Behavior and Applications of Magnetostrictive Materials

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ABSTRACT

Magnetostrictive materials deform under the action of magnetic fields, and their magnetization changes when they are deformed. This mechanism for bidirectional energy transduction between magnetic and elastic regimes has been effectively employed in actuator and sensor applications. Current and anticipated industry needs dictate that transducers employed in diverse processes operate over broader frequency bandwidths and be multifunctional. However, at the high operating regimes in which these performance criteria are met, magnetostrictive materials exhibit hysteresis and nonlinearities to a degree which other smart materials often do not. Basic and applied research on magnetostrictive materials therefore focuses on addressing these issues through the development of innovative modeling techniques and control strategies. Because the magnetostrictive effect is intrinsically stochastic, accurate models to be used in design and control applications must be constructed from constitutive laws describing material behavior in terms of its inherent physical properties. This paper presents an overview of Joule magnetostriction, magnetostrictive materials, and actuator configurations which employ advanced crystalline materials capable of producing strains in excess of $1600 \times 10^{-6}$.

1 INTRODUCTION

The study of magnetostriction began in 1842 when James P. Joule first observed that a sample of iron changes its length when magnetized with a magnetic field. The term magnetostriction refers to any change in dimension of a magnetic material caused by a change in its magnetization. Changes in magnetization result from domain distortions originated in the interatomic forces created by magnetic moment rotations. These rotations can be brought about by the application of magnetic fields, heat, or stresses. Figure 1 illustrates the Joule magnetostriction $\Delta L/L$ of a cylindrical sample, which results from a magnetic field being applied along the longitudinal axis. The Joule magnetostriction is commonly employed in actuator and sensor applications. While most magnetic materials exhibit Joule magnetostrictions, only a small number of compounds containing rare earth elements provide magnetostrictions in excess of $1000 \times 10^{-6}$. These large magnetostrictions are a direct consequence of a strong magnetoelastic coupling arising from the dependency of magnetic moment orientation with interatomic spacing. Referring to Figure 1, if the magnetostriction is positive, the sample elongates irrespective of the direction of rotation of the magnetic moments, and the diameter is reduced such that the volume remains constant. If the magnetostriction is negative, the sample length decreases, and the diameter increases. A symmetric magnetostriction curve is obtained when the field is cycled. If a uniaxial stress is applied, interatomic displacements lead to magnetic moment reorientation and a subsequent change in total magnetization. This effect provides a mechanism for sensing.

Because magnetostriction is an inherent property of magnetic materials, it does not degrade over time as can be the case with some piezoelectric substances. Furthermore, newer magnetostrictive materials provide strains, forces, energy densities, and coupling coefficients which compete advantageously with more established transducer technologies such as those based on piezoelectric materials. A number of design and modeling issues, however, complicate the implementation of magnetostrictive materials. For instance, due to the required solenoid and related magnetic circuit components, magnetostrictive transducers are usually larger and bulkier than their piezoelectric or electrostrictive counterparts. Hence a primary application for magnetostrictive materials is vibration control of heavy structures. One addi-
Figure 1: Joule magnetostriction produced by a magnetic field \( H \). (a) \( H \) is approximately proportional to the current \( i \) that passes through the solenoid when a voltage is applied to it, and (b) curve \( \Delta L/L \) vs. 
\( H \) obtained by varying the field sinusoidally (inset).

Figure 2: Diagrams illustrating the effects of magnetostriction.

A significant technological consideration is that the most technologically advanced magnetostrictive compounds are costly to manufacture. Advanced crystalline transducer drivers are manufactured by means of crystal growth techniques that produce directional solidification along the drive axis, in combination with precision machining of laminations, final diameters, and parallel ends of cut-to-length pieces.

