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New feature extraction for applied stress detection on ferromagnetic material using magnetic Barkhausen noise

Song Ding [a,b,*], GuiYun Tian [c,a], V. Moorthy [d], Ping Wang [a]

[a] School of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China
[b] School of Automation and Electrical Engineering, Nanjing Tech University, Nanjing, Jiangsu 211816, China
[c] School of Electrical and Electronic Engineering, Merz Court, Newcastle University, Newcastle NE1 7RU, UK
[d] Design Unit, Stephenson Building, Newcastle University, Newcastle NE1 7RU, UK

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ABSTRACT

This paper reports on the new feature extraction for the determination of applied stress using magnetic Barkhausen noise (MBN). Low frequency triangular waveform excitation is used to produce alternative magnetic field on case-carburized and tempered En36 steel specimens. Under applied elastic stress, both of the compressive and tensile type, the MBN signal is measured and the profile of MBN signal is obtained. Effective damping in Barkhausen noise for asymmetric shape is studied with compressive and tensile applied stress characterization. Then the skewness of the MBN profile is presented as a new feature for stress detection. Non-linear behavior and sensitivity of the new feature are compared with root mean square (RMS) peak value and peak position. Domain wall energy and eddy current damping are discussed as the reason of the phenomenon.

1. Introduction

The magnetic Barkhausen noise (MBN) technique is a potential non-destructive evaluation method for the characterization and measurement of stress in ferromagnetic materials. Especially, it is presented as a new method to evaluate the micro residual stress (MRS) of IIIrd order in iron-based materials [1,2]. Micro magnetic structure not only decides the size and shape of domains but also dominates the kinematic characteristics of domain wall movement when the material is dynamically magnetized. The domain wall movement is influenced by the interaction between the magnetic structure and lattice defects like dislocations, grain boundaries, second phase precipitates and applied or residual stress (RS). In previous studies, features such as the peak value and the peak position of the root mean square (RMS) signal of the profile were extracted from the MBN signals and the MBN technique has been applied in many research areas [3–5].

Recent research on magnetic domains focused on nano-scale mechanisms and their potential future magnetic memory [6], logic devices [7] and domain wall dynamics including the eddy current damping effect [8,9]. For example, domain wall dynamics behavior corresponds to its relaxation time. Zapperi et al. [10] have studied domain wall characteristic relaxation and verified that it is a signature of negative effective mass of domain wall in ferromagnetic slice, which can be tracked by the skewness peak time of the shape of the MBN signal. It provides a relationship between the MBN signal and material relaxation time in micro-scale, which reflects domain wall dynamic behaviors in micromagnetics. Additionally, it is well known that domains are next to each other through magnetic domain walls in magnetic microstructure.

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* Corresponding author at: School of Automation and Electrical Engineering, Nanjing Tech University, Nanjing, Jiangsu 211816, China. Tel.: +86 13951898115.

E-mail address: dingsong@njtech.edu.cn (S. Ding).

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According to Ref. [11], the domain wall motion will be damped by the internal friction or specific damping induced by adjacent domains, micro eddy-current during magnetization process. Due to the relaxation time, a signature of negative effective mass of domain wall in ferromagnetic slice, the early response of the MBN signal illustrates the dynamic behaviors of domain walls [12]. Therefore, extending from the analysis in Ref. [10], the skewness of the MBN signal profile is proposed as a new feature for microstructure characterization, influenced by applied stress.

In this paper, the skewness is utilized as a new feature for applied stress detection and compared with RMS peak value and peak position, the most common features of MBN signal. Different levels of compressive and tensile applied stress are utilized to En36 steel specimens to evaluate the effectiveness of this new feature. Domain wall dynamic is discussed subsequently to explain how the wall energy and viscous damping affect relaxation frequency, which is the determinant of the skewness of MBN signal profile.

