International Journal of Engineering Science 81 (2014) 82–99

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Micromechanics of magnetostrictive composites

Jacob Aboudi [a,*], Xiaojing Zheng [b], Ke Jin [b]

[a] School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, Ramat Aviv 69978, Israel
[b] Key Laboratory of Mechanics on Environment and Disaster in Western China, The Ministry of Education of China, Department of Mechanics and Engineering Sciences, School of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu 730000, China

ARTICLE INFO

Article history:
Received 3 March 2014
Accepted 14 April 2014
Available online 13 May 2014

Keywords:
Magnetostriction
Terfenol-D
Magnetostrictive composites
Micromechanics analysis
High-fidelity generalized method of cells

ABSTRACT

A micromechanical analysis is offered for the prediction of the effective behavior and internal field distribution of multiphase magnetostrictive composites. The analysis is based on the homogenization technique for periodic composites. The nonlinear coupled constitutive relations of the monolithic magnetostrictive have been recently established at room and elevated temperatures and verified by comparisons with experimental results. Due to the nonlinearity of these constitutive equations, the micromechanical method is based on an incremental procedure which provides the instantaneous magneto-thermo-elastic concentrations tensors that relate the local field to the externally applied loading. In addition, the analysis provides the instantaneous effective tangent tensors as well as the macroscopic constitutive equations which govern the current global behavior of the magnetostrictive composite. The present analysis provides an efficient tool for analyzing magnetostrictive composites with continuous and arbitrary inclusion phases. Results present a parametric study of the effect of applied pre-stresses, elevated temperatures and magnetostrictive phase geometry and volume fraction on a magnetostrictive/epoxy composite response that is subjected to external magnetic field. The distributions of the induced magnetostrictions in the constituents are shown in various circumstances.

1. Introduction

Magnetostriction refers to the phenomenon in which an applied magnetic field generates elastic strain in ferromagnetic materials which can be utilized for sensing, actuating and control. The induced strain exhibits a nonlinear dependence on the applied magnetic field approaching a saturation as the intensity of the latter increases. This behavior can be modified by applying pre-stresses or temperature. The most known magnetostrictive material is Terfenol-D (a metallic compound) which may generate strains of about 1.5×10^{-3} at a magnetic field intensity of 200 kA/m. A characterization of this material has been conducted by Moffet et al. (1991).

In order to model, design and analysis a magnetostrictive structure, multiaxial constitutive relations which are nonlinear and involve a coupling between magnetic field and mechanical deformations, need to be established. Such constitutive relations have been proposed by Carman and Mitrovic (1995), Duenas, Hsu, and Carman (1996), Wan, Fang, and Hwang (2003) and Linnemann, Klinkel, and Wagner (2009), for example.

* Corresponding author. Tel.: +972 3 6408131; fax: +972 3 6407617.
E-mail address: aboudi@eng.tau.ac.il (J. Aboudi).

http://dx.doi.org/10.1016/j.ijengsci.2014.04.007
0020-7225/

Liu and Zheng (2005) proposed multiaxial constitutive equations for magnetostrictive materials which by comparisons with measured data have been shown to provide, as compared with other models, accurate prediction under various circumstances including applied pre-stresses. These relations are based on establishing the Gibbs free energy function which is expressed in terms of the stresses and magnetization. One dimensional magnetostrictive rods and 2-D thin films are obtained as special cases from the established multiaxial equations. In these relations, in addition to the Young's modulus and Poisson's ratio of the isotropic material, just four parameters are needed to characterize a magnetostrictive material which forms a significant advantage of the model. Recently, these equations have been further generalized by Jin, Kou, and Zheng (2012a) to incorporate elevated temperature effects. A recent paper by Jin, Kou, and Zheng (2012b), presents application of the magneto-thermo-elastic model to investigate the resonance frequency shift of Terfenol-D rods together with comparisons with experiments. This article also cites references to other applications of the derived constitutive equations and their verifications by comparisons with measured values.

