3D-FEM-Simulation of Magnetic Shape Memory Actuators

M.Schautzgy*[1/2], U.Kosiedowski[2] and T.Schiepp[1]
[1]ETO MAGNETIC GmbH, Hardtring 8, 78333 Stockach, Germany
[2]University of Applied Science Konstanz, Brauneggerstrasse 55, 78462 Konstanz, Germany
*Corresponding author: Hardtring 8, 78333 Stockach, Germany, m.schautzgy@etogroup.com

Abstract: The magneto-mechanical behavior of **M**agnetic **S**hape **M**emory (MSM) alloys has been investigated by means of different simulation and modeling approaches. Based on these approaches the target of this work is to simulate actuators driven by MSM alloys with the 3D-FE-tool COMSOL Multiphysics® (AC/DC module). The results are compared with measurements and existing 2D-FE-simulations of the alloy. For this work an existing standard magnetic circuit is used to perform the tests. One approach of modeling MSM actuators is described in this paper. The used approach is so far the most accurate but also the most time consuming. Reaching sufficient precise results with a 3D-FE-software-tool like COMSOL Multiphysics® would increase efficiency and quality of developing products based on magnetic shape memory alloys.

Keywords: Magnetic Shape Memory Alloys, Smart Materials, Magnetic Anisotropy

1. Introduction

Electromagnetic actuators are a well known field where finite element simulations are applied. Magnetic Shape Memory actuators represent a new type of smart electromagnetic actuators where the MSM material elongates and contracts when applying a magnetic field. The MSM material typically is a monocrystalline Ni-Mn-Ga Heusler alloy [1]-[2], which has the ability to change its size and shape many million times repeatedly [3]. Well known alloys are able to achieve a strain of up to 6 -12% [4]. The ability of the MSM material to change its size, shape and magnetization curve causes several effects on the MSM actuator like a change of the inductance and the magnetic resistance [5]. That means that MSM alloys are classified as strongly nonlinear materials. Since in practical applications actuators should be small and efficient these effects have a great impact when considering that small actuators produce only a limited amount of magnetic energy. Over the last decades industrial development cycles have become considerably shorter, accompanied by a continuous demand for the reduction of development costs. For a further commercialization of the MSM actuator technology such tools as well as simulation strategies must be established for engineering purposes. Target of this research is to propose the magneto-mechanical behavior of MSM alloys as precise as possible by using the first time a 3D-FEM-tool for the considered simulation approach.

2. MSM Alloys in this simulation

2.1 Twinning Structure

The typical bulk sample has a tetragonal shape and each edge is several millimeters long. Such a sample is often called MSM stick or MSM element. Fig. 1 shows the effect of a MSM stick in an actuator. An induced magnetic field (red arrows) between the pole shoes of an iron core (green blocks) actuates the MSM stick (blue block) which changes his shape by extending a first the long and shrinking a second the short edge.

Figure 1 MSM stick as an actuator [7]

In this work a stick with a shape of 2 x 3 x 15 mm³ is used. To simulate the shape memory effect of the MSM stick it is necessary to describe more detailed the structural behavior of the alloy. During cooling from the high temperature austenite parent phase a self-accommodated martensite variant structure is formed in Ni-Mn-Ga MSM materials. The transformation occurs by a shear-like mechanism involving a minor shift of atomic positions, driven by the lower level of free energy of martensite. Based on the asymmetric crystal structure of the martensite several regions with different orientations (but with the same crystallographic structure) are formed. These are called twin variants and are separated by a coherent variant boundary. Movement of these twin boundaries by mechanical stress or magnetic field leads to the macroscopic shape change of MSM materials. The mechanical stress needed to move the twin boundaries is called twinning stress, and is an important parameter used in MSM materials characterization and actuator design. In MSM materials, twinning occurs on different length scales in a hierarchical manner. It should be noted, that this work suggests a representation only of the macroscopic twin structure in the FEM simulation with a typical twin sizes ranging from a few 10's of micrometers up to higher millimeters range. Possible effects of micro twins are not considered here.

