Investigation of Magnetic Barkhausen Noise and Dynamic Domain Wall Behavior for Stress Measurement

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Abstract. Magnetic Barkhausen Noise (MBN) is an effective non-destructive testing (NDT) technique for stress measurement of ferromagnetic material through dynamic magnetization. However, the fundamental physics of stress effect on the MBN signals are difficult to fully reveal without domain structures knowledge in micro-magnetics. This paper investigates the correlation and physical interpretation between the MBN signals and dynamic domain walls (DWs) behaviours of an electrical steel under applied tensile stresses range from 0 MPa to 94.2 MPa. Experimental studies are conducted to obtain the MBN signals and DWs texture images as well as B-H curves simultaneously using the MBN system and longitudinal Magneto-Optical Kerr Effect (MOKE) microscopy. The MBN envelope features are extracted and analysed with the differential permeability of B-H curves. The DWs texture characteristics and motion velocity are tracked by optical-flow algorithm. The correlation between MBN features and DWs velocity are discussed to bridge the gaps of macro and micro electromagnetic NDT for material properties and stress evaluation. Further studies for residual micro-stress measurement, local area DWs and grain-boundary influence, limitation of 2D surface domain imaging information and arbitrary location will be implemented in the future.

Keywords: Magnetic Barkhausen Noise (MBN), Domain wall motion, Magneto-Optical Kerr Effect (MOKE), stress measurement

1. Introduction

Different electromagnetic methods have been applied in non-destructive testing (NDT) for the characterization of material degradations [1-3]. Among of them, the magnetic Barkhausen noise (MBN) is an effective NDT technique for stress measurement of ferromagnetic object based on the dynamic magnetization processes [2-4]. When an alternating magnetic field is applied to ferromagnetic material, the MBN signals are observed due to sudden switching of magnetic domains at pinning sites [1]. The cycled magnetization processes induce stochastic fluctuations (B noise) originated from the random nature of
domain walls (DWs) dynamic movements, domain rotational processes of the magnetization vectors and the interactions with material microstructures [2] e.g. dislocation, grain boundary, phase shift and etc. The MBN signals are discontinuous changes in magnetization of ferromagnetic material which are strongly dependent on the macro point of magnetic hysteresis loops (B-H curves) and along with dynamic DWs behaviour in micro-magnetics. There have been widespread attempts in the past to describe the evident features of MBN signal for stress measurement. Jiles et al. [1] provided the mathematical description of dynamics of domain magnetization and Barkhausen effect for stress evaluation. Dobmann et al. [2] proposed a microstructure sensitive NDT techniques named micromagnetic multiparameter microstructure and stress analysis (3MA) for stress measurement. Wang et al. [3] extracted the features of average amplitude, root mean square (RMS), pulse count, the peak value ratio width at half maximum (PRW) from the MBN envelope for applied stress measurement. Ding et al. [4] investigated the skewness features of MBN profile to measure applied elastic stress and discuss the DWs energy influence. Kypris et al. [5] analysed the frequency spectrum of MBN for stress depth characterization. Vashista et al. [6] demonstrated the shape of MBN profile reveals the detailed microstructural information in magnetization process. Shu et al. [7] investigated the stress effect on the average volume of MBN jumps and magnetic DWs irreversible displacement. The macro-magnetic properties of ferromagnetic material are determined by its magnetic microstructures, which the domains observation is essential to know magnetization processes. To gain better understanding of how stress effect on MBN, its influence on magnetic microstructures should be considered. The correlations between MBN and domain structures are timely required to understand the physics of dynamic magnetization processes and electromagnetic NDT mechanism for material and stress characterization [8-10].

To observe the magnetic microstructures, the advances in magnetic microscopy are developed based on different physics e.g. the magneto-optical Kerr effect (MOKE), magnetic force microscopy (MFM), scanning electron microscope (SEM) and X-ray diffraction [11-13]. The domain observation by the MOKE is based on a weak dependence of optical constants on the direction of magnetization, which is suitable for domain dynamics visualization during magnetization process [12]. Richert et al. [14] conducted the dynamic magneto-optical imaging of domains and grain boundaries of an electrical steel assisted with magneto-optical indicator film (MOIF). Perevertov et al. [15-16] applied the MOKE to study tensile and residual stress influences on the domain structures variation and hysteresis curve. Qiu et al. [17] linked the hysteresis curve features and DWs dynamic behaviours together to discuss the tensile stress effect on the macro and micro magnetics responses using the MOKE system. Jue et al. [18] proposed a differential Kerr imaging method to measure the DWs velocity during magnetization process. However, there is little work to discuss the observed DWs dynamic behaviours link to the MBN signal features for the micro and macro magnetic physics interpretation and material stress characterization.

