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A physically based model for stress sensing using magnetostrictive composites

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ABSTRACT

Magnetostrictive composites are of considerable interest for real-time remote force sensing and structural health monitoring. In this paper, we introduce a new procedure for modeling the magnetic field induced by an external load applied on an epoxy-based composite material filled with Terfenol-D particles. This model is based on an assumed sequence of physical processes that occur at the microscopic scale, and it includes both domain switching and magnetization rotation. The modeling procedure is demonstrated on a problem relevant for load sensing applications in which the magnetostrictive composite is subjected to a uniaxial compression. Comparison of the calculated and experimental results strengthens the validity of the assumed sequence of physical processes and provides valuable insights important for application developments.

1. Introduction

Magnetostrictive materials offer a unique way for stress and strain sensing. When a magnetostrictive material is mechanically loaded, its magnetization state undergoes changes that can be measured by a magnetic sensor and can be inversely translated into an indication of the stress or strain in the material. The most common magnetostrictive material is an alloy, $Tb_xDy_{1-x}Fe_{2-y}$, $x \approx 0.3,\ 0 < y < 0.2$ (Clark, 1992), commercially known as Terfenol-D© (TD). TD is unique because of its high magnetostriction coefficient $\lambda_{111} = 1.64 \cdot 10^{-3}$ (Jiles and Thoelke, 1994), which makes it useful for transducer and sensor applications. However, TD is a brittle material, and it is difficult to form into different shapes. These problems can be overcome by incorporating TD particles into a polymer matrix to form a magnetostrictive composite material.

Load sensing based on magnetostrictive composites offer two unique advantages over other sensing methods. First, the magnetic field sensor can be mounted remotely from the magnetostrictive material and second, a variety of miniature and complicated sensor shapes can be easily formed. These two advantages allow a significant freedom for mechanical design.

An example for a possible potential application is a thin layer load sensor for measuring compressive forces between fastened mechanical parts. This application is of great need in the field of assembly line reliability, in which simulation experiments are performed on fastened mechanical structures subjected to vibration, acceleration and shock load conditions. For this purpose, sensors in the form of washers can be produced for monitoring forces in bolted joints.

A more challenging application is in the field of structural health monitoring (SHM). SHM is an emerging approach for non-destructive inspection, in which stresses or strains in a load-bearing structure are monitored in real-time using

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embedded or attached sensors. The current approaches for SHM are based on sensors such as fiber-optic Bragg-gratings (DU et al., 1998), piezoelectrics (Park et al., 2006) and strain-gauges, which suffer from two major limitations: (1) they require wiring and a constant power supply, and (2) they only measure local strains. Stress sensing by magnetostrictive materials can offer an alternative approach that does not suffer from these limitations and can be applied, for example, for composite material structures and bonding interfaces.

Previous experimental studies of the magneto-mechanical response of magnetostrictive composite materials revealed several important effects. Nersessian et al. (2003) suggested poling the magnetostrictive composite by exposing it to a strong magnetic field during the curing of the epoxy. This process is expected to align the magnetization of the TD particles along the direction of the external magnetic field. It has been shown that the particles are ordered in a chain-like fashion and that the stress-induced magnetic flux changes are significantly increased as a result of this process (Or and Carman, 2005). Furthermore, it has also been shown that there is a saturation point at which an increase in the applied poling field does not improve the magnetostrictive response (Dong et al., 2010). The saturation poling field depends on the volume fraction of TD particles. Additional effects examined in previous experimental works are the effect of the volume fraction of TD particles in the composite and the effect of particle size. Nersessian et al. demonstrated that higher volume fractions of TD particles in the composite provide an enhanced magnetostrictive response (Nersessian et al., 2003), and Dong et al. reported that for composites with a low volume fraction of TD particles, there is an optimal particle size for the maximum magnetostrictive response. Additionally, they showed that the best response is obtained using polydispersed particles, i.e., a distribution of different sized particles (Dong et al., 2009). An important observation, which appears in some of the studies, is that a significant non-reversibility occurs in the magnetic flux readings during loading and unloading of the specimen (Quattrone et al., 2000). This problem must clearly be solved to develop reliable force sensing and SHM technologies. Another observation, which is shown in this article and is important for practical applications, is that above some stress value, the slope of the magnetic field vs. stress curve, which is a measure of the sensitivity, dramatically decreases and there is almost a saturation in the magnetic flux signal.

Although some of the aforementioned experimental effects and observations are somewhat intuitive, they have not been explained in a detailed and quantitative manner. One of the aims of this article is to provide a quantitative explanation for some of these effects. For this purpose, as well as for the ability to predict the measured magnetic field as a function of the mechanical load, models for calculating the magneto-mechanical behavior of magnetostrictive composite materials have to be developed.

Models of magnetostrictive composite materials must be based on models of monolithic TD. In some previous studies, the magnetomechanical response of TD was modeled based on a simplified assumption of linear constitutive relations between the stress, strain and magnetization (Moffett et al., 1991), analogous to the piezoelectric constitutive relations. However, such linear relationships are valid only in a narrow range of stresses and are dependent on the initial magnetization state of the material. In general, the response of TD is highly non-linear (Moffett et al., 1991). In fact, there are no constitutive relations for TD due to several reasons, which are explained herein.

All ferromagnetic materials have crystallographic easy axes, which are energetically favored directions for magnetization. The easy axes in TD at room temperature belong to the group of $\langle 111 \rangle$ directions, which form eight energetically equivalent variants that each have different magnetization directions. Due to a coupling between the magnetization and strain, different magnetic variants have different strains, but the strain has a higher symmetry such that anti-parallel magnetization variants have the same strain. Any finite element of a TD material may be divided into different (usually numerous) domains, in which the magnetization is aligned along different directions of the $\langle 111 \rangle$ group. There are many combinations of magnetic domains that have the same average strain but different average magnetizations and vice versa. Consequently, there is no one-to-one relation between strain and magnetization for the TD material element.

There are two mechanisms through which the overall magnetization of a ferromagnetic material can be changed: domain switching and magnetization rotation (Chikazumi, 1997). Domain switching is a process in which there is a redistribution of magnetic domains in the crystal such that the volume fraction of the variant preferred by the external load or field increases at the expense of the other variants. Magnetization rotation is a process in which the local magnetization within domains rotates off the easy axes in a continuous manner and aligns along directions that are favored by the external load or field.

In TD, magnetization rotation is more difficult than domain switching (Chikazumi, 1997) due to the high coefficients of magnetocrystalline anisotropy energy. This property has led to a micro-magnetic modeling approach that only considers the domain switching process (DeSimone and James, 1997). In this approach, it is assumed that the magnetization is constrained to one of the eight crystallographic variants. The volume fraction of each variant is calculated by energy minimization of the overall energy of the TD crystal. Because all variants have the same magnetocrystalline energy, this term does not affect the energy minimization.

An effect that complicates the micro-magnetic modeling approach is the demagnetization or self-magnetic energy of the ferromagnetic material, which is associated with the demagnetizing field produced by the self-magnetization of the material (both inside and outside the magnetic material). This effect acts to diminish the average magnetization of the ferromagnetic body,$\langle M \rangle$, thereby diminishing the long-range magnetic field created by the body. The demagnetization energy is affected by the shape of the ferromagnetic body. For ellipsoidal bodies, the demagnetization energy per unit volume is given by

$$U_D = \frac{1}{2}\mu_0 \langle M \rangle D \langle M \rangle \tag{1}$$