2.2 Magnetization curve

The magnetization curve of the simulated MSM stick was measured as a function of an external magnetic field *H*. The field was induced like shown in Fig. 1. MSM alloys are highly nonlinear anisotropic materials with different relative permeability μ_r depending on orientation and strain of the stick. That means that the relative permeability μ_r and thus the magnetizations of the easy and hard axis exchange their orientation with the elongation depending on the magnetic field *H*. The magnetization curve for the hard axis was measured in a compressed, the easy axis in a fully elongated stick. The switching behavior of the axis is taken into account in the FEM model by using a magnetization curve which corresponds locally to the switching status (globally to the strain) of the MSM stick. The resulting *B*(*H*) curve of the magnetization is shown on Fig. 2. For the simulations only the positive part of the hysteresis is modeled.

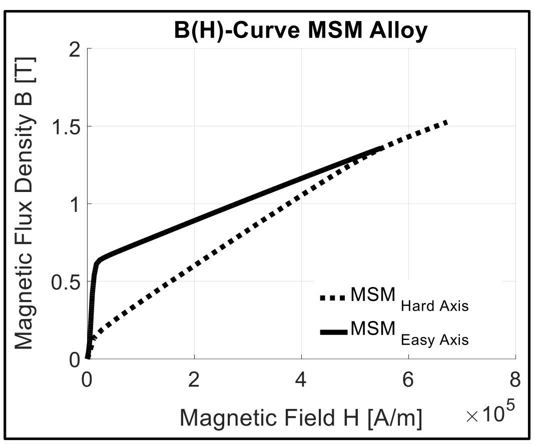

Figure 2 *B(H)* curve of 2 x 3 x 15 mm³ MSM stick

Regarding the fact that anisotropic properties of magnetic materials in COMSOL Multiphysics® (AC/DC module) are described with the relative permeability μ_r it is necessary to model the *B(H)* curves for the hard and easy axis of the MSM stick as a function of the relative permeability μ_r depending on the magnetic flux density *B*. This can be formulated with the fundamental equation for *B* (1) and μ_r (2).

$$B = \mu_0 \cdot \mu_r \cdot H \tag{1}$$

$$\mu_r = \frac{B}{\mu_0 \cdot H} \tag{2}$$

For every measured point on the magnetization curve the equation for μ_r (2) is used. Mathematically μ_r can be described as function of the flux density *B* (3).

$$B = \mu_0 \cdot \mu_r(B) \cdot H(B) \tag{3}$$

Observing a correct physically behavior the initial permeability μ_i has to be formulated (4).

$$\mu_i(B) = \frac{1}{\mu_0} \cdot \lim_{B\to 0} \frac{B}{H(B)} \tag{4}$$

With this correlation the relative permeability can be formulated with (5) and (6):

$$\mu_r(B) = \frac{B}{\mu_0 \cdot H(B)} + \mu_i(B) \tag{5}$$

$$\mu_r(B) = \frac{B}{\mu_0 \cdot H(B)} + \frac{1}{\mu_0} \cdot \lim_{B\to 0} \frac{B}{H(B)} \tag{6}$$

Applying those equations on the dataset of the *B(H)* curve (Fig. 2) a function diagram for μ_r shown on Fig. 3 can be created.

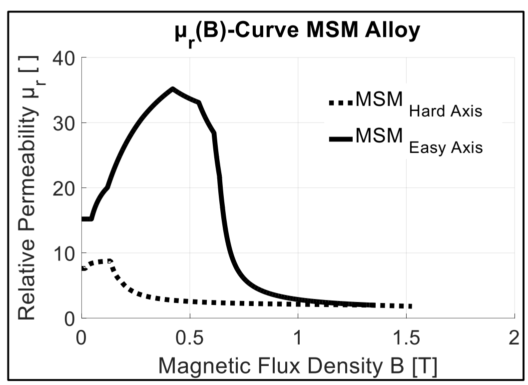

Figure 3 $\mu_r(B)$ curve of 2 x 3 x 15 mm³ MSM stick

A maximum relative permeability $\mu_r(B) \sim 35$ of this MSM stick is reached by a magnetic flux density $B \sim 0.4$ T.
Approximating the saturation of the material $\mu_r(B)$ decreases very fast. This effect is physically and mathematically fully correct. The anisotropic relative permeability of the MSM stick can be formulated as a diagonal matrix (7):

$$B = \mu_0 \cdot \begin{bmatrix} \mu_{r_{xx}} & 0 & 0 \\ 0 & \mu_{r_{yy}} & 0 \\ 0 & 0 & \mu_{r_{zz}} \end{bmatrix} \cdot H(B) \qquad (7)$$