From a device implementation standpoint, magnetostrictive materials exhibit significant nonlinearities and hysteresis to a degree which other smart materials, for instance electrostrictives, typically do not. The deleterious effects due to these behaviors can be circumvented through feedback control techniques. However, the development of broadband feedback control solutions that do not degrade in performance over a large performance range has been elusive in many magnetostrictive systems, because in these systems the efficacy of real-time monitoring and feedback control is diminished by noise inherent to measurements, thermal creep, and strong material property variations. One effective means of accounting for and limiting the deleterious effects of these issues is through the development of feedforward loops utilizing constitutive laws describing material behavior in terms of its inherent physical properties. Important advances on the modeling of magnetostrictive materials and structures have taken place recently, and as transducer designers find opportunities to develop new applications, model completeness and accuracy will surely follow. In addition, recent advances in materials science research have enabled more capable magnetostrictive materials in various forms, including amorphous or crystalline thin films, magnetostrictive particle-aligned polymer matrix composite structures, and sintered powder compacts suitable for mass production of small irregular shapes. In the following sections, concepts concerning magnetostrictive materials, modeling considerations, and actuator implementation are discussed.

2 MATERIALS OVERVIEW

During the early 1960’s, a breakthrough in magnetostrictive materials took place with the discovery of the largest-known magnetostriction in the rare earth elements terbium and dysprosium. These elements exhibit strains of up to \( 10,000 \times 10^{-6} \), or three orders of magnitude larger than those of nickel. However, these strains are achieved at cryogenic temperatures. The temperature limitation and the fact that the field of piezoelectricity was gaining technical maturity hindered the development of magnetostrictive materials and led in the early 1970’s to a search for a new class of transducer materials capable of high room-temperature strains. Highly magnetostrictive rare earths (R), principally samarium (Sm), terbium (Tb) and dysprosium (Dy), were combined with the magnetic transition metals nickel, cobalt and iron by direct compound synthesis and by rapid sputtering into amorphous alloys. In contrast to the normal Curie temperature behavior of the R-Ni and R-Co compounds, the R-Fe compounds were found to exhibit an increase in the Curie temperature with increasing rare earth concentration [10]. This unusual property gives the R-Fe compounds huge room temperature magnetostrictions, of up to \( 3,000 \times 10^{-6} \) in the case of the TbFe\(_2\) system. However, because magnetostriction originates in the strain dependence of magnetic anisotropy, the large magnetostriction in these compounds is obtained at the expense of large anisotropy. This poses a technological limitation in that impractically large fields of over \( 2 \text{ MA/m} \) are needed to bring these compounds to technical saturation.
Partial substitution of dysprosium for terbium in the TbFe$_2$ system resulted in improved magnetostriction and anisotropy properties. The resulting pseudobinary compound Tb$_{0.3}$Dy$_{0.7}$Fe$_{1.9-1.95}$ has been available commercially since the 1980’s under the name Terfenol-D (Ter =terbium, Fe = iron, D = dysprosium, NOL = Naval Ordnance Laboratory.) Terfenol-D exhibits magnetostrictions of up to 1600×10$^{-6}$ at a moderate saturation field of 0.16 MA/m, but even larger magnetostrictions of up to 3600×10$^{-6}$ are possible when this material is employed in transducers driven at resonance. The utility of Terfenol-D as a rugged, high power transducer driver has been increasingly recognized in recent years. At present, Terfenol-D is used in active noise and vibration control systems; sonar; linear and rotational motors; ultrasonic cleaning, machining and welding; micropositioning; and for detection of motion, force and magnetic fields. Terfenol-D is currently available in a variety of forms, including monolithic rods [13, 27], particle-aligned polymer matrix composites [2, 7, 12], and thin films [3, 28]. Because of the large magnetostriction anisotropy and strong magnetoelasticity, Terfenol-D and other pseudobinary rare earth-iron compounds can be synthesized to exhibit a broad range of properties [10]. In Table 1, the properties saturation magnetostriction, density, saturation magnetic induction, Curie temperature, elastic modulus, and magnetoelastic coupling are listed for some typical materials.

A second new magnetostrictive material was introduced in 1978 which is based on amorphous metal, produced by rapid cooling of iron, nickel, and cobalt alloys together with one or more of the elements silicon, boron, and phosphorus. These alloys are known commercially as Metglas (metallic glass) and are commonly produced in thin-ribbon geometries. Because of the extremely high coupling coefficients ($k > 0.92$), Metglas is attractive for sensor applications in which mechanical motion is converted into an electrical voltage [27].