This paper investigates the correlation and physical interpretations between the MBN signals and dynamic DWs behaviour for stress measurement. The MBN signals, BH curves and domain textures of a grain-oriented electrical steel sample are simultaneously obtained in experiments using the MBN system and longitudinal MOKE microscopy. The correlation between the MBN features and dynamic DWs behaviours e.g. textures and motion velocity are discussed with BH curves for material properties and stress characterization. The rest of paper is organized as below. Section 2 introduces theory and methods of the MBN for stress measurement. Section 3 presents experimental studies including the test setup including the MBN device and MOKE microscopy system and a grain-oriented electrical steel sample. Section 4 demonstrates results and feature correlations between MBN envelopes, differential permeability of BH curves and DWs textures and motion velocities under applied field and tensile stresses. The conclusions and future works are derived in Section 5.
2. Theory and method

The MBN is an electromagnetic NDT method of considerable importance for magnetic microstructural and mechanical properties characterization of ferromagnetic object, e.g. the grain size, stress state evaluation. The fundamental physics of MBN is based on the Barkhausen jumps, which are discontinuous changes during magnetization processes which occur in ferromagnetic material under the time-varying magnetic field [1, 8]. The dynamic magnetization processes in ferromagnetic material is shown in Fig. 1. During the processes of alternating magnetization, the hysteresis loops is not smooth, but increases in random steps and the discontinuous irreversible jumps happen. The local magnetization changes give rise to electromagnetic noise signal received by the pick-up coil on the surface of test object, which is termed as the Barkhausen noise. Due to the sensitive to stress, MBN can be employed for the NDE of elastic and plastic deformation [2-4].

It has been accepted that the MBN is generated by the DWs dynamic movement, domain rotation of magnetization vectors at pinning sites and their interactions with material micro-structures [6, 9, 15]. In demagnetized state, the magnetization vectors of various domains are oriented that the object as a whole shows magnetization of zero. During magnetization process, the size of magnetic domains with directions parallel or nearly parallel to the external magnetizing field increase. In magnetization saturation state, the multi-domain state is convert into a single domain, which all domain directions are same as the external applied field. The DWs, e.g. 90° and 180° DWs, movement take place discontinuously because the DWs are temporarily pinned by microstructural obstacles like dislocation, precipitates, phase, grain-boundaries or stress in ferromagnetic material [9, 16]. The macroscopic magnetic properties e.g. hysteresis loops, MBN, depend on the magnetic microstructural behaviours e.g. DWs movements and their interactions with material microstructure and stress state [12].

3. Experimental setup and sample

To analyse the correlation and physics between MBN and dynamic DWs behaviours of ferromagnetic object for stress measurement, experimental studies are conducted to measure the MBN signals and observe the dynamic DWs textures simultaneously. A grain-oriented electrical steel (GOES) sheet produced by the Kawasaki Japan with the specification of 23Z110 is employed as test sample, which includes a silicon level of 3% by mass. The grain size of this sample is range from 5mm~10mm. It has a coating film applied on the surface of sample, which has the size of $0.200 \times 0.200 \times 0.23$ mm.

Fig. 2 shows a scheme of the experimental setup for the domain observation via the longitudinal MOKE microscopy assisted with MOIF and the MBN measurement under applied tensile stresses. The tensile stresses range from 0 MPa to 94.2 MPa were applied on
the sample along the rolling direction \([0 0 1]\). An alternating magnetic field \(H\) up to 300 A/m was applied to sample using two solenoid driving coils of 355 turns accompany with a yoke. The excitation was a sinusoidal waveform with the frequency of 0.4 Hz. The pick-up coil with 363 turns was to measure magnetic flux variation inside the sample for calculation of the hysteresis loops (B-H curves). A MBN probe with a cylinder coil of 5000 turns are placed on the sample surface around domain observation area to measure the MBN signals simultaneously. The domain textures and dynamic DWs behaviours of sample were observed by a longitudinal MOKE microscopy assisted with MOIF under the condition without removing sample surface coating layer. The domain texture images are acquired by a high speed CCD camera with the frame 16/s during dynamic magnetic processes under applied magnetic field and stress loading.

![Fig. 2. Schematic diagram of the experimental setup for the domain observation via the longitudinal MOKE microscopy assisted with MOIF and the MBN measurement under applied tensile stresses](image)

4. Results and analysis

The MBN signals of the employed GOES sample have been measured simultaneously with domain textures observation through the MOKE assisted with MOIF imaging under different tensile stresses. The characteristics of MBN signals and features, e.g. envelope, root mean square (RMS), are extracted and analysed with magnetization curve (BH curve) information, e.g. differential permeability. Dynamic DWs textures and velocity features in micro-magnetics are extracted for stress effect discussion and correlation with the MBN and BH curve in macroscopic of magnetic properties.

