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Characterization of applied tensile stress using domain wall dynamic behavior of grain-oriented electrical steel

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ABSTRACT

Stress measurement that provides early indication of stress status has become increasingly demanding in the field of Non-destructive testing and evaluation (NDT&E). Bridging the correlation between micro magnetic properties and the applied tensile stress is the first conceptual step to come up with a new method of non-destructive testing. This study investigates the characterization of applied tensile stress with in-situ magnetic domain imaging and their dynamic behaviors by using magneto-optical Kerr effect (MOKE) microscopy assisted with magneto-optical indicator film (MOIF). Threshold magnetic field (TMF) feature to reflect 180° domain wall (DW) characteristics behaviors in different grains is proposed for stress detection. It is verified that TMF is a threshold feature with better sensitivity and brings linear correlation for stress characterization in comparison to classical coercive field, remanent magnetization, hysteresis loss and permeability parameters. The results indicate that 180° DWs dynamic in the inner grain is highly correlated with stress. The DW dynamics of turn over (TO) tests for different grains is studied to illustrate the repeatability of TMF. Experimental tests of high permeability grain oriented (HGO) electrical steels under stress loading have been conducted to verify this study.

1. Introduction

Different electromagnetic non-destructive testing and evaluation (NDT&E) methods including integration of macro and micro magnetics have been applied for stress characterization [1–5]. Magnetic hysteresis loop technique is one of the typical macroscopic NDT&E methods to characterize the stress in ferromagnetic test object [1,2,6]. The correlation between mechanical stress and the major/minor hysteresis loop has been widely studied by many researchers [6,7]. The features extracted from magnetic hysteresis loops e.g. the coercive field, remanent magnetization and hysteresis loss have been conducted to characterize stress status of ferromagnetic object [6,8,9]. Dobmann [10] applied the 3MA methods to characterize the applied and residual stress of steel through multi-parameters of macroscopic magnetic detection signals. However, the macro B-H curves reflecting the average magnetic response in different areas has a low spatial resolution for stress assessment. Moreover, classical magnetic properties (e.g. coercivity, remanent magnetization, hysteresis loss, permeability) from global B-H loops are unable to detect small stress variation because of relative low sensitivity and non-linearity.

Due to the progress in magnetic microstructure observation techniques, dynamic characteristic of domain wall (DW) is becoming a topic of interest not only due to its potential applications to magnetic memory, logic devices and soft magnetic materials [11–14], but also because of the fascinating future for the high spatial resolution [8,9,15,16] measurement of stress in ferromagnetic materials. Perevertov et al. [8,9] revealed that the tensile stress removed the closure domains of grain oriented Fe-3%Si steel. Klimczyk et al. [17] reported that cutting stress induced the creation of a surface magnetic domain stress pattern. Batista et al. [18,19] studied DW interactions with cementite precipitate along with macro magnetic responses. The above researches of DW dynamic behavior are confined in the discussion of qualitative analysis. However, the quantitative analyses are essential for stress measurement. Qiu et al. [15] and Gao et al. [16] employed DW motion velocity feature to evaluate the tensile stress in electrical steel. Threshold based magnetic/current field features are widely used for the investigation of DW propagation characteristics under pinning condition [11–14,20]. It is verified that the threshold field value has linear relationship with pinning potential [11,13,21]. This work extends threshold field feature for stress evaluation.

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Grain-oriented electrical steels are extensively used in industry e.g. electrical transformers and motors. During production, an insulating surface coating are applied on the electrical steel to prevent corrosion, avoid planar eddy currents and reduce magnetic loss [22,23], and it is easy to induce beneficial stress and residual stress in the object. Residual stress with applied beneficial loading has a strong influence on DW movement [23]. To evaluate the stress in the electrical steel, in-situ inspection of magnetic microstructure and their correlation with stress status is timely required. However, the samples preparation e.g. polishing process is a critical issue for magnetic microstructure observation technique. Both bulk magnetic properties and magnetic microstructure are sensitive to insulating surface coating on the electrical steel [22–24]. This limits in-situ measurement of magnetic domain. Richert et al. [25] proposed an approach for direct domain texture observation by using magneto-optical Kerr effect (MOKE) microscopy with the help of magneto-optical indicator film (MOIF). This paper extends the method for stress characterization. The 180° DWs behaviors of a coated grain-oriented electrical steel under different levels of tensile stress along the [001] direction are measured. The relationship between the behaviors of magnetic dynamic domains and applied tensile stress is investigated. Specifically, surface hysteresis loops considering the 180° DW motion are reported for stress assessment. Threshold magnetic field (TMF), where all 180° DW propagation is finished, is measured under different levels of stress. It is verified that the TMF feature has better sensitivity and linearity for stress evaluation.