The latest research on magnetostrictive materials includes, among others, the development of new compounds to minimize magnetic anisotropy and hysteresis, and new manufacturing techniques to produce Terfenol-D thin films in an efficient manner [20]. Substantial materials science advances have been achieved with the quaternary compounds Terfenol-DH, which are produced by substitution of holmium for terbium and dysprosium [22]. In addition, new manufacturing techniques are enabling the production of multi-layered driver rods which will lead to reduced dynamic losses, thus facilitating the operation over substantially higher frequencies than it is currently possible. Ferromagnetic shape memory alloys are another class of magnetically-activated materials which hold much promise due to the large strains that they can provide. While the nickel-titanium alloy Nitinol features large recoverable strains of the order of 60,000×10$^{-6}$, it suffers from inferior dynamical response. The possibility of combining the desirable aspects of shape memory with magnetostriction through actuating an SMA with a magnetic field is currently being investigated. Promising candidate materials are the Ni$_2$MnGa system and the Fe-based invars, which exhibit, in principle, the desired characteristics. Further details on the Ni-Mn-Ga alloys can be found in [21, 26].

3 JOULE MAGNETOSTRICTION

Joule magnetostriction refers to strains produced in the field direction and constitutes the magnetostrictive effect most commonly used in applications. Because this effect occurs at constant volume, there must be a transverse strain with opposite sign to that of the Joule magnetostriction,

$$\lambda_\perp = -\frac{\lambda}{2}.$$ 

3.1 Isotropic spontaneous magnetostriction

When a ferromagnetic material is cooled below its Curie temperature, a transition from paramagnetism to ferromagnetism takes place, and magnetic moments become ordered giving origin to a spontaneous magnetization $M_s$ within domains. This process is accompanied by a spontaneous magnetostriction $\lambda_0$. It is possible to derive a relationship between $\lambda_0$ and the saturation magnetostriction $\lambda_s$. To that end, we consider an isotropic material in the disordered state above $T_c$, which is therefore modeled with spherical volumes as shown in Figure 2(a). Magnetic domains are represented in Figure 2(b) by ellipsoids with spontaneous strain $e$. Since the material is assumed to be isotropic, the magnetic domains are oriented randomly; each domain bears an angle $\theta$ with respect to the field direction. The net magnetization is consequently zero, and the length in the field direction is given by [11]

$$e(\theta) = e \cos^2 \theta.$$ (1)
Then, the average domain deformation on the onset of spontaneous magnetostriction is obtained by integration in all possible directions,

\[ \lambda_0 = \int_{-\pi/2}^{\pi/2} e \cos^2 \theta \sin \theta \, d\theta = \frac{e}{3}. \]

Spontaneous magnetostriction \( \lambda_0 \) is homogeneous in all directions, so in Figure 2(b) the material has changed its dimensions but not its shape. On application of a magnetic field, the magnetic domains rotate and become aligned either parallel to the field or perpendicular to it, depending on whether the material exhibits positive or negative magnetostriction. Assuming positive magnetostriction, the domains rotate into the field direction as depicted in Figure 2(c). Near saturation, the material becomes a single domain and the total strain becomes \( e \). Then, the total available saturation magnetostriction is given by

\[ \lambda_s = e - \lambda_0 = \frac{2}{3} e = 2\lambda_0. \tag{2} \]

This expression provides a method of measuring the spontaneous strain \( \lambda_0 \) by measuring \( \lambda_s \). Methods to determine \( \lambda_s \) are discussed next.

### 3.2 Saturation magnetostriction

Assuming again for simplicity that the medium is isotropic, the saturation magnetostriction at an angle \( \theta \) to the field direction is given by [11]

\[ \lambda_s(\theta) = \frac{3}{2} \lambda_s \left( \cos^2 \theta - \frac{1}{3} \right). \tag{3} \]

Table 1: Magnetoelastic properties of some magnetostrictive materials. Unless otherwise specified, all measurements were performed at room temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \frac{1}{2} \lambda_s \times 10^{-6} )</th>
<th>( \rho ) (g/cm(^3))</th>
<th>( B_s ) (T)</th>
<th>( T_c ) (°C)</th>
<th>( E ) (GPa)</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tb(<em>{0.6})Dy(</em>{0.4})</td>
<td>6000 (–196°C) [23]</td>
<td></td>
<td></td>
<td></td>
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Figure 2: Diagram illustrating the magnetostriction of a ferromagnetic material: (a) paramagnetic state above \( T_c \); (b) after it has been cooled through \( T_c \); and (c) after it has been brought to saturation by field \( H \).
where $\lambda_s(\theta)$ is the saturation magnetostriction at an angle $\theta$ to the field and $\lambda_s$ is the saturation magnetostriction along the direction of magnetization.

