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Appendix A

3-D model for magnetostrictive specimen when magnetic field is applied along the longitudinal axis

For Terfenol-D the 3-D anhysteretic constitutive relations as shown in Eq. (3.29) and (3.31), when homogenous external magnetic field is applied in the longitudinal direction (x-direction) of the specimen can be written as

The relations for $\tilde{\sigma} \geq 0$ (i.e., when $\varepsilon_{ij} = \varepsilon_{ij}^{t}$)

$$
\begin{Bmatrix} \varepsilon_{xx}^{t} \\ \varepsilon_{yy}^{t} \\ \varepsilon_{zz}^{t} \\ 2\varepsilon_{yz}^{t} \\ 2\varepsilon_{zx}^{t} \\ 2\varepsilon_{xy}^{t} \end{Bmatrix}
=
\begin{bmatrix}
\frac{1}{E_{in}} & -\frac{\nu}{E_{in}} & -\frac{\nu}{E_{in}} & 0 & 0 & 0 \\
-\frac{\nu}{E_{in}} & \frac{1}{E_{in}} & -\frac{\nu}{E_{in}} & 0 & 0 & 0 \\
-\frac{\nu}{E_{in}} & -\frac{\nu}{E_{in}} & \frac{1}{E_{in}} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G}
\end{bmatrix}
\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{Bmatrix}
+
\begin{Bmatrix}
\lambda_s \left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) tanh\left(\frac{|\tilde{\sigma}|}{\sigma_s}\right) + \alpha \Delta T \\
\lambda_s \left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) tanh\left(\frac{|\tilde{\sigma}|}{\sigma_s}\right) + \alpha \Delta T \\
\lambda_s \left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) tanh\left(\frac{|\tilde{\sigma}|}{\sigma_s}\right) + \alpha \Delta T \\
0 \\ 0 \\ 0
\end{Bmatrix}
$$

$$
-\frac{\lambda_s\, tanh\left(\frac{|\tilde{\sigma}|}{\sigma_s}\right)}{\left(M_s(T)\right)^2}
\begin{bmatrix}
\left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) & 0 & 0 & 0 \\
\left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) & 0 & 0 & 0 \\
\left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{Bmatrix} M_x^2 \\ M_y^2 \\ M_z^2 \\ M_y M_z \\ M_x M_z \\ M_x M_y \end{Bmatrix}
\quad (A.1)
$$

$$
+\frac{1}{\left(M_s(T)\right)^2}\begin{bmatrix} \lambda_s+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & 0 & 0 & 0 \\ -\frac{\lambda_s}{2}+\beta\Delta T & \lambda_s+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & 0 & 0 & 0 \\ -\frac{\lambda_s}{2}+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & \lambda_s+\beta\Delta T & 0 & 0 & 0 \\ 0 & 0 & 0 & 3\lambda_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 3\lambda_s & 0 \\ 0 & 0 & 0 & 0 & 0 & 3\lambda_s \end{bmatrix}\begin{Bmatrix} M_x^2 \\ M_y^2 \\ M_z^2 \\ M_yM_z \\ M_xM_z \\ M_xM_y \end{Bmatrix}
$$

The relations for $\tilde{\sigma} < 0$ (i.e., when $\varepsilon_{ij} = \varepsilon_{ij}^c$)

$$
\begin{Bmatrix} \varepsilon_{xx}^c \\ \varepsilon_{yy}^c \\ \varepsilon_{zz}^c \\ 2\varepsilon_{yz}^c \\ 2\varepsilon_{zx}^c \\ 2\varepsilon_{xy}^c \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{in}} & -\frac{\nu}{E_{in}} & -\frac{\nu}{E_{in}} & 0 & 0 & 0 \\ -\frac{\nu}{E_{in}} & \frac{1}{E_{in}} & -\frac{\nu}{E_{in}} & 0 & 0 & 0 \\ -\frac{\nu}{E_{in}} & -\frac{\nu}{E_{in}} & \frac{1}{E_{in}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{bmatrix}\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{Bmatrix} + \begin{Bmatrix} \frac{\lambda_s}{2}\left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) tanh\left(\frac{2|\tilde{\sigma}|}{\sigma_s}\right)+\alpha\Delta T \\ \frac{\lambda_s}{2}\left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) tanh\left(\frac{2|\tilde{\sigma}|}{\sigma_s}\right)+\alpha\Delta T \\ \frac{\lambda_s}{2}\left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) tanh\left(\frac{2|\tilde{\sigma}|}{\sigma_s}\right)+\alpha\Delta T \\ 0 \\ 0 \\ 0 \end{Bmatrix}
$$

$$
-\frac{\lambda_s\, tanh\left(\frac{2|\tilde{\sigma}|}{\sigma_s}\right)}{2\left(M_s(T)\right)^2}\begin{bmatrix} \left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{xx}}{|\tilde{\sigma}|}\right) & 0 & 0 & 0 \\ \left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{yy}}{|\tilde{\sigma}|}\right) & 0 & 0 & 0 \\ \left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) & \left(\frac{\tilde{\sigma}_{zz}}{|\tilde{\sigma}|}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} M_x^2 \\ M_y^2 \\ M_z^2 \\ M_yM_z \\ M_xM_z \\ M_xM_y \end{Bmatrix} \qquad \text{(A.2)}
$$

