

Chapter 1. Introduction

1.1. Overview and motivation

Fracture is essentially a ubiquitous phenomenon in our everyday lives. If one of our ceramic plates fell to the floor, it would most likely shatter into many pieces. A food can's notched lid shreds when opened. Some of these events spontaneously occur, while others are within our direct control. We, as humankind, are never satisfied in our quest to learn more about the nature and instinctively fascinated by the processes that lead to the initiation and spread of cracks. This solid mechanics problem gets more intriguing for giant magnetostrictive materials employed in sophisticated sensing and actuation devices.

The so-called giant magnetostrictive materials deform significantly in the presence of external magnetic fields and undergo considerable magnetization variations when pre-stresses are applied. As well, giant magnetostrictive materials exhibit nonlinear magneto-thermo-elastic coupling phenomena. This magnetic material experiences shape deformation (Joule magnetostriction) in response to an applied magnetic field due to tendency of magnetic domains to turn in the direction of the field and maintain volume consistency. Conversely the magnetization state of giant magnetostrictive material changes on the application of mechanical stresses and temperature. Whenever a load is applied, the magnetic domains align themselves in a plane perpendicular to the direction of applied load. This induces a change in magnetization and known as Villari effect. Additionally, the ability to change its shape (in μ -strains) in noticeably short duration (in milli-seconds) make such materials well suited to precise sensing and actuating systems. Thus, these materials found potential applications in sensors, actuators, acoustic transducers, stress monitoring devices,

linear motors, micro-pumps and micro-positioners, energy harvesting devices [1–3] [4,5] etc. as shown in **Figure 1.1-Figure 1.4**.

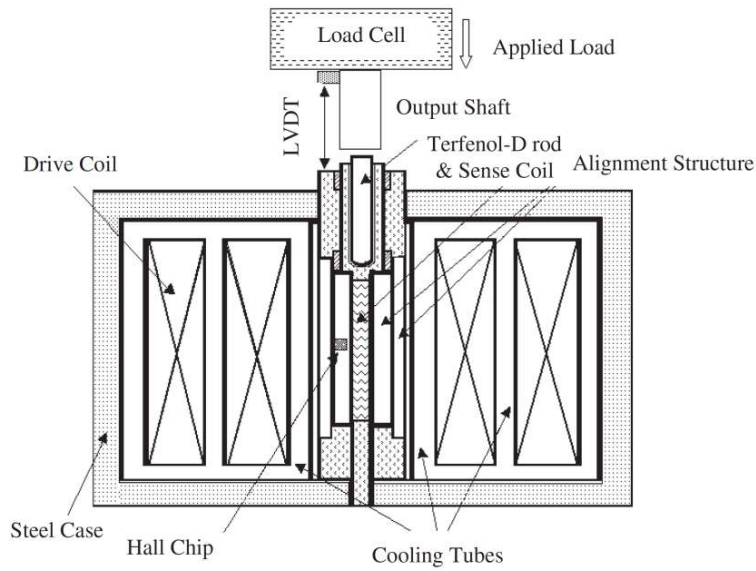


Figure 1.1 Terfenol-D based Transducer. Reprinted with kind permission from [3].

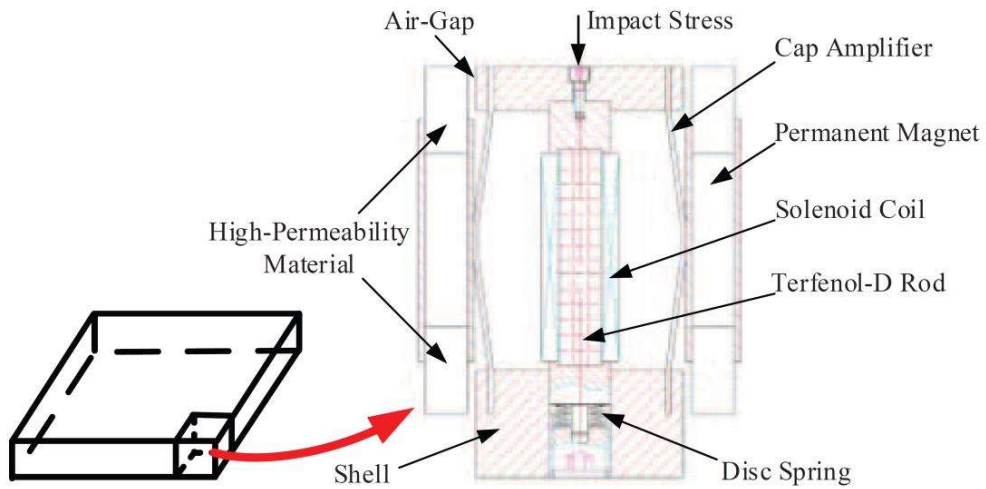


Figure 1.2 Magnetostrictive vibration energy harvester for power generating floor systems [6] © [2015] IEEE.

