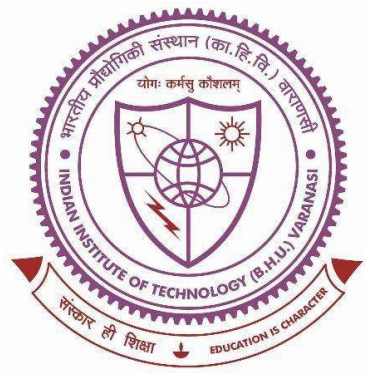
FRACTURE MECHANICS ANALYSIS OF GIANT MAGNETOSTRICTIVE MATERIAL IN THE COUPLED MAGNETO-ELASTIC FIELD



Thesis submitted in partial fulfilment

for the award of degree

Doctor of Philosophy

by

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CERTIFICATE

This is to certify that the work contained in the thesis titled ***"Fracture Mechanics Analysis of Giant Magnetostrictive Material in the Coupled Magneto-Elastic Field"*** by ***"PRAVEEN KUMAR SINGH"*** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

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DECLARATION BY THE CANDIDATE

I ***"Praveen Kumar Singh"***, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of ***"Prof. S. K. Panda"*** from ***" July 2015*** to ***DECEMBER 2022"***, at the ***"DEPARTMENT OF MECHANICAL ENGINEERING"***, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma.

I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

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Abstract

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 sensing and actuation field. Taylor series expansion of Gibbs free energy density function for elastic deformation, the physics of demagnetization and the Weiss molecular field coupled with the thermodynamic relations have been used to develop a generalized nonlinear hysteretic thermo-magneto-elastic vector model with potential application for the development of sensors and actuators. The nonlinear elastic strains in the magnetostrictive material are induced due to the magnetic domain rotation caused by tensile and compressive stresses in giant magnetostrictive materials. A vector function of the hyperbolic tangent is defined to take into account this nonlinear characteristic validating the elastic stress field boundary condition. The vector generalized Jiles-Atherton hysteresis model with modified Langevin equation is employed to incorporate the pinning of magnetic domain walls in the mathematical model. Thus, derived macroscopic model is put to the test for 1D, 2D and 3D nonlinear magnetostriction, magnetization and elastic constitutive relation with Terfenol-D (giant magnetostrictive materials) as a potential candid material. Finite element analyses for rods and films have been conducted using the general $\boldsymbol{H}(\boldsymbol{B})$ relation coded in the C programming language. Employing the calibrated physical and experimental parameter, the confidence of the model is checked with existing analytical and experimental models. The magnetization and magnetostriction hysteresis responses have been evaluated considering the variation of a broad range of the prestress (up to 110 MPa), temperature (0 °C to 80 °C) and applied magnetic field (0 A/m to 193.2 kA/m).

The numerical simulation of this fully coupled phenomenological model demonstrates good agreement with the experimental data. The theoretical modelling error obtained from averaging the normalized root mean square error for each experimental data set is found to be maximum of 2.8 % and hence vindicates the efficacy of the present model.

Then, the proposed the generalized nonlinear hysteretic thermo-magneto-elastic constitutive model is used to derive a universal path independent integral that represents the energy release rate or flux during crack extension in a homogeneous and isotropic material for mode I fracture problem. This version of integral includes the effect of elastic strain, thermal strain, body forces and magnetic strain. Particularly focus is made on magneto-thermo-elastic strains. Some physics-based experiments for magnetization and magnetostriction hysteresis loops and mechanical compression tests under the applied magnetic field are conducted for Terfenol-D based specimens. A finite element study is performed using the proposed constitutive model and consequently, numerical results are compared with experiments to optimize the material parameters. The single edge notch bend (SENB) specimen is subjected to three-point flexure testing in the absence and presence of an external magnetic field in accordance with ASTM E399. The digital image correlation technique is used to capture the load line and crack opening displacement variation peak fracture load data. Two parameter Weibull statistical theory of strength has been utilised to forecast the mean peak fracture load. The Weibull modulus and goodness of fit are assessed using linear regression analysis (LIN2), biased and unbiased maximum likelihood estimation (MLE2-B & MLE2-U) approach. A finite element model based on optimized nonlinear constitutive relations is built concerning to magnetization and stress dependent elasticity problem of Terfenol-D fracture. 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. The influence of bi-nonlinear modularity and applied external

magnetic field on the fracture behaviour of the Terfenol-D SENB specimen were compared with the unimodular experimental results and substantial difference was reported. The stipulation and importance of considering the bi-nonlinear critical strain energy release rate J_{Ic} in the context of a coupled magneto-elastic field was discussed in detail.

