, this paper discusses the ambiguity phenomenon when compressive stress above 75MPa amplitude is applied. The same behavior were presented in Beck's research results. Further discussion based on domain wall energy and distance between pinning edges are carried out. These two factors are considered as the reason for the reverse increase of skewness curve when the applied compressive stress is higher than 75MPa for this kind of material.

Finally, different frequency and waveform excitations are used to estimate the effect of excitation parameters on skewness. Due to skewness has been proved mainly associated with the characteristic relaxation time, an inherent micro-magnetic property of material, the applied fields with different frequencies and waveforms can hardly alter skewness curve. Thus, skewness shows an insensitivity against excitation variation, especially in the low frequency range.

ACKNOWLEDGMENTS. This work is supported by FP7 "NDE and SHM for Health Monitoring of Offshore Wind Farm (HEMOW)" (FP7-PEOPLE-2010-IRSES) project, Jiangsu Graduate Student Innovation Found (CXLX11_0184).

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