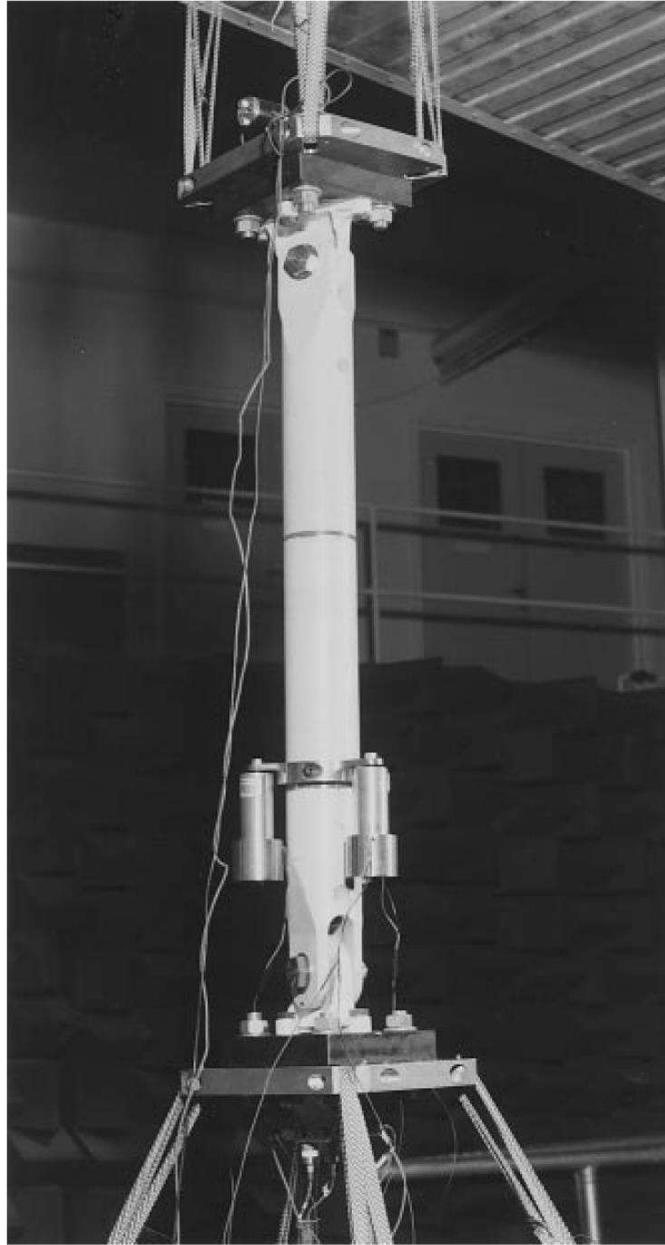


Figure 1.3 Three magnetostrictive actuators were attached to the strut of helicopter externally by means of a collar for active vibration suppression. Reprinted from *Journal of Sound and Vibration*, 205(1), T. J. Sutton, S. J. Elliott and M. J. Brennan, Active isolation of multiple structural waves on a helicopter gearbox support strut, 81-101, copyright (1997), with permission from Elsevier [7].

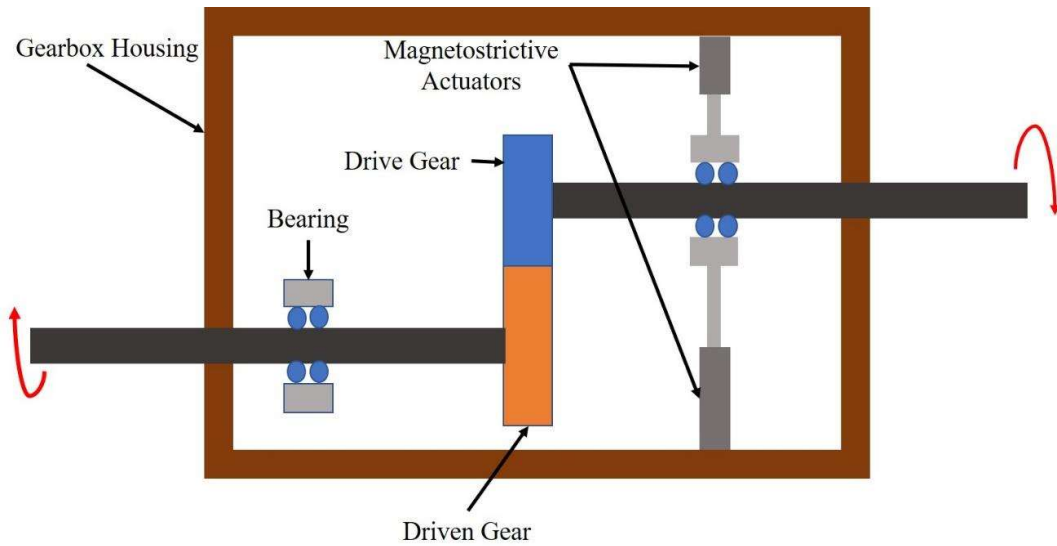


Figure 1.4 Active control of Gearbox vibration with two pairs of magnetostrictive actuators supporting the bearing [8].

The erstwhile applications exploit magnetostrictive material's potential to transform magnetic energy into an elastic deformation or else it relies on its capability to modify the magnetic field to the response of deformation. These unique characteristics makes them most sought after intelligent material with contemporary applications in the state of art technology sector of automotive, avionics, construction engineering, micro-magneto-mechanical systems, healthcare and automation industrial sectors [1,3,9,10]. Such application areas may induce dynamic forces in intelligent devices, resulting in unwanted operating conditions and structural vibrations. These adverse circumstances can lead to material fracture, poor device reliability and safety concerns. The strength of giant magnetostrictive materials is greatly dependent on the coupled magneto-thermo-mechanical loading. Thus, it becomes necessary to understand the mechanics and physics of giant magnetostrictive material's fracture in the coupled magneto-thermo-elastic environment.

1.1.1. Giant magnetostrictive materials (GMM)

The phenomenon of magnetostriction was initially discovered in ferromagnetic materials including iron, nickel, cobalt, and their alloys. The magneto-strains of such ferro-materials were limited to 100 ppm. The application of nickel based magnetostrictive alloys in SONAR transducers in early 19th century sparked interest in magnetostrictive material research. Since then, however, the discovery of a new class of ceramic materials capable of delivering piezoelectric strains on the scale of a thousand parts per million (ppm) was taken the spotlight from magnetostrictive material.

