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Phase field simulations on domain switching-induced toughening in ferromagnetic materials

Yinuo Shi [a], Hongjun Yu [b], Takahiro Shimada [c], Jie Wang [a, d, *], Takayuki Kitamura [c]

[a] Department of Engineering Mechanics, School of Aeronautics and Astronautics, Zhejiang University, 38 Zheda Road, Hangzhou 310007, China
[b] Department of Astronautic Science and Mechanics, School of Aeronautics and Astronautics, Harbin Institute of Technology, Harbin 150001, China
[c] Department of Mechanical Engineering and Science, Kyoto University, Nishikyo-ku, Kyoto 615-8540, Japan
[d] Key Laboratory of Soft Machines and Smart Devices of Zhejiang Province, Zhejiang University, 38 Zheda Road, Hangzhou 310007, China

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A B S T R A C T

A real-space phase field model is employed to investigate the domain switching-induced shielding or anti-shielding of a crack in ferromagnetic materials with single and multi-domain states. Phase field simulations demonstrate that magnetization switching takes place from the crack tip due to the highly concentrated stress in a ferromagnetic thin plate with a stationary crack. Based on the stress obtained from phase field simulations, the crack-tip stress intensity factors (SIFs) are calculated by linear extrapolation in the ferromagnetic thin plate subjected to different values of mechanical loads. The calculation results indicate that domain switching decreases the crack-tip stress intensity factors, resulting in domain-switching toughening in ferromagnetic materials. Furthermore, the domain switching in the multi-domain ferromagnetic plate induces a much larger decrease of stress intensity factor than that in the single-domain one, which suggests that engineering magnetic domains leads to the design of tougher ferromagnetic materials.

1. Introduction

Ferromagnetic materials, such as FeGa and NiMnGa, have received considerable attention due to their unusual physical properties and wide applications for actuators, sensors and memory devices (Andriamandroso et al., 1984; Nakano et al., 2011; Park and Min, 2010). However, defects such as voids and cracks are unavoidable in the ferromagnetic materials during fabrication and application (Soh et al., 2004; Xiong and Liu, 2007). The highly concentrated stress and magnetic fields near the crack tip may induce unusual behaviors of ferromagnetic materials (Rahm, 2004; Wan et al., 2003; Yoshimura et al., 2004). Extremely nonlinear behaviors, such as magnetization switching or magnetic yielding (Avakian and Ricoeur, 2016, 2017; Soh et al., 2004), may exhibit near the crack tip, which will influence the functionality of the materials. Therefore, a deep understanding of the magnetoelastic nonlinear behaviors near the crack tip in a ferromagnetic material is necessary for the practical application of ferromagnetic materials.

In the presence of defects, ferromagnetic materials are susceptible to cracking at all scales, ranging from magnetic domains to devices. Cracking may result in critical failure and malfunction of ferromagnetic devices through the propagation of cracks (Fang et al., 2008). The fracture behavior of ferromagnetic material is complicated because of the coupling between the mechanical and magnetic fields in the materials. Most of previous studies on magneto-elastic problem are based on linear theoretical models (Bagdasarian and Hasanian, 2000; Chen, 2009; Fang et al., 2004, 2008; Shindo, 1977; Yoshimura et al., 2004). However, the distributions of stress and magnetization derived from linear theories are not satisfied with the experiment results very well. Although the nonlinear models such as strip electric-magnetic breakdown model (Zhao and Fan, 2008) and small scale magnetic yielding (Soh et al., 2004) has been proposed to investigate the facture of ferromagnetic materials, the magnetic domain switching around a crack tip and its influence on the fracture of the materials has not been investigated in the literature.

Domain switching near the crack tip of ferromagnetic materials can be described as the evolution of magnetic domain structure under concentrated stress and/or magnetic field, in which the long-

* Corresponding author. Department of Engineering Mechanics, School of Aeronautics and Astronautics, Zhejiang University, 38 Zheda Road, Hangzhou 310007, China.

E-mail address: jw@zju.edu.cn (J. Wang).

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range elastic and magnetic interactions between different domains play an important role (James and Wuttig, 1998; Kittel, 1946). It is difficult to get an analytical solution to the magneto-elastic problem when an arbitrary domain structure is considered during the evolution. Therefore, different numerical models have been proposed to investigate the domain evolution in ferromagnetic materials. For example, the micromagnetic model proposed by Brown (Brown, 1966) is the most widely-used model in traditional numerical simulation of ferromagnetic materials. It successfully predicts the domain structure (Schrefl and Fidler, 1996; Williams et al., 1989) and its evolution (Chunsheng et al., 2008; Shir, 1978) in ferromagnetic materials subjected to an external magnetic field. However, most of the micromagnetic simulations do not explicitly include the effect of inhomogeneous stress on domain evolution, which predominates mechanical and magnetic behavior of giant magnetostrictive materials. In recent years, phase field models based on the Landau-Lifshitz-Gilbert (LLG) and time-dependent Ginzburg-Landau (TDGL) equations have been proposed (Wang and Zhang, 2013; Yi and Xu, 2014; Zhang et al., 2016; Zhang and Chen, 2005) to investigate the domain evolution in ferromagnetic materials, in which the effect of inhomogeneous stress is considered. The phase field models with inhomogeneous stress successfully give the quantitative prediction of the nonlinear magneto-elastic coupling problem, such as the magnetization reverse (Li et al., 2014) under mechanical loads. The domain switching around a crack tip in ferromagnetic materials is analogous to that of ferroelectric materials (Ricoeur and Kuna, 2003; Wippler et al., 2004). Various phase field models have been employed to simulate the ferroelectric domain switching near a crack tip of ferroelectric materials, which successfully predict the domain switching-induced toughening for ferroelectric materials (Van Lich et al., 2015; Wang and Zhang, 2007). Therefore, it is expected that the phase field model is an effective method to investigate the domain switching around a crack tip and its influence on the fracture behavior of ferromagnetic materials.