2.3 Macroscopic Material structure

The twin boundaries of the MSM sticks are tilted by 45° with respect of the sample edges [4]. The stick is computationally divided in different areas. These areas will be called slices. Each slice has a defined magnetic orientation [7]. Fig. 4 exemplary shows a stick with varying orientation of the easy axis (red arrows). Corresponding to chapters **2.1** and **2.2** the iterative increase of current reorients these slices at certain local field strengths. According to the orientation of the individual slices the complete MSM stick will change. Existing 2D-FEM-models are using this macroscopic structure with more than 150 slices for simulating the magneto-mechanical behavior of MSM sticks in actuators [7]. This approach represents the twin structure and twin boundary motion in an effective manner in the FEM-model.

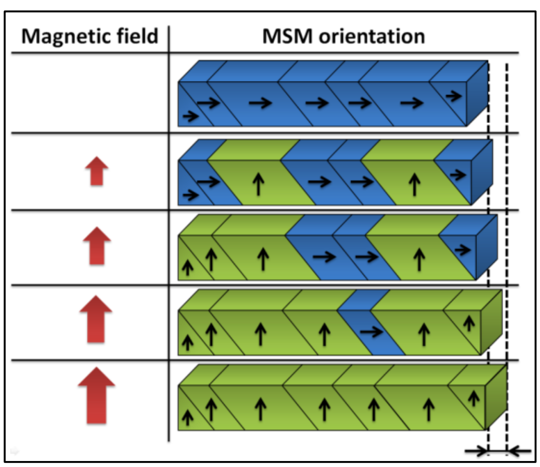

Figure 4 Switching behavior of the MSM stick [7]

Modeling MSM alloys in 3D will open new possibilities like simulating and visualizing the shape memory behavior as a multiphysical effect in one model. Regarding the fact that this work constitutes the first investigations and tests with 3D simulations for the considered simulation approach the structure for the simulated model will be simplified as far as possible. This means that the number of slices for the stick are strongly reduced and the twinning boundaries are tilted vertically (90°) i.e. the stick is divided into five slices which are modeled in each case as a rectangular shaped block with the geometric dimensions 2 x 3 x 5 mm³. This simplification could yield poorer results. Taking into account using the first time an 3D-FEM-tool to model this simulation approach for the nonlinear and anisotropic MSM it's necessary to ensure in a first step the physical characteristic. The macroscopic structure used in this work modified from the model of Fig. 4 is shown on Fig. 5.

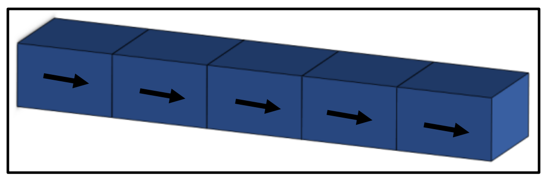

Figure 5 Macroscopic structure of MSM stick in this simulation model (fully compressed)

2.4 Stress based approach

Using the MSM stick for actuation (like a solenoid) several types of stress are affected to the MSM stick. These stresses can be divided into internal and external stresses [8]. The internal stress in the MSM stick can be subdivided into magneto-stress and the twinning stress σ_t. The maximum magneto-stress σ_{max}^{mag} is caused by an external magnetic field and depends on the magnetic anisotropy factor K_1 and the maximum strain ε_0 of the material which is determined directly from the ratio of the lattice constants of the tetragonal lattice [9]. This can be formulated with equation (8).