It was in the 1970s when scientists at the United States Naval Ordinance Laboratory initially synthesized a unique intermetallic alloy Terfenol-D, which comprises of terbium (Tb), iron (Fe) and dysprosium (Dy); and can generate giant strains (in order of 2000 ppm) under modest magnetic fields [5]. Galfenol (Iron-gallium alloys), a relatively new class of giant magnetostrictive material, has been discovered recently and can exhibit up to 400 ppm magnetostriction [11]. The emergence of such giant magnetostrictive materials (GMM) rekindles research interest in the magnetostrictive based sensing and actuating applications.

More specifically, giant magnetostrictive materials are a class of energy conversion functional materials capable of exhibiting a few peculiar properties, such as high saturation magnetostriction, high compressive strength, variability in Young's modulus, high energy density, high Curie temperature and faster response to operating stimulus[4,5]. Such distinct features make the GMMs attractive for micro-sensors, micro-actuators, or tunable acoustic wave devices in smart structures[1,3]. Terfenol-D based magnetostrictive films and laminates are now-a-days being actively used in the coil-free magneto-electric energy harvesting devices to convert the unwanted mechanical vibrations into electric power [9,10].

Among the giant magnetostrictive materials, Terfenol-D ($Tb_{0.27}Dy_{0.73}Fe_{1.93}$) alloy demonstrates the highest magnetostriction.

The experimental studies [12–17] on Terfenol-D have revealed that the magneto-thermo-mechanical response of such stimuli sensitive materials are nonlinearly coupled and hysteretic in nature as shown in **Figure 1.5** and **Figure 1.6** [13]. The magnetization and magnetostriction curves for a Terfenol-D rod or film not only manifest the saturation phenomenon but also are sensitive to prestress, ambient temperature, and the direction of an applied magnetic field.

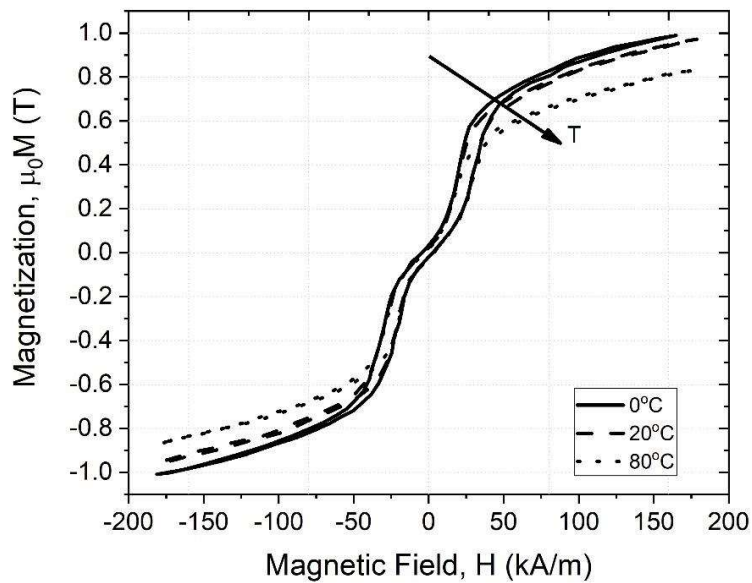


Figure 1.5 Magnetization curves of Terfenol-D at different temperature levels. Reprinted from [13] [Clark AE, Teter JP, McMasters OD. Magnetostriction “jumps” in twinned $Tb_{0.3}Dy_{0.7}Fe_{1.9}$. *J Appl Phys* 1988;63:3910–2], with the permission of AIP Publishing.

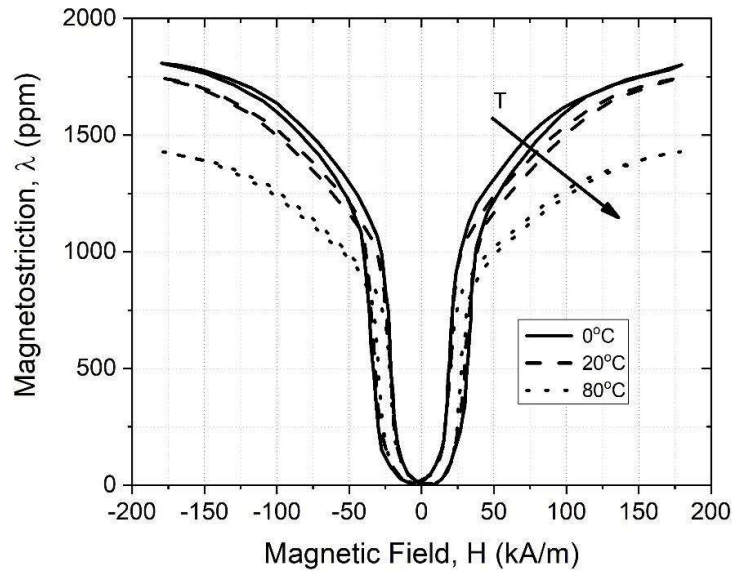


Figure 1.6 Magnetostriction curves of Terfenol-D at different temperature levels. Reprinted from [13] [Clark AE, Teter JP, McMasters OD. Magnetostriction “jumps” in twinned Tb_{0.3}Dy_{0.7}Fe_{1.9}. J Appl Phys 1988;63:3910–2], with the permission of AIP Publishing.

