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.