

A MAGNETO-MECHANICAL FULLY COUPLED MODEL FOR GIANT MAGNETOSTRICTION IN HIGH TEMPERATURE SUPERCONDUCTOR[★]



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ABSTRACT This paper presents a fully coupled model to account for the flux pinning induced giant magnetostriction in type-II superconductors under alternating magnetic field. The superconductor E-J constitutive law is characterized by power law where the critical current density is assumed to depend exponentially on the flux density. The governing equations of the two-field problem (i.e., the interactions of elastic and magnetic effects) are formulated in a two-dimensional model. The magnetostriction curves and magnetization loops are calculated over a wide range of parameters. The effects of applied magnetic field frequency f and amplitude B_0 and critical current density on magnetostriction and magnetization are discussed. Results show that the critical current density of high temperature superconductor (HTS) YBCO has a significant effect on the magnetization and magnetostriction. The pinning-induced magnetostriction which has been observed in experiment can be qualitatively simulated by this model.

KEY WORDS high temperature superconductor (HTS), giant magnetostriction, magnetization, magneto-mechanical couple, alternating magnetic field

I. INTRODUCTION

High temperature superconductors (HTS) have been widely used in recent years owing to their excellent properties. For instance, HTS can generate large magnetic fields, which is very attractive to a variety of applications, such as motors, permanent magnets etc.^[1]. Bulk type II superconductors can trap high magnetic fields that are generated by superconducting persistent currents circulating macroscopically within the superconductor^[2]. HTS also manifests a phenomenon observed as giant magnetostriction which couples elastic, electric, magnetic field and in some cases, thermal fields^[3,4]. Research on the magnetostriction mechanism was generally based on the flux-pinning in the superconductor. A flux-pinning-induced magnetostriction model was firstly described by Ikuta et al.^[3,4]. Çelebi and Inanir^[5,6] reported normal-state contribution to the pinning induced magnetostriction. Johansen^[7-9] analyzed theoretically the electromagnetic force arising from flux pinning on superconductor. The mechanical stress caused by flux pinning on superconductor is investigated theoretically by Johansen and Yong^[10,11]. The stress distributions were evaluated analytically by Ren et al.^[12] and Johansen^[13] through a single

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flux-pinning-induced magnetostriction model. Yong and Zhou quantitatively illustrated the effects of coupling parameters on the magnetostriction and magnetization^[14].

Numerical simulation is playing an ever increasing role in design and optimization of HTS machines. Recent progress in this field provides the possibility of using numerical tools to tackle such engineering problems as the fracture problem in HTS magnetization^[15–17] and the AC loss in superconducting coated conductors^[18]. An accurate solution of such problems often requires a realistic modeling of the complex couplings between different real magneto-thermo-mechanical behaviors of HTS. In electromagnetic devices, the magnetic materials are subject to elastic deformation under the action of magnetic force. Inversely, the magnetic fields and their force distributions are more or less influenced by the deformation. Therefore, a study of such interaction requires simultaneous consideration of both magnetic and mechanical fields^[19]. This work develops a quantitative model based on the coupled magneto-mechanical analysis of HTS. Ultimately, this work aims to illustrate how some of these couplings, viz. the elastic strains of magnetic origin can be taken into account in the coupled magneto-elastic analysis of HTS. The coupled method is based on a set of partial differential equations in which the magnetic field is used as a state variable.

The paper is organized as follows. The basic equations of the coupled magneto-mechanical analysis while the electromagnetic force will be reviewed in §II. Discussion of the qualitative features of obtained results will be given in §III. The conclusions of this research will be presented in §IV.

II. THE GOVERNING EQUATIONS

2.1. The Electromagnetic Governing Equations

In this paper, the pinning-induced magnetostriction is calculated for a YBCO specimen with infinite length in the z -direction which is normal to the plane of the x - y as shown in Fig.1. The problem is thus simplified into a two-dimensional case with the demagnetization effect ignored.

The macroscopic electromagnetic phenomena in superconducting materials are described by Maxwell's equations, a set of equations stating the relationship between the fundamental electromagnetic quantities. The governing equation of electromagnetic phenomena is generally one of the four Maxwell's equations which can be written, in their most general form, as

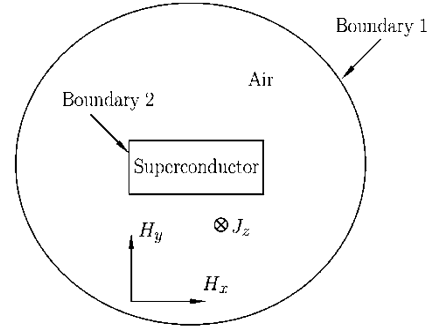


Fig. 1 Illustration of the 2D configuration of subdomains and boundaries.

$$\text{Faraday's law : } \nabla \times \mathbf{E} = -\mu_0 \mu_r \frac{\partial \mathbf{H}}{\partial t} \quad (1)$$

$$\text{Ampere's law : } \nabla \times \mathbf{H} = \mathbf{J} \quad (2)$$

$$\text{Gauss's law : } \nabla \cdot \mathbf{D} = q \quad (3)$$

$$\text{Gauss's law for magnetism : } \nabla \cdot \mathbf{B} = 0 \quad (4)$$

where $\mathbf{E}$ is the electric field intensity vector, $\mathbf{D}$ is the electric displacement or electric flux density, $\mathbf{H}$ is the magnetic field intensity, $\mathbf{B}$ is the magnetic flux density, $\mathbf{J}$ is the current density, and q is the electric charge density.

The electrical behavior of the superconducting material is modeled by the E-J power law since the exponential model is most suitable for describing the measured magnetostriction:

$$E_{sc-z} = E_0 \left(\frac{J_{sc-z}}{J_c(B)} \right)^n \quad (5)$$

where J_c is the critical current density. $E_0 = 1 \times 10^{-4} \text{ Vm}^{-1}$ and $n = 21$ are typical values for type-II superconductor^[20]. J_c is field dependent,

$$J_c(B) = \frac{J_{c0} \cdot B_0}{B_0 + B} \quad (6)$$

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