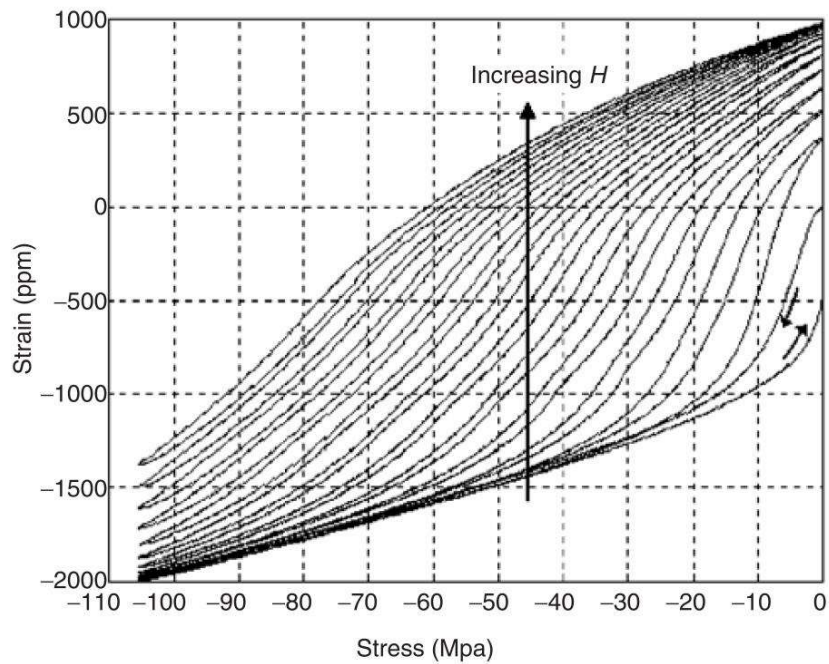


Figure 1.7 Strain vs stress loop for DC applied field levels H (0–193.2 kA/m at 16.1 kA/m steps). Reprinted with kind permission from [17].

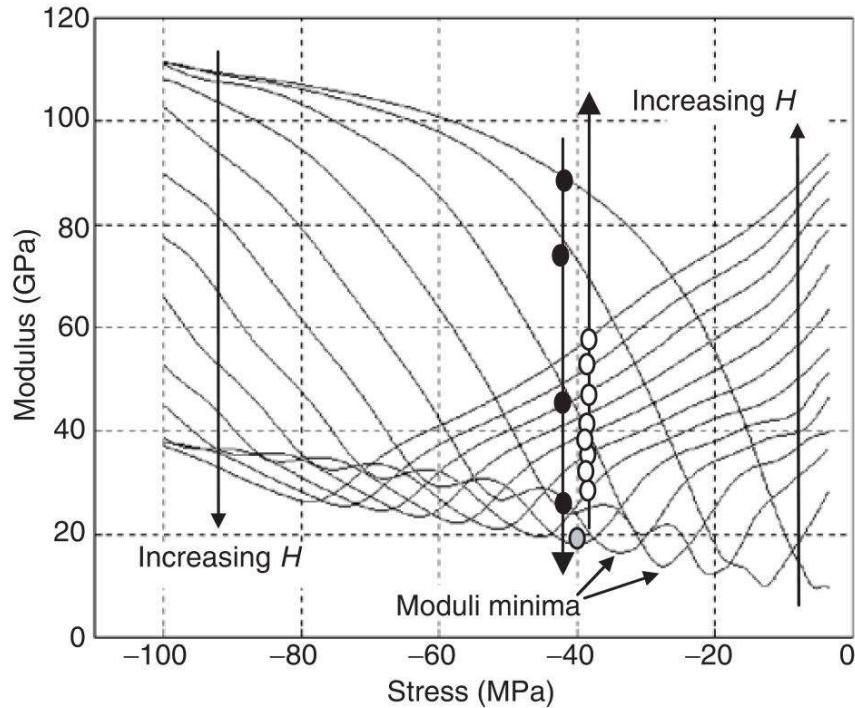


Figure 1.8 Young's Modulus for DC applied field levels H (0–193.4 kA/m at 16.1 kA/m steps) Reprinted with kind permission from [17].

The strain-stress loops show the considerable hysteretic losses occurring when the Terfenol-D rod is subjected to a compression and decompression loading cycle as shown in **Figure 1.7** [17]. The increased hysteresis loss compared to conventional metals are related to the coupled effect of magneto-mechanical field energy. Moreover Terfenol-D shows the variability in the elastic modulus, which is nonlinearly changes with the application of stresses, magnetic field and temperature as demonstrates in **Figure 1.8** [17]. Hence, the inherent multi-physics of magneto-thermo-elasticity phenomena have introduced a broad application prospect of the Terfenol-D in an array of intelligent devices with the requirement of actuation and sensing properties.

1.1.2. Fracture and Fatigue failure of giant magnetostrictive materials

Giant magnetostrictive materials (GMM) exhibit nonlinear magneto-thermo-elastic coupling phenomena and possess such distinctive properties as high saturation magnetostriction, variable elastic modulus, high curie temperature and faster response to operational factors, thereby finding potential applications in sensors, actuators, acoustic transducers, stress monitoring devices, linear motors, micro-pumps and micro-positioners [1–3] [4,5]. However, the attractiveness comes with a cost, that the Terfenol-D is an expensive alloy and challenging to manufacture owing to the high reactivity of its constituent elements and impurities [18,19]. The biggest drawback of Terfenol-D is its extremely brittle characteristics, and in the presence of manufacturing flaws, it has a substantially lower tensile strength than its compressive strength [20]. Manufacturing flaws such cracks, cavities, inclusions, de-bonding, and dislocations can concentrate stress, leading to critical crack propagation and ultimately mechanical failure. Now a days, giant magnetostrictive material based intelligent devices are widely used in industries such as automotive, avionics, and construction engineering. The dynamic forces generated by these kinds of industrial applications could cause undesired operating circumstances and structural vibrations in intelligent devices. In helicopters, for instance, the variable stiffness of the gear mesh causes extreme vibration, which in turn causes excessive noise inside the chopper (up to 120 dB) and pilot fatigue. Terfenol-D actuators are used in parallel to helicopter gearbox support strut to attenuate the kinetic energy by 30-40 dB on the fuselage connection side as shown in **Figure 1.3**. The internal combustion engine and gearbox in a vehicle are major sources of vibration that, depending on the engine's rotational speed, can cause a wide range of audible and tangible discomfort. **Figure 1.4** shows a gear box assembly incorporating two pair of Terfenol-D actuators around the driving shaft to attenuate the gearbox vibrations. So, the high level of brittleness, low tensile strength, manufacturing flaws, and unwanted operating

conditions limit the broader use of Terfenol-D based smart sensing devices in such industries and make them prone to in-service fatigue-fracture failure, particularly in the presence of a magnetic field. The failure and fracture pattern which might be considered stochastic in nature to predict with certainty can therefore compromise its performance.