2. Experimental setup

The specimens used in this experiment are made of En36 steel, which is standard material in gear manufacturing. The chemical composition of En36 steel is illustrated in Table 1. The bar specimens (10 × 12 × 120 mm, $D \times W \times L$) in our study were carburized to 1 mm case-depth. The specimens were case-carburized at 935 °C for a target surface carbon content of 0.72% followed by slow cooling. Then the specimens were reheated up to 820 °C for 2 h followed by oil quenching and tempering at 175 °C for 2 h. The grain boundary oxidization layer near the surface has been removed by surface-grinding, which was managed to avoid grinding-burn and re-hardening.

A triangular waveform signal at low frequency of 0.2 Hz is amplified as excitation and drives a U-shaped magnetic yoke made of iron core. This electro-magnetic yoke generates an applied magnetic field with the maximum strength of 20 kA/m. A pick-up coil with ferrite core is placed on the center of the surface of the specimen to get the MBN signal. The MBN signal is amplified to a gain of 72 dB and filtered by a 1 kHz high-pass filter. The applied voltage and the MBN signal are acquired using two channels of a 12-bit ADC (Pico Technology-ADC-212). The long bar specimens were subjected to bending in a cantilever beam set-up with extended arm for loading. The MBN device is placed on the top surface of the specimens to measure the tensile applied stress effect and shifted to the bottom surface of the specimens to measure the compressive applied stress effect. For elastic deformation, the applied stress is calculated based on the standard bending moment equation and limited between −452 MPa and 452 MPa. The other parameters of the detection system are described in Ref. [13]. This is repeated for different applied stress value and the average of the MBN signal generated in four magnetization cycles are calculated.

Table 1
Composition (wt%) of the En36 steel used in this study.

C	Ni	Cr	Mn	Si	P	S	Fe
0.14	3.31	0.9	0.5	0.27	0.005	0.014	Bal.

3. Results and discussion

Figs. 1(a) and 1(b) show the RMS voltage of the average MBN signal as a function of the voltage applied to the electromagnet under different levels of applied stress. Peak 1 appears at lower applied voltage and peak 2 appears at higher applied voltage. It is reported in Ref. [13] that in case-hardened materials the magnetic soft core of the material can be easily magnetized at lower applied field strength, which produces the peak 1. While the hard surface of the specimen can be magnetized until the applied strength reaches to higher value, which results in the peak 2 [13]. The influence of applied elastic tensile and compressive stress on the MBN profile is obvious, both the MBN peaks increase with tensile applied stress and decrease with compressive applied stress. The RMS value decreases from 1250 mV to 670 mV as the applied compressive stress increases from 0 to 452 MPa (Fig. 1(a)). Conversely, the RMS value increases from 1250 mV to 2880 mV as the applied tensile stress increases from 0 to 452 MPa (Fig. 1(b)). Meanwhile, compressive stress shifts the peak 2 to the right side to higher magnetizing fields and tensile stress shift peak 2 to the left side. It means that higher voltage needs to be applied to the electromagnet to produce maximum Barkhausen noise emission from both the hardened and soft layer at greater compressive stress, while the Barkhausen noise emission reaches maximum value at lower applied voltage with increased tensile applied stress. In this experiment the peak 2 position of RMS profile shifts to the right side about 0.2 mV at compressive applied stress, while there is only 0.05 mV left-side shift of peak 2 position with tensile stress effect. The detailed variation of peak 1 and peak 2, including the peak value and relative position, has been discussed in previous studies [13].

It is well known that tensile applied stress can decrease the domain wall energy and compressive stress increases the energy, which not only alters the RMS peak value but also shifts the peak position, which indicates the field strength where 180° Bloch wall activity is the highest, i.e. in the vicinity of coercivity of this microstructure. As mentioned previously, in nanoscale, the skewness of the MBN signal shape of a single domain wall movement is influenced by damping mechanisms, include eddy current damping and structure damping, which can be modified by applied stress [8]. Nanoscale research has proved that the motion of a single domain wall only continues for several nanoseconds. However, the movement of the total of domain walls can continue for about 100 microseconds. The distribution of domain wall energy and eddy current damping are considered the major elements. Magnetization is a complex process of domain wall motion. Applied stress changes the status of grain boundaries, dislocations and other imperfections. The distribution of Barkhausen jumps and the eddy current interaction of