Terfenol-D is a brittle soft material which is difficult to machine, therefore magnetostrictive Terfenol composites are produced by combining the magnetostrictive phase with a non-magnetic matrix. In many cases a polymeric (e.g., epoxy) or metallic (e.g., aluminum) matrix is employed in which Terfenol-D particles, flakes or rods are embedded. The inclusion of a matrix increases the strength and toughness of the composite, and thus its susceptibility to cracking is improved. In addition, a better mechanical flexibility of the magnetostrictive composite is obtained renders it easier to machine. Furthermore, laminated magnetostrictive composites can be produced from such combinations. By varying the volume fraction of the composite, the intensity of the applied magnetic field in a given direction that is required to generate certain values of mechanical strain components can be controlled.

Experimental investigations of the behavior of magnetostrictive composites with various types of geometrical arrangement have been carried out by Anjanappa and Wu (1997), Chen et al. (1999), Duenas and Carman (2000), Ryu, Priya, and Kim (2002), McKnight and Carman (2001, 2002), Lo, Or, and Chan (2006) and Kaleta, Lewandowski, and Mech (2010), for example.

A sophisticated micromechanical analysis can provide an efficient tool for the prediction of the effective (overall) behavior of magnetostrictive composites as well as the field variables distributions within the composite's constituents. Such a micromechanical modeling should enable the prediction of the most important field variable namely, the generated magnetostriction (induced strains) and their distributions in the composite as a function of the applied magnetic field, the applied pre-stresses, temperature, constituents properties, their volume and aspect ratios, orientations and geometrical shapes. To this end, Herbst, Capehart, and Pinkerton (1997) proposed a simple and approximate spherical model for the prediction of magnetostriction in isotropic composites. Nan and Weng (1999) employed the Green's function technique in conjunction with quite simple constitutive equations to estimate the magnetostriction in composite materials. This approach is confined to the prediction the effective saturation magnetostriction but not of the response to applied loading. In Armstrong (2000), the Mori–Tanaka mean field approximation based on Eshelby's equivalent inclusion approach has been employed for ellipsoidal magnetostrictive particles embedded in epoxy matrix for the prediction of the nonlinear effective behavior of the composite.

The high-fidelity generalized method of cells (HFGMC) is a micromechanical method that is capable of predicting the macroscopic (global) behavior of multiphase periodic composites as well as the field distribution in their constituents. The method is based on the homogenization technique for periodic composites. The reliability of its prediction has been assessed and examined for many types of composites under various circumstances by comparisons with analytical, numerical and experimental results. The reader is referred to Aboudi, Arnold, and Bednarcyk (2013) for an extensive presentation of HFGMC together with its applications in various cases and, in particular, to Aboudi (2001) where HFGMC had been implemented for the prediction of the linear behavior of electro-magneto-thermo-elastic multiphase composites. In the present investigation the HFGMC is generalized and extended for the prediction of the response of magnetostrictive composites to applied magnetic field, pre-stresses and elevated temperatures including the resulting distributions of the field variables, and in particular the generated magnetostriction. The constitutive coupled equations of the magnetostrictive constituent are those established by Jin et al. (2012a) at room and elevated temperatures. Due to the nonlinearity of these equations, an incremental procedure is adopted that establishes the instantaneous stress-magnetic flux density and thermal stress-magnetic flux density tensors of the monolithic material. Subsequently, the HFGMC micromechanical analysis establishes the effective instantaneous stress-magnetic flux density and thermal stress-magnetic flux density tensors of the magnetostrictive composite. The derivation also establishes the instantaneous stress-magnetic and thermal stress-magnetic concentration tensors which relate the local strains and magnetic field intensities and/or the local stresses and magnetic flux densities to the externally applied far-field magneto-elastic loading and temperature. Results are given illustrating the magnetostriction prediction and its distributions in continuously oriented magnetostrictive fibers as well as spherical particles and rods embedded in epoxy matrix in various circumstances.

This paper is organized as follows. Section 2 concerns with the constitutive relations of monolithic magnetostrictive material, their incremental formulation and the establishment of the instantaneous magneto-thermo-elastic tensors. Section 3 provides a detailed derivation of the micromechanical method and the establishment of the instantaneous local and global magneto-thermo-elastic tensors and, in particular, the instantaneous macroscopic constitutive equations of the magnetostrictive composite. This is followed by the application section. A conclusion section summarizes the paper and offers several generalizations and possible future investigations.