These constraints encourage authors to dig further into the subject of defect susceptibility in Terfenol-D. Significant efforts have been made to investigate the influence of crack and notches on the tensile behaviour of the brittle materials and in past decades [21–23]. Consequently, extensive research has also been carried out concerning the performance of the giant magnetostrictive materials, but only a minimal effort has been dedicated to understanding the fracture behaviour of such material. This material is brittle enough to exhibit catastrophic fracture dominant failure behaviour without any precursor warning.

Numerical and experimental studies were performed by Narita et al. [24] to examine the three-point bending fracture behaviour of the Terfenol-D under the open mode loading condition. Decrements in the fracture load was cited for single-edge bend specimen under magnetic ambience. Colussi et al. [25] included the averaged strain energy density (SED) criterion to correlate the reduction in the fracture load to the rise in energy release rate as the magnetic field increased. Peron et al. [26] recently investigated the mixed-mode I-II crack growth behaviour of U-notched specimens under a magnetic field, and subsequently validated the Narita et al. [24] results. They reported that although mode I was usually dominant in fracture, increased contribution of mode II caused higher fracture loads. The experimental findings were compared with the distinct failure criteria, and it was found that the strain energy density approach demonstrates superior estimates in the presence and absence of external fields. The cyclic fatigue behaviour in single-edge bend specimens of GMMs in the presence of a magnetic field is numerically and experimentally investigated

by Narita et al. [27]. The three-point bend test is employed to obtain the number of cycles required for failure in sinusoidal mechanical loads in the presence and absence of a magnetic field. A decrement in the number of cycles to failure for Terfenol-D is observed in the presence of a magnetic field. Though the material is highly brittle requiring more number of specimens to certify its mechanical properties with a certain degree of confidence, in all the relevant studies [24–26], the number of experimental specimens for each case is restricted to 3-4, which might otherwise be ascribed to its high cost and requirement of specific skill set/accessories for ASTM experimentations.

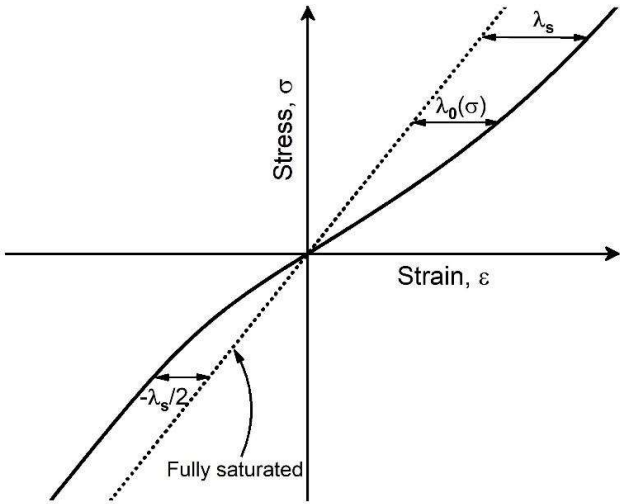


Figure 1.9 Stress-strain curve for Terfenol-D rod when magnetization $M = 0$. Where, $\lambda_0(\sigma)$ is Stress Dependent Nonlinear Strain caused by the Magnetic Domain Rotation and λ_s is Saturated Magnetostriction

In earlier works, the mean fracture load was determined by simple averaging of the obtained data set. Not ignoring the constraints and complications being many, in reality, the reported fracture load data suggested substantial variance and obtaining the mean value by simple averaging would be error-prone. Moreover, the linearized piezomagnetic constitutive laws along with the second-order magneto-elastic constants were applied to evaluate the plane

strain energy release rate values, though it was well established that the material is bi-nonlinear with different stress-strain characteristics in tension and compression as shown in **Figure 1.9**. The magneto-thermo-elastic response of such sentient magnetostrictive materials (e.g., Terfenol-D) are also nonlinear and hysteretic as demonstrated in numerous experimental studies [5,14,17,28]. Additionally, the magnetization and magnetostriction curves are sensitive to applied stresses, ambient temperature, external magnetic field direction and demagnetizing field and exhibit the saturation phenomena. The experiments performed by J. L. Butler [28] demonstrated that the stress-strain relationship of Terfenol-D is essentially nonlinear and different under tension and compression in the absence of an applied magnetic field. This bi-nonlinear behaviour changes with the increasing magnetization of the material, and at saturation, the relationship becomes linear. In addition, Kellogg and Flatau [3] experimental findings revealed that the nonlinear magneto-elastic strain of Terfenol-D is not only dependent on stresses but also varies with the change in the applied magnetic field. Thereby, Terfenol-D displays the variability in Young's modulus (i.e., ΔE effect), which has nonlinear dependence on the stress and magnetic field. It is a well-recognized fact that the singular stresses are present near the crack front of a fracture process zone. The bi-nonlinearity also imparts ambiguity in the failure behaviour of the smart devices, resulting in an unwarranted compromise on the safety aspects. Inadequate explanations for several catastrophic failures of such devices built on highly brittle magnetostrictive materials lead to serious design errors and susceptibility of the component in general.

