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Deformation and fracture of electromagnetic thin films and laminates under multi-field loading

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Abstract

The deformation and fracture behaviors of magnetoelectric materials under mechanical loading are affected considerably by an external electric or magnetic field. To provide a deep understanding of the intrinsic coupling properties, several macro/micro-nano multi-field instruments have been designed and constructed, including an electro-magneto-mechanical nanoindentation apparatus and a multi-field bulge-test instrument. With these instruments, several new experimental results have been observed, such as multi-field indentation scaling relationship and magnetic field control of 180° ferroelectric domain switching for magnetoelectric laminates. Furthermore, an electro-magneto-mechanical coupling model considering the effects of surface stress and a finite element based real-space phase field model are developed, which provide reference for structure design of magnetoelectric intelligent device at small scale.

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Keywords: Deformation; fracture; multi-field loading; electromagnetic thin films; laminates;

1. Introduction

Electromagnetic functional materials, such as ferroelectrics, ferromagnetics and magnetoelectric thin films and composite laminates, have been widely used in sensors, transducers, microwave devices, and other novel multifunctional devices [1], owing to their excellent multi-field coupling properties and quick responses. For decades, the conventional single-phase electromagnetic materials such as the bulk piezoelectric materials and ferroelectric/ferromagnetic materials have been studied comprehensively and thoroughly. These researches include the multi-field coupling experiments [2,3], the constitutive theories [4] and the multi-scale calculation

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methods [5]. However, higher practical requirements have been put forward to electromagnetic functional materials due to the development of modern industry, which means these requirements can not be satisfied by the conventional single phase materials [6]. Thus the magnetoelectric (ME) materials become the promising materials to meet the demand of the current application.

Multiferroic magnetoelectric materials have more complicated structure than traditional ferroelectric/ferromagnetic materials. They not only exhibit ferroelectric and ferromagnetic properties, but also present magnetoelectric coupling effect (ME effect) [7]. For instance, the external magnetic field can induce polarization and in turn the external electric field can induce magnetization. For macro magnetoelectric materials, ME effects arise from elastic coupling between the two constituent phases, including 0-3 particulate composites [8], 1-3 fiber-array composites [9], and 2-2 laminate composites [10]. Recentlly the layered laminate composites have attract considerable interest for its higher magnetoelectric coupling coefficient [11]and better application prospect. Strain transfer through the interface is the major mechanism for the laminates. However, the strain transfer efficiency and the failure of the interface greatly affect the magnetoelectric coupling properties [12].

Extensive studies [13-16] have been reported from the perspective of material preparation, structural design, theoretical prediction of magnetoelectric coefficient, nonliear magnetoelectric response and microwave magnetoelectric coupling effect, etc. Nevertheless, there are still several important scientific problems to be solved, such as researches of the multi-field coupling mechanical behaviors including modulus and hardness, the failure and fracture. Therefore, it is of vital significance to develop multi-field coupling instruments to test and characterize the mechanical properties of multiferroic materials under electric and magnetic fields, which are also meaningful for the design of devices and the quality assessment of new products.

2. Development of multi-field coupling instrument

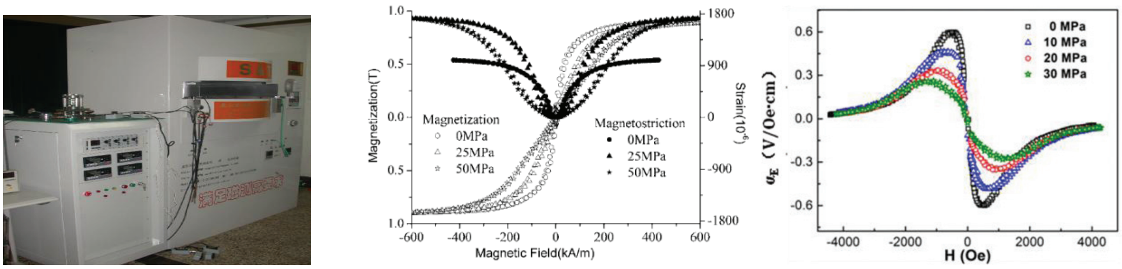

Fig. 1. (a) Photograph of the multi-field coupling device; (b) Static measurements under magneto-mechanical loading; (c) Dynamic measurement of ME coefficient under different stresses.

Various experimental instruments [17-19] have been reported to test electromagnetic materials under multi-field coupling conditions. However, Most of them focus on the static measurements of mechanical behaviors under either uniaxial electro-mechanical or magneto-mechanical loading, and are mainly aimed at single-phase ferroelectric or ferromagnetic materials. In order to investigate the static and dynamic mechanical behaviors of layered magnetoelectric composites under multiaxial electro-magneto-mechanical fully-coupled loadings, a macroscopic magneto-electro-mechanical coupling apparatus has been constructed [20]. The apparatus combines a hydraulically driven mechanical loading system with a dipole electromagnet, which is capable of producing mechanical forces up to 2000 kg and magnetic fields up to 2.4 T with a pole gap of 100 mm. Cyclic silicone oil bath is used to heat the specimen up to 300 degrees of temperature, and can also ensure the insulation between high voltage phases and relative ground in the electric power system. The mechanical force can be applied in any angle with the magnetic field to realize multiaxial magneto-mechanical loading. As an example, the simultaneous