4.1 MBN and features against tensile stresses

To investigate the MBN characteristics under different tensile stresses, the MBN signals of the electrical steel sample under 0 MPa, 21.7 MPa and 65.2 MPa are illustrated in Fig. 3 (a-c) with the hysteresis loops (BH curve) in Fig. 3(d). It can be seen that the MBN signal is separated into two parts under tensile stresses 21.7 MPa and 65.2 MPa in contrast to the 0 MPa as shown in Fig. 3(a-c). The duration of MBN noise and the distance between two parts noises are increasing against the tensile stress increase. Compared with the BH curve without stress, there are obvious curve changes under tensile stresses in Stage-2 magnetization process with the applied magnetic field range from about \(\pm 50\) A/m. The slopes of BH curve with 21.7 MPa and 65.2 MPa in Stage-2 seems nearly to be constant or linear trend which are corresponding to the MBN signal variation that there is no obvious noise generated during this stage. This stress effect on the MBN signals and BH curve is also related to the sample material properties e.g. the grain-oriented characteristics and domain textures behaviours.
In order to measure tensile stress and find specific correlation between MBN signals and magnetization curves, the envelopes of MBN signals are extracted as well as the features [3] of RMS, average amplitude (AVE), ring number (ZL, Barkhausen jumps number) and maximum amplitude (YMAX) as shown in Fig. 4(a-b). The differential permeability of ascending BH curve is also calculated together with its features extraction of peak value and $\Delta H$ value as shown in Fig. 4(c-d). It can be seen that the distance between two peak point of envelopes under 21.7 MPa and 65.2 MPa is increasing as well as the peak amplitudes as shown in Fig. 4(a). The MBN features e.g. RMS, AVE and YMAX are going up in opposition to ZL feature against tensile stress increase as shown in Fig 4(b). However, the differential permeability amplitudes e.g. peak value is decrease and two peak values appear with the $\Delta H$ value increase against tensile stress loading increase as shown in Fig. 4(c-d). The envelopes of MBN and differential permeability of ascending BH curve reflect the magnetization process and their dynamic variation characteristics under tensile stress loading, which can be interpreted based on the domain textures and dynamic behaviours observation.

4.2 Dynamic DWs textures and velocity against tensile stresses

To understand how the tensile stress influence MBN signals and BH curves, the domain textures during dynamic magnetization process are observed simultaneously using the MOKE microscopy assisted with MOIF. Fig. 5 demonstrates the domain textures of sample under different stresses with the applied magnetic field at 60 A/m after subtracting domain image in saturation state. It can be seen the image grey level, which denotes the domain magnetization vectors [12], is increasing against tensile stress going up. Additionally, the width of DWs is decreasing in opposition with the number of DWs increasing against the
increase of tensile stress. It demonstrates the stress effect on the domain magnetization vectors, size and numbers in magnetic microstructures, which are also reflected in macro-magnetics.

![Fig. 5. Domain textures against different tensile stresses](image)

To understand the dynamic magnetization process under tensile stresses, domain motion behaviour e.g. DWs velocity is a critical factor which is promising to be correlated with the macro-magnetics e.g. MBN and BH curve responses. Fig. 6(a) shows the domain texture under the stress 65.2 MPa and applied field at 60 A/m as well as the DWs velocity distribution extracted from adjacent domain image using optical-flow (OF) algorithm [17, 18] as shown in Fig. 6(b). It is obviously that the DWs velocities in different local areas are different, in particular the area around grain boundary. The DWs motion velocity is higher in the local region close to grain boundary and the right side area of it with big size domains than the left side area of it with small size domain. After calculating the integral value of DWs velocity images in the whole magnetization process, the DWs motion velocity against the applied magnetic field under tensile stresses 0MPa, 21.7 MPa and 65.2 MPa is shown in Fig. 6(c). It shows that DWs velocity curve also appear two peak points with tensile stress going up in contrast to the curve without stress. This behaviour of DWs velocity is well corresponding to MBN and BH curves with differential permeability characteristics in Fig 4.

![Fig. 6. Domain walls motion velocity against different tensile stresses](image)

5. Conclusions and future works

This paper investigates the correlation and physics interpretation of MBN signals and dynamic DWs behaviours of an electrical steel sample under applied tensile stresses. The MBN signals and BH curves have been measure simultaneously with domain textures observation through the MOKE assisted with MOIF imaging during magnetization process. The characteristics of MBN signals and features e.g. envelope are extracted and analysed with BH curves information e.g. differential permeability. Dynamic DWs textures and velocity features in micro-magnetics are extracted for stress effect discussion and correlation with the MBN and BH curve in macroscopic of magnetic properties. It demonstrates the well corresponding relationship of MBN signal, BH curve features and DWs dynamic behaviours in particular the DWs motion velocity characteristics. It also provides potential research impact on the local residual micro-stress, local area DWs and grain-boundary influence characterization in the future as well as the linkage with MBN signal spectrum analysis for
stress depth evaluation. The limitations of 2D surface domain imaging information, arbitrary local information and the repeatability of dynamic magnetization process are also will be discussed in the future works.

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