The nature of failure of the Terfenol-D is highly brittle and its tensile strength is varying in range of 25-50 MPa [14,18,28], which induces a great uncertainty in its fracture load. In such scenarios, Weibull distribution is considered to be widely employed to characterize the mechanical experimentation data [29,30]. From the numerous investigations performed on

different materials, for example, Green and Campbell [31] found that Weibull statistical model is appropriate to characterize the tensile strength of casted Al-Si alloys. On the application of Weibull statistical model, Guazzato et al. [32] concluded that the Inceram-Zirconia composites have substantial lower strength than zirconia. Gong et al. [33] elaborated on the variation of the experimentally observed indentation toughness. Bhushan and Panda [34] characterized the fracture load data of nuclear grade graphite samples using two and three parameter based Weibull distribution. The experimental fracture load data of Terfenol-D is seen to be statistically distributed and this is ascribed to the inhomogeneous distribution and orientation of the flaws in the material. Therefore, its fracture behaviour can be predicted with a weakest link theory-based Weibull approach by evaluating the Weibull parameters (specifically Weibull modules and Weibull characteristics strength) for enhancing the reliability of structures at extreme service conditions.

Thus, for the structural integrity of giant magnetostrictive materials, which is a serious concern, it is necessary to delve deeply into the mechanisms of fracture under magneto-thermo-elastic loading to develop a reliable intelligent system with a certain degree of satisfactory functionality. Then, this research aims to advance the state-of-the-art by experimentally and numerically investigating the fatigue and fracture strength of the giant magnetostrictive material with an accurate numerical hysteretic constitutive law capable of predicting the coupled bi-nonlinear deformation behaviour of the material efficiently, specifically, at high-stress regimes.

1.1.3. Constitutive modelling

The theoretical foundations of the coupled constitutive model from the macroscopic point of view goes back to Maugin and Eringen (1972) [35] and their research citations. In early attempts, a linear piezomagnetic model was established[1,5], which is still most extensively applied in engineering applications. The piezomagnetic model is only relevant when the

applied magnetic field and stress in the magnetostrictive material display very limited variation near its operating regime comprising of a magnetic bias state. As well, the piezomagnetic coefficient ($d_{33} = \partial \varepsilon(\sigma, H) / \partial H$) exclusively rely on the variations of the stresses and applied magnetic field. The piezomagnetic coefficient varies nonlinearly with applied magnetic field and prestress in the region of low to moderate applied magnetic field [14]. At high magnetic field levels, saturation occurs and the piezomagnetic coefficient becomes independent of applied magnetic field and prestress. Even with the inclusion of second-order magneto-elastic constants in the fracture study, the updated piezomagnetic model is cumbersome and inexpedient to comprehensively characterize the inherent nonlinear phenomenon of the giant magnetostrictive material over a wide range of the stress and externally applied magnetic fields.

In a first, Carman and Mitrovic[36] presented a coupled non-linear constitutive model for magnetostrictive materials from thermodynamic principles using the truncated polynomial/Taylor series expansion of Gibbs free energy with only relevant and experimentally verified constants. However, the constitutive model defining the variability of Young's modulus (ΔE) with the change in the state of stress and magnetic field nonlinearity was a challenge for further development of piezomagnetic smart systems. In regard to stimulating the intrinsic nonlinear phenomenon, Wan et al.[37] established three magneto-elastic coupled constitutive models, i.e. the standard square (SS) model, hyperbolic tangent (HT) model and density of domain switching (DDS) based model. The SS model is accurate in estimating the experimental results in the low and moderate magnetic field. In contrast, HT and DDS models can simulate the saturated magnetostriction up to some extent. Duenas et al. also [38] used magnetization, temperature and stress as variables to account nonlinear coupling effects in magneto-strain under weak and moderate magnetic field. But, it is noticed that predictions made by these models [36–38] have shown significant

discrepancies with experimental results of Moffett et al.[14] in the high field and high prestress levels and cannot describe the ΔE effect. To aid in this process, Zheng et al.[39,40], Zhang et al.[41] and Zhou et al.[42] developed the relevant nonlinear one-dimensional constitutive theories for isotropic magnetostrictive materials under the combined effect of the applied magnetic field, prestresses and temperature, based on the fact that nonlinear part of elastic strain is related to magnetic domain rotation. Although, the aforementioned 1-D models have been able to capture the ΔE effect to some extent but restricted to describe the anhysteretic nature of magnetostrictive materials.

At present, some extensively used approaches to describe the magnetic hysteresis are Preisach model, Free energy model and Jiles-Atherton model. The Preisach model [43,44] is a kind of macroscopic model, which possess a large amount of physically irrelevant parameters. Thus, it cannot be adapted for variable operating conditions. Whereas, the Free energy model [45] analyses Helmholtz free energy at the lattice or domain level with stochastic distributions to accommodate material and field non-homogeneities to obtain macroscopic hysteresis model. This model is limited to the one-dimensional case and neglects the thermal effects as well as the crystalline anisotropy, which is a crucial parameter at low-stress levels. As an example, the analysis for the strength of magnetostrictive material requires a fully coupled 3-D hysteresis model that can capture hysteresis effects when magnetostrictive material is subjected to a wide range of stresses, i.e., from zero stress level to singular stresses. Next, Jiles and Atherton[46] introduced a physics-based theory of ferromagnetic hysteresis for isotropic polycrystalline materials that rely on the domain wall structure. In this theory, impedances to domain wall motion due to pinning sites is considered as a significant cause of hysteresis, while the magnetic moments interactions are shown to be of secondary importance. This model has been widely used due to its inherent advantages, such as few physical material parameters and computational simplicity. In subsequent

studies, numerous extensions [47–51] of this model were reported to include the effect of stress, temperature and exchange interaction energy. Furthermore, Zheng and Sun [52] added the hysteresis behavior in the nonlinear one dimensional constitutive model for magnetostrictive materials on the basis of the Jiles-Atherton hysteresis model. Since these one-dimensional nonlinear models are inadequate to characterize the magnetostriction in magnetostrictive films, thus Liu et al.[53] linearized the nonlinear part of elastic strain for small prestresses to establish a more general 3-D constitutive model for isotropic magnetostrictive materials. Subsequently, Jin et al.[54] extended this approach to include the hysteresis behavior of nonlinear magneto-thermo-elastic coupling.