This paper is organized as follows: Section 2 introduces the magnetic microstructure observation using the hybrid MOKE with MOIF for the grain boundary (GB) and magnetic domain observation. Section 3 reports experimental results analysis including dynamic 180° DW behaviors, TMF feature and B-H curve for stress evaluation. Finally, the conclusions and future work are given in Section 4.

2. Methodology

2.1. Hybrid MOKE with MOIF for microstructure observation

MOKE with assistance of MOIF technique is an indirect imaging method based on the magneto-optical Faraday Effect for the visualization of magnetic stray fields and domains of magnetic materials [25,26]. The magneto-optical Faraday Effect is an interaction between polarized light and a transparent magneto-optical garnet film [26–28], which causes a rotation of the plane of polarization in correspondence with the magnetic field strength. The film with out-of-plane anisotropy has an easy axis of magnetization normal to the sensor surface to make them sensitive to vertical magnetic fields. The magnetic domain structure of the MOIF without magnetic field in the space is shown in Fig. 1(a). It suggests that the total area of light and dark domains is equal. This can be sketched in Fig. 1(b). When the MOIF is placed onto the surface of magnetic materials, there has to be a small out of plane component of magnetization in the materials that causes surface poles and thus emerging a stray field [25,29] as shown in Fig. 2(a). Then the

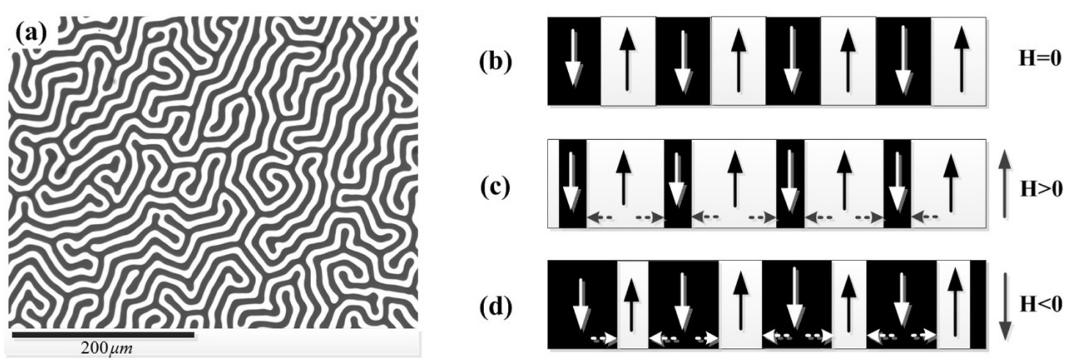

Fig. 1. (a) Magnetic domain pattern of the magneto-optical garnet film, imaged by Faraday microscopy in a polarizing microscopy; Lateral schematic of domains (b) without magnetic field; (c) with a upward magnetic field; (d) with a downward magnetic field.

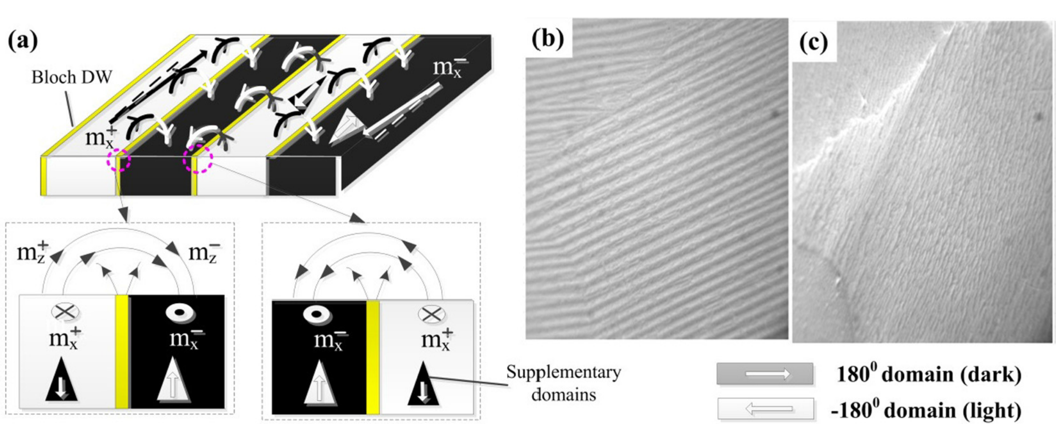

Fig. 2. (a) Magnetic stray field caused by the surface poles generating from a small out of plane component of magnetization [29], where the m_x and m_z are in-plane and out-of-plane magnetization components, respectively; (b) Magnetic domains of high permeability grain-oriented (HGO) electrical steel in demagnetized state; (c) GB profile of HGO at a magnetic field of 880 A m^{-1} where the dimension of the domain pattern picture is 16.19 mm × 10.78 mm.