The saturation magnetostriction is calculated from the difference between the maximum magnetostriction with the field parallel to a given direction ($\lambda_{s||}$) and that with the field perpendicular to the given direction ($\lambda_{s\perp}$). Substituting $\theta = 0^\circ$ and $\theta = 90^\circ$ in (3) gives

$$\lambda_{s||} - \lambda_{s\perp} = \lambda_s + \frac{1}{2} \lambda_s - \frac{3}{2} \lambda_s,$$

which defines $\lambda_s$ independently of the domain configuration in the demagnetized state.

Magnetostriiction data from Clark [10] taken from polycrystalline $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_y$ is reproduced in Figure 3(a). The data points correspond to $\lambda_{s||} - \lambda_{s\perp}$ at room temperature and field values of $H = 10$ kOe (0.8 MA/m) and $H = 25$ kOe (2 MA/m). Near $x = 0.3$, the magnetostriiction curve shows a peak in accordance with the near zero magnetic anisotropy observed at this composition. From the magnetostriiction value at the peak, of about $1600 \times 10^{-6}$, Eq.(4) gives $\lambda_s = 1000 \times 10^{-6}$ which is a widely employed value for the saturation magnetostriiction of Terfenol-D.

Crystal anisotropy is present to some degree in all magnetic materials, and therefore the saturation magnetostriiction needs to be defined in relation to the axis of magnetization. One exception is nickel, whose magnetostriiction is almost isotropic. Recognizing that cubic materials exhibit two independent magnetostriction constants $\lambda_{100}$ and $\lambda_{111}$, the saturation magnetostriiction assuming single crystal, single domain material is given by a generalization of Eq.(3) for isotropic materials,

$$\lambda_s = \frac{3}{2} \lambda_{100} \left( \alpha_1^2 \beta_1^2 + \alpha_2^2 \beta_2^2 + \alpha_3^2 \beta_3^2 - \frac{1}{3} \right) + 3 \lambda_{111} \left( \alpha_1 \alpha_2 \beta_1 \beta_2 + \alpha_2 \alpha_3 \beta_2 \beta_3 + \alpha_3 \alpha_1 \beta_3 \beta_1 \right),$$

where $\lambda_{100}$ and $\lambda_{111}$ are the saturation magnetostriictions along the $<100>$ and $<111>$ axes of the crystal. The cosines $\alpha_i$ ($i = 1, 2, 3$) define the direction along which the magnetic moments are saturated, while the cosines $\beta_i$ define the direction in which the saturation magnetization is measured. The saturation magnetostriiction along the field direction is obtained by using $\alpha_i = \beta_i$ in Eq.(5), which leads to

$$\lambda_s = \lambda_{100} + 3 (\lambda_{111} - \lambda_{100}) \left( \alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2 \right).$$

Note that expressions (5) and (6) apply only to single domain materials. In the saturated state, the entire specimen consists of a single domain whose magnetization $M_s$ aligned parallel to the applied field. However, when a domain structure is present such as in polycrystals, the magnetostriiction can be calculated only by averaging the effects since the domain structure is typically unknown a priori. Note that radically different domain configurations can give the same bulk magnetization and different magnetostriictions. So, assuming that there is no preferred grain orientation, formula (6) further simplifies to

$$\overline{\lambda_s} = \frac{2}{5} \lambda_{100} + \frac{3}{5} \lambda_{111}.$$  

Magnetostriiction data on $\text{R-Fe}_2$ compounds can be found in [10], while calculations of $\lambda_s$ for different crystallographic structures such as cubic, hexagonal, and polycrystalline can be found in [11, 15, 19, 27].