The shortcomings of the traditional linearized phenomenological models arise due to the several magneto-elastic approximations which are unrealistic and not physically meaningful for practical application, such as analysis of singular stresses near a crack tip in the fracture region of magnetostrictive materials[55]. They induce substantial errors, including unfeasible results at large prestress levels and the broader region of magnetic spectrum, thereby rendering the developed smart structure unreliable with a susceptible response. More importantly, the effect of demagnetization should be considered for the case of magnetostrictive films or bars. Since the surface divergence of magnetization vector rises the demagnetizing field [56,57], the magnetization distribution in non-ellipsoidal shapes [58–60] (such as bars, films) is no longer uniform, thus affecting the operation of magnetostrictive devices. Therefore, in order to determine more accurately the performance and in-service strength of magnetostrictive devices, a comprehensive generalized coupled magneto-thermo-elastic nonlinear hysteretic constitutive model is required.

1.2. Research objectives

The significance of the term “magneto-elastic fatigue and fracture” relevant to giant magnetostrictive materials in literature emphasizes the importance of such an analysis. Very few studies are performed related to evaluate the fracture and fatigue parameters, however all the concerning studies are limited to small number of experimental samples and piezomagnetic (linear) models. Evidently, the magneto-elastic response of the such giant magnetostrictive materials (e.g., Terfenol-D) is hysteretic, nonlinear and demonstrates the saturation phenomenon. The stress-strain relationship of Terfenol-D is bi-nonlinear in the absence of an applied magnetic field. This bi-nonlinear behaviour changes as the magnetization of the material increases, and the relationship becomes linear at saturation. Additionally, Terfenol-D shows the ΔE effect, which has nonlinear dependence on the stress and magnetic field. Thus, the nature of the failure in a bimodular material is influenced by the state of tension and compression regions in the flexure loading, which is largely neglected in existing literature. It is a well-recognized fact that the singular stresses are present near the crack front of a fracture process zone. In such cases, determining the position of the neutral axis is crucial to accessing the stress state singularity. When the stress-strain behaviour is different in tension and compression, it becomes tedious to determine a closed form solution accounting the singularity at the crack front. This happen to be a classical stress-dependent elasticity problem and additionally, for magnetostriction fatigue-fracture studies, the multi-physics of magnetic field domain must be coupled to the elasticity solution. It would be unwise to ignore this real field phenomena which might otherwise have caused many unwarranted failures in design of smart devices based on such materials. Also, the three-dimensional treatment is necessary to analyses this nonlinear fracture phenomenon [55,61,62]. A robust fracture and fatigue parameters prediction model for magneto-

elastically coupled GMMs that will be appropriate for numerical analysis, is required as the most potent driving force in GMMs fracture research. The constraints are threefold:

1. The coupled hysteretic constitutive model for giant magnetostrictive material must be suitable to include the effect of magnetic field and mechanical stresses, especially in the regions of high field and stresses.
2. The adequate characterization of stochastic experimental failure data by using the proper probabilistic technique.
3. The numerical model must be suitable for evaluating fatigue and fracture parameters based on nonlinear coupled field physics phenomena.

Hence, objectives of present research work are

1. to establish a hysteretic and nonlinearly coupled magneto-thermo-elastic constitutive model of bulk giant magnetostrictive material by employing a novel vector generalized hyperbolic function.
2. validation of the proposed coupled magneto-thermo-elastic constitutive model with the existing experiments of magneto-thermo-elastic response for Terfenol-D rods and films.
3. formulation of 3-D path independent J-integral for the coupled magneto-thermo-elastic field.
4. experimental characterization of the coupled magneto-elastic response of procured Terfenol-D and optimize the material parameters for Terfenol-D used in the proposed coupled magneto-thermo-elastic constitutive model.

5. to conduct the three-point flexure fracture testing of the single edge notch bend (SENB) specimen in the absence and presence of an external magnetic field in accordance with ASTM standards and evaluate the experimental fracture toughness.
6. to forecast the mean peak fracture load for Terfenol-D SENB specimens using the Weibull statistical theory of strength.
7. to update the 3-D path independent J-integral based on the proposed coupled magneto-thermo-elastic constitutive model and numerically evaluate the critical strain energy release rate J_{Ic} using the mean peak fracture load in both the absence and presence of the external magnetic field.
8. to conduct the three-point flexure fatigue testing of the single edge notch bend (SENB) specimen in the absence and presence of an external magnetic field in accordance with ASTM standards (i.e., E399 and E 647) and determination of the propagation of crack growth with the number of cycles.
9. numerical determination of updated Paris law constants from the correlation of the crack growth rate with the values of ΔJ for a set of particular load ratio, magnetic field and cyclic frequency.
10. to compare the experimentally and numerically evaluated data for fracture loads with the number of cycles spent.

1.3. Scope of research

A hysteretic and nonlinearly coupled magneto-thermo-elastic constitutive model of bulk giant magnetostrictive material is proposed. Specifically, this theory employs a novel vector generalized hyperbolic function to include the effects of a wide range of stress and magnetic field. This constitutive model works efficiently in the presence of simultaneous application of the three-dimensional magnetic field by including the vector generalization approach for

the Jiles-Atherton model to three dimensions, the physics of demagnetization, and the Weiss molecular field. The functional forms of the constitutive relations are specified. This novel hysteretic constitutive model is used to predict the coupled magneto-thermo-elastic response of the giant magnetostrictive material. This fully coupled hysteretic constitutive description along with the governing equations of magnetic field, elastic field, and thermal field has been implemented into a finite-element based code COMSOL Multiphysics by using a general $\mathbf{H}(\mathbf{B})$ relation is coded in the C programming language. This model can fully describe the combined effect of prestress, temperature and applied magnetic field on the magnetostriction, magnetization and elastic strain inclusive of the ΔE effect.