In the present study, we firstly employ a real-space finite-element-based phase filed model to simulate the magneto-elastic behavior of a ferromagnetic FeGa thin plate with a stationary semipermeable crack. The domain evolution under the external stress was predicted by phase filed simulation. Secondly, based on the stress and magnetic field from phase field simulations, the crack-tip stress intensity factors (SIFs) are calculated by linear extrapolation in the ferromagnetic thin plate subjected to different values of mechanical loads. The calculated crack-tip SIFs suggest that domain switching decreases the crack-tip SIFs, resulting in domain switching-induced toughening in the ferromagnetic materials.

2. Phase field model

In recent years, phase field models has been widely used to predict the domain evolution of ferroelectric and ferromagnetic materials in the literature (Balakrishna et al., 2016; Kontsos and Landis, 2010; Schrade et al., 2015; Wang and Zhang, 2013; Yi et al., 2015). One of the real-space phase field models of ferromagnetic materials is based on the Ginzburg–Landau theory (Wang and Zhang, 2013), which is employed to predict the domain switching around a crack tip in the present work. For the convenience to readers, we briefly introduce the phase field model (Wang and Zhang, 2013) in this section. The magnetization vector $M=(M_1,M_2,M_3,t)$ is chosen as the order parameter in the phase-field model. According to the fundamental thermodynamics, the domain structures are determined by the competition between different energies of the materials. The total free energy density of the ferromagnetic material can be described by

$$E=E_{anis}+E_{exch}+\ E_{elas}+\ E_{mag}+E_{cons}, \tag{1}$$

where $E_{\rm anis}, E_{exch}, E_{elas}, E_{mag}$ and E_{cons} denote the magnetocrystalline anisotropy energy density, the exchange energy density, the elastic energy density, the magnetostatic energy density and the constrain energy density, respectively.

The magnetocrystalline anisotropy energy density is related to the crystal structure. The form of magnetocrystalline anisotropy energy density for cubic crystal can be described by

$$E_{anis}=\frac{K_1}{M_s^4}\left(M_1^2M_2^2+M_1^2M_3^2+M_2^2M_3^2\right)+\frac{K_2}{M_s^6}\left(M_1^2M_2^2M_3^2\right), \tag{2}$$

where K_1 and K_2 are the anisotropy constants, M_i are the components of the magnetization, and M_s is the magnitude of the saturation magnetization.

The exchange energy density, which describes the exchange coupling energy in ferromagnetic, can be written as

$$E_{exch}=\frac{A}{M_s^2}\left(M_{1,1}^2+M_{1,2}^2+M_{1,3}^2+M_{2,1}^2+M_{2,2}^2+M_{2,3}^2+M_{3,1}^2 + M_{3,2}^2+M_{3,3}^2\right), \tag{3}$$

where A is the exchange stiffness constant, and $M_{i,j}=\partial M_i/\partial x_j$ denotes the components of derivative of the magnetization vector M_i with respect to x_j.

The elastic energy density contains the pure elastic energy density and interaction between magnetization and strain. It can be expressed as

$$\begin{aligned}E_{elas}=E_{pure}+E_{cou}=&\frac{1}{2}c_{11}\left(\varepsilon_{11}^2+\varepsilon_{22}^2+\varepsilon_{33}^2\right)+c_{12}(\varepsilon_{11}\varepsilon_{22}+\varepsilon_{11}\varepsilon_{33}\\&+\varepsilon_{22}\varepsilon_{33})+2c_{44}\left(\varepsilon_{12}^2+\varepsilon_{13}^2+\varepsilon_{23}^2\right)-\frac{3\lambda_{100}}{2M_S^2}(c_{11}-c_{12})\\&\left(\varepsilon_{11}M_1^2+\varepsilon_{22}M_2^2+\varepsilon_{33}M_3^2\right)-\frac{6\lambda_{111}}{M_S^2}c_{44}(\varepsilon_{12}M_1M_2\\&+\varepsilon_{13}M_1M_3+\varepsilon_{23}M_2M_3),\end{aligned} \tag{4}$$

where c_{11}, c_{12}, and c_{44} are the elastic constants, and ε_{ij} is the elastic strain, λ_{100} and λ_{111} are the magnetostrictive constants of cubic crystal.

The magnetostatic energy density can be expressed as

$$E_{mag}=-\frac{\mu_0}{2}\left(H_1^2+H_2^2+H_3^2\right)-\mu_0(H_1M_1+H_2M_2+H_3M_3), \tag{5}$$

where H_i is the magnetic field in materials, and μ_0 is the permeability of a vacuum.

In addition, to make sure the magnetization is satisfied Heisenberg-Weiss constraint, i.e. the magnitude of magnetization $\sqrt{M_1^2+M_2^2+M_3^2}=M_s$ almost everywhere in the system, we adopt the following energy density to enforce the restriction (Landis, 2008)

$$E_{cons}=A_s(M-M_s)^2, \tag{6}$$

where $M=\sqrt{M_1^2+M_2^2+M_3^2}$ is the magnitude of magnetization and A_s is the constraint energy constant, which can be calculated by the relative permeability $\chi_{\rm m}$ of material, $A_s=(1+\chi_m)/2\chi_m$.