Finally, a combined numerical and experimental study has been conducted to understand the influence of magnetic fields on the cyclic fatigue behavior of Terfenol-D. A three-point flexure fatigue experimental scheme is employed 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). A finite element simulation procedure is used to determine 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. 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.

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Praveen Kumar Singh

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Nomenclature

Acronyms

GMM	Giant Magnetostrictive Material
SENB	Single Edge Notch Bend
FE	Finite Element
J-A	Jiles-Atherton
LIN2	Linear Regression Analysis (For two parameter Weibull statistical distribution)
MLE2-B	Maximum Likelihood Estimator- Biased (For two parameter Weibull statistical distribution)
MLE2-U	Maximum Likelihood Estimator- Unbiased (For two parameter Weibull statistical distribution)

Greek characters

ν	Poisson's ratio
σ_{ij}	Total Stress Tensor
$\tilde{\sigma}_{ij}$	Effective Stress Tensor
$\lvert\tilde{\sigma}\rvert$	Max ($\lvert\tilde{\sigma}_{xx}\rvert, \lvert\tilde{\sigma}_{yy}\rvert, \lvert\tilde{\sigma}_{zz}\rvert$)
σ_s	Saturation Stress
ε_{ij}	Total Strain Tensor
δ_{ij}	Kronecker delta
ϵ_{ijk}	Levi-Civita symbol
α	Isotropic Coefficient Of Thermal Expansion
β	Isotropic Linear Variation Coefficient
$\lambda_0(\sigma)$	Stress Dependent Nonlinear Strain caused by the Magnetic Domain Rotation
λ_s	Saturated Magnetostriction
μ_o	Vacuum Permeability
k	Relaxation Factor
χ_m	Initial Susceptibility
η'	Isotropic Weiss Molecular Field Coefficient

χ	Auxiliary Vector Variable
K	Pinning Parameter
c	Reversible Coefficient
ξ	Variation of Anhysteretic Magnetization as a Function of Effective Field
ρ	Mass Density
η_{el}	Elastic geometric factor
$\acute{\alpha}$	Ratio of crack length and width of SENB specimen
$\acute{\beta}$	Ratio of beam span and width of SENB specimen
φ	Magnetic scalar potential

Latin characters

s_{ij}	Stress Deviator Tensor
J_2	Second Invariant of Stress Deviator Tensor
I_σ	First Invariant of Stress Tensor
H_k	Magnetic Field Components
M_k or M_l	Magnetization Components
M_{an}	Anhysteretic Magnetization
H_{eff}	Effective Magnetic Field
B	Magnetic Induction
E_{in}	Intrinsic Young's Modulus
ΔE	Variability in Young's Modulus
M_s	Saturation Magnetization
N_{kl}	Demagnetizing Factor
u_i	Displacements
f_i	Body Forces
P_{max}	Peak Fracture Load
J_{Ic}	Critical Strain Energy Release Rate
K_{Ic}	Fracture Toughness
$\mathcal{W}$	Strain Energy Density
$\mathcal{T}$	Kinetic Energy Density

X_1, X_2, X_3	Rectangular Cartesian Coordinates
S	Span of Specimen
W	Width of Specimen
a	Length of Single Edge Notch
B	Breadth of Specimen
P_f	Probability of Failure
P_u	Threshold Load Parameter
P_θ	Scale Parameter or Characteristic Strength Parameter
m	Distribution Shape Parameter or Weibull Modulus
R^2	Goodness of Fit
T	Ambient temperature
T_r	Easy axis transformation temperature
T_c	Curie temperature
N	Number of cycles

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Preface

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. A robust fracture 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 present work is primarily organised into two parts. The first part presents the theoretical framework including literature review and basic concepts of magneto-elasticity. In this part at first, 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. Then, a 3-D path independent integral for mode I crack has been formulated. 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. This part serves as the foundation for next part.

The second part of this work 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). At first, the magneto-elastic coupled field experimentation conducted 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 to be further used in the constitutive model of the numerical fatigue and fracture analysis. Then an experimental study has been performed 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. Finally, 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). A finite element simulation performed 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.

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