From the literature studies, it was apparent that experimental and numerical stochastic works are a few for such coupled magnetic and stress-dependent elasticity fatigue-fracture studies of giant magnetostrictive materials such as Terfenol-D. The present study laid a procedure to accurately determine the in-service fatigue and fracture strength of the Terfenol-D. It constitutes exclusive magneto-elastic experiments to characterize the magnetic response parameters and material elasticity constants, Weibull statistical analysis to determine the Weibull parameters and finite element analyses to investigate the fatigue and fracture parameters of the bi-nonlinear Terfenol-D. The magneto-elastic coupled field three-point bend experimentation on two sets of single edge notch bend (SENB) specimens of Terfenol-D is carried out in the presence and absence of the magnetic field. Consequently, the failure load (P) data is determined for quasi-static and cyclic loading conditions. A three-dimensional magneto-elastic J-integral definition for characterizing the fracture behaviour has also been presented employing the Eshelby [63] four-dimensional dynamic energy-momentum tensor. The critical strain energy release rate of the Terfenol-D SENB specimen under an applied external magnetic field is determined by employing a vector generalized nonlinear hysteretic magneto-thermo-elastic constitutive model into finite element based

COMSOL Multiphysics. In case of fatigue failure, the updated Paris law constants from the correlation of the crack growth rate with the values of ΔJ for a particular set of load ratio, magnetic field and cyclic frequency has been numerically determined. Additionally, the experimentally and numerically evaluated fatigue-fracture load data with the number of cycles spent has been compared for the validation and applicability of evaluated updated Paris law constants.

1.4. Dissertation outline

The present dissertation is structured in accordance with the hierarchical order of the research objectives and consists of eight chapters, an appendix, and a bibliography of cited references. This dissertation is primarily organised into two sections. The first section presents the theoretical framework and covers chapters 2 through 4. A novel hysteretic and nonlinearly coupled magneto-thermo-elastic constitutive model of bulk giant magnetostrictive material is proposed. A three-dimensional magneto-elastic J-integral formulation has also been presented. The second section of this dissertation from chapter 5 to chapter 8 details the experimental and numerical analysis plan to characterize the magneto-elastic response, and fatigue and fracture parameters of giant magnetostrictive material (i.e., Terfenol-D). The contents of each chapter are listed below.

The first chapter provides motivation, identifies objectives, and outlines the dissertation.

The chapter 2 gives an overview of the basic concepts of electromagnetism, magneto-elasticity, and fatigue and fracture mechanics. The electromagnetism section of this chapter consists of a description of fundamental magnetic phenomena of giant magnetostrictive material featuring a discussion on magnetostriction and magnetization processes, material properties, and the effect of prestresses, applied field and environment temperature on the materials response. The magneto-elasticity section discusses the magneto-mechanical coupling effect on the constitutive relations of the material. The last section provides a

glimpse on the fundamentals of the magneto-elastic fracture and fatigue mechanics. This serves as the foundation for chapters 3-9.

Starting from the third chapter, a generalized nonlinear hysteretic thermo-magneto-elastic vector model of bulk giant magnetostrictive material is proposed using the thermodynamic relations coupled with the Taylor series expansion of Gibbs free energy density function for elastic deformation, the physics of demagnetization, and the Weiss molecular field. The magneto-thermo-elastic responses for rods/bars and, more importantly, for thin films/plates are numerically predicted and compared with the existing experimental ones in the literature for verification. The relative influence of magnetization, elastic, and thermal parameters on the coupled field response is characterized.

A 3-D path independent integral for mode I crack has been formulated in Chapter 4. For maintaining the generality, the influence of magneto-thermo-elasticity is taken care of with the thermal strain, magnetic strain, and the magnetic body force terms. However, the present fatigue and fracture investigation is primarily focused on the magneto-elastic physics.

Chapter 5 describes the magneto-elastic coupled field experimentation scheme for the procured Terfenol-D specimens to evaluate the magnetization, magnetostriction, and compressive stress-strain behaviour of the material as per the outlines mentioned in the respective ASTM standards. Then, the material properties are calibrated for the Terfenol-D specimens based on the physical and experimental evidence for magnetization and magnetostriction curves. The material parameters are optimized in this chapter to be further used in the constitutive model of the numerical fatigue and fracture analysis.

Chapter 6 provides an experimental plan to characterize the fracture parameters of giant magnetostrictive material (GMM) in the coupled magneto-elastic field as per ASTM E399/E1820. The mean peak fracture load has been forecasted by using the two parameter

Weibull statistical theory of strength. Then a numerical scheme is described to compute the fracture parameters of the Terfenol-D SENB specimen under an applied external field. A finite element model of the specimen has been created similar to the experimental one and the critical strain energy release rate J_{Ic} was calculated using the mean peak fracture load in both absence and presence of the external magnetic field.

Chapter 7 describes the three-point flexure fatigue experimental scheme that is used to evaluate the propagation of crack growth with the number of cycles in Terfenol-D SENB specimen with the absence and presence of an external magnetic field as per ASTM standards (i.e., E399 and E 647). This chapter also presents a finite element simulation procedure to determine the updated Paris law constants from the correlation of the crack growth rate with the values of ΔJ for a set of load ratio, magnetic field, and cyclic frequency. The experimentally and numerically evaluated fatigue failure data with the number of cycles spent were then compared to determine the validation and relevance of evaluated Paris law constants.

This dissertation is drawn to a conclusion in Chapter 8, which provides a summary of the major findings and a list of potential areas for future study.

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