$$+\frac{1}{\left(M_s(T)\right)^2}\begin{bmatrix} \lambda_s+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & 0 & 0 & 0 \\ -\frac{\lambda_s}{2}+\beta\Delta T & \lambda_s+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & 0 & 0 & 0 \\ -\frac{\lambda_s}{2}+\beta\Delta T & -\frac{\lambda_s}{2}+\beta\Delta T & \lambda_s+\beta\Delta T & 0 & 0 & 0 \\ 0 & 0 & 0 & 3\lambda_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 3\lambda_s & 0 \\ 0 & 0 & 0 & 0 & 0 & 3\lambda_s \end{bmatrix}\begin{Bmatrix} M_x^2 \\ M_y^2 \\ M_z^2 \\ M_yM_z \\ M_xM_z \\ M_xM_y \end{Bmatrix}$$

$$\begin{Bmatrix} H_x \\ 0 \\ 0 \end{Bmatrix} = \frac{1}{k}\begin{bmatrix} f^{-1}\left(\frac{M_x}{M_s(T)}\right) & 0 & 0 \\ 0 & f^{-1}\left(\frac{M_y}{M_s(T)}\right) & 0 \\ 0 & 0 & f^{-1}\left(\frac{M_z}{M_s(T)}\right) \end{bmatrix} + \begin{bmatrix} N_{xx}-\eta' & 0 & 0 \\ 0 & N_{yy}-\eta' & 0 \\ 0 & 0 & N_{zz}-\eta' \end{bmatrix}\begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} +$$

$$\frac{2\beta I_\sigma \Delta T}{\mu_o\left(M_s(T)\right)^2}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} - \frac{\lambda_s}{\mu_o\left(M_s(T)\right)^2}\begin{bmatrix} 2\tilde{\sigma}_x-\lambda_{0ij}\sigma_{ij} & 2\tilde{\tau}_{xy} & 2\tilde{\tau}_{xz} \\ 2\tilde{\tau}_{xy} & 2\tilde{\sigma}_y-\lambda_{0ij}\sigma_{ij} & 2\tilde{\tau}_{yz} \\ 2\tilde{\tau}_{xz} & 2\tilde{\tau}_{yz} & 2\tilde{\sigma}_z-\lambda_{0ij}\sigma_{ij} \end{bmatrix}\begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} \quad \text{(A.3)}$$

where

$$\lambda_{0ij}\sigma_{ij} = \begin{cases} \frac{3J_2}{|\tilde{\sigma}|}tanh\left(\frac{|\tilde{\sigma}|}{\sigma_s}\right) & \tilde{\sigma} \geq 0 \\ \frac{3J_2}{2|\tilde{\sigma}|}tanh\left(\frac{2|\tilde{\sigma}|}{\sigma_s}\right) & \tilde{\sigma} < 0 \end{cases} \quad \text{(A.4)}$$

List of Publications

International Journal (SCI)

1. **P. K. Singh,** Ashish Singh Pareta, S. K. Panda, "Influence of the bi-nonlinearity on the characterization of Mode I fracture parameter J_{Ic} for a cracked giant magnetostrictive material in the coupled magneto-elastic field: An experimental and numerical study", *Engineering Fracture Mechanics,* vol. 279, p. 109046, Jan. 2023, doi: https://doi.org/10.1016/j.engfracmech.2023.109046

2. **P. K. Singh**, S. K. Panda, and C. Rath, "Hysteretic response of bulk magnetostrictive material employing a novel hyperbolic vector generalized magneto-thermoelastic constitutive model," *Sensors Actuators A Phys.*, vol. 331, p. 112963, Nov. 2021, doi: 10.1016/J.SNA.2021.112963.

3. A. Bhushan, S. K. Panda, **P. K. Singh**, P. Kartheek, R. Kumar, and Y. Mittal, "3D Path independent integral for thermoelastic and magnetostriction problem," *Mech. Res. Commun.*, vol. 92, pp. 15–20, 2018, doi: 10.1016/j.mechrescom.2018.06.005.

4. **P. K. Singh**, Ashish Singh Pareta, S. K. Panda, "Evaluation of fatigue fracture life of giant magnetostrictive materials under coupled magneto-thermo-elastic loads: experimental and numerical analysis". (Communicated in Int. journal of fatigue, ELESVIER)

International Journal (SCOPUS)

1. **P.K. Singh**, A.S. Pareta, A. Bhushan and S.K. Panda. 2022, "Effect of Thickness Ratio on the Magnetic Properties of the Magnetostrictive Thin Film Composite", *Int. J. Vehicle Structures & Systems*, 14(6), 758-762. doi:10.4273/ijvss.14.6.12.

2. **P.K. Singh**, A.S. Pareta, A. Bhushan et al., The effect of temperature on giant magnetostrictive thin films in high pre-stress environment for sensor application, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2023.04.681

International Conferences

1. **P.K. Singh**, Ashish Singh Pareta, Awani Bhushan, S. K. Panda. "Effect of thickness ratio on the magnetic properties of magnetostrictive thin-film composite" International Conference on Applications in Computational Engineering & Sciences 2021, VIT, Chennai.
2. Ashish Singh Pareta, **P.K. Singh**, Awani Bhushan, S. K. Panda. "Influence of thermal and high prestress environment on the response of Giant magnetostrictive thin films" International Conference on Applications in Computational Engineering & Sciences 2021, VIT, Chennai.
3. **P.K. Singh**, Ashish Singh Pareta, Awani Bhushan, S. K. Panda. "The effect of temperature on giant magnetostrictive thin films in high pre-stress environment for sensor application" SESBT 2022, VIT, Chennai