### 3.3 Magnetostriiction below saturation

Although saturation magnetostriiction $\lambda_s$ can be determined employing the methods previously discussed, the magnetostriiction between the demagnetized state and saturation is structure sensitive, so general constitutive relations for the magnetostriiction are not feasible. However, an explicit solution exists for cases when the strains are due primarily to $90^\circ$ domain rotations. In practice, these rotations occur in: (i) a single crystal that has uniaxial anisotropy in which the field is applied in a direction perpendicular to the easy axis or (ii) a polycrystalline material in which the magnetic moments have been brought to complete alignment in a direction perpendicular to the applied field, such as Terfenol-D under extreme compression or nickel under tension. The latter requires perpendiclar stresses sufficient to dominate the material’s crystal anisotropy energy. For that regime, combining Eq.(1) and Eq.(2) gives

$$\lambda = \frac{3}{2} \lambda_s \cos^2 \theta,$$

where $\theta$ is the angle between the $M_s$ vectors and the field direction. Recognizing that the bulk magnetization in the field direction is given by $M = M_s \cos \theta$, Eq.(7) becomes

$$\lambda = \frac{3}{2} \lambda_s \left( \frac{M}{M_s} \right)^2,$$
which provides a quadratic relationship between magnetization and magnetostriction. It has been shown that this expression is sufficiently accurate in a broad range of transducer regimes in which high mechanical preloads are employed to optimize transducer performance [6]. A generalized version of this equation has been given in [16]. More elaborate models for magnetostriction hysteresis have been presented in [9, 14, 24, 25]. Additional effects such as stress dependences have been also considered [1, 16]. Finally, the dependence of the magnetostriction of the R-Fe$_2$ compounds on temperature has been discussed in [10].

4 MAGNETOSTRICTIVE ACTUATORS

A strain vs. magnetic field curve produced by a typical Terfenol-D actuator is shown in Figure 3(b). Due to the relatively high strain and force produced by magnetostrictive materials, especially Terfenol-D, the number of applications for these materials is continuously increasing. Even though the cost of Terfenol-D is currently a concern, the range of applications will likely continue to increase as manufacturing techniques are perfected and prices decline. Figure 4(a) illustrates a typical magnetostrictive transducer consisting of a cylindrical magnetostrictive rod, a surrounding copper-wire solenoid, a preload mechanism consisting of a bolt and spring washer, magnetic couplers and a barrel-like permanent magnet which provides a bias magnetization. This design has been employed, among others, in the following applications: sonar, chatter control of boring tools, high-precision micropositioning, borehole seismic sources, geological tomography, hydraulic valves for fuel injection systems, deformable mirrors, hydraulic pumps, bone-conduction hearing aids, exoskeletal telemamipulators, self-sensing actuators, degassing in manufacturing processes such as rubber vulcanization, and industrial ultrasonic cleaning. Figure 4(b)-(d) illustrates some typical designs based on magnetostrictive materials. The reader is directed to [13, 27] for further details.
5 CONCLUDING REMARKS

The phenomenon of magnetostriction is ultimately due to the coupling between magnetic moment orientation and interatomic spacing, or magnetoelastic coupling. This form of coupling provides a robust mechanism for bidirectional conversion of energy between magnetic and elastic regimes. Newer materials such as Terfenol-D or amorphous metallic ribbons provide a unique combination of high forces, strains, energy densities, operating bandwidths and coupling coefficients which has justified their use in an ever-increasing number of industry applications. Basic and applied research is currently underway with the goal to improve the feasibility of magnetostrictive materials in a broader range of applications requiring actuation, sensing, or self-healing capabilities. Issues being considered in the development of new modeling techniques must often focus on hysteresis and system nonlinearities. Because of the deleterious effects due to the nonlinearities, the implementation of magnetostrictive materials in feedback control systems presents challenges in a way which other less capable smart materials do not. However, as evidenced by the increasing number of patented devices based on magnetostrictive principles, transducer designers continue to overcome these challenges and make advances in magnetostrictive transducer performance. Furthermore, clever transducer designs are possible solely due to the rich performance space which arises as a consequence of the otherwise undesirable nonlinear characteristics of these materials. As material advances continue, it is expected that magnetostrictive device designers will find new magnetostrictive solutions to an ever-growing variety of transducer applications.
References