$$\sigma_{\max}^{\text{mag}} = K_1/\varepsilon_0 \qquad (8)$$

The magneto-stress $\sigma_{\max}^{\text{mag}}$ is the maximum stress, which each slice can generate under a magnetic field. The twinning stress σ_t hinders the reorientation of the martensitic twinning boundaries. Therefore it shall be as low as possible [6]. For the twinning stress σ_t random values of measurements are chosen because this kind of stress cannot be predicted with a trivial formulation. The external stresses $\sigma_{x,y}^{ext}$ on the MSM element in x- and y-direction for example result from a return spring, from Maxwell forces, other external forces of friction effects. Depending on its direction the external stresses $\sigma_{x,y}^{ext}$ support or impede a reorientation of twins and therefore the macroscopic strain of the MSM element. In this work the analyzed actuator contains external stresses $\sigma_{x,y}^{ext}$ only from a return spring.

2.5 Prototype actuator in COMSOL Multiphysics®

In order to validate the simulation results of COMSOL Multiphysics® with measurements and existing 2D-FEM simulation results a well known and existing actuator model is used. Fig. 6 shows this actuator with two symmetrically arranged coils and geometrically optimized yoke parts made from annealed magnetic steel. Its overall size measured about 40 x 35 x 20 mm³ with a Ni-Mn-Ga MSM stick of 2 x 3 x15 mm³. As described before the restoring force is applied to the MSM element by a spring. The force-elongation curve is taken into account for the evaluation of the results. The spring is not modeled in COMSOL Multiphysics®.

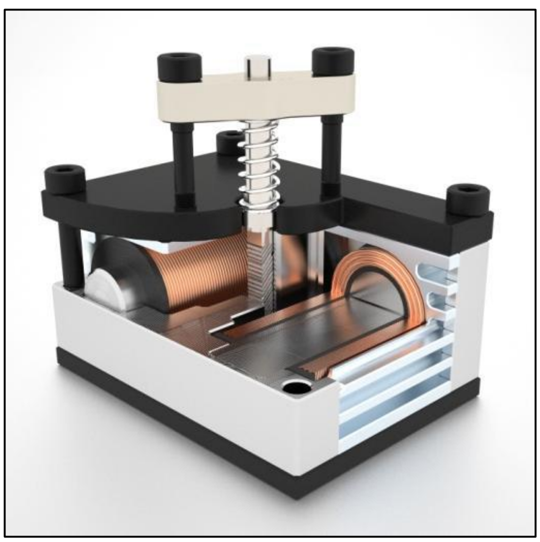

Figure 6 MSM prototype actuator (rendered sectional image)

The coils are energized with a current of 2 A. This current produces the full magnetic field which induces a strain of about ~1 mm (~ 6 %) within less than 5 *ms*. The model is geometrically simplified for the simulation. That means that all unnecessary components are deleted. Only the iron core, the coils and the MSM stick are taken into account. The model for the simulation is shown on Fig. 7. It shows the current insulation (green boundaries). The red arrows indicate the direction of current flow.

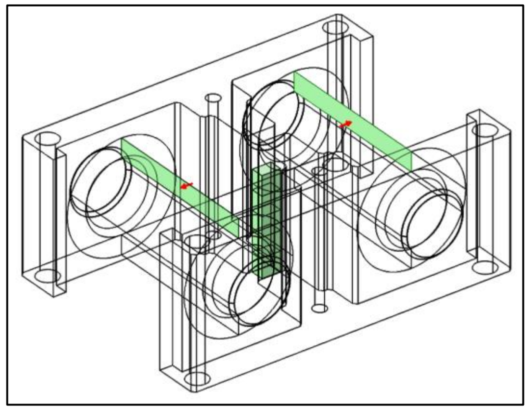

Figure 7 COMSOL Multiphysics® model of the prototype actuator

The meshing process is done semi-automatic. The critical areas like the highly nonlinear MSM stick are meshed manual with a very fine element density. Regarding the computational burden an automatic mesh refinement is not used for this simulation. The mesh is refined manually in an iterative way. This results in a better understanding of the mesh influence on this physical problem. The meshed model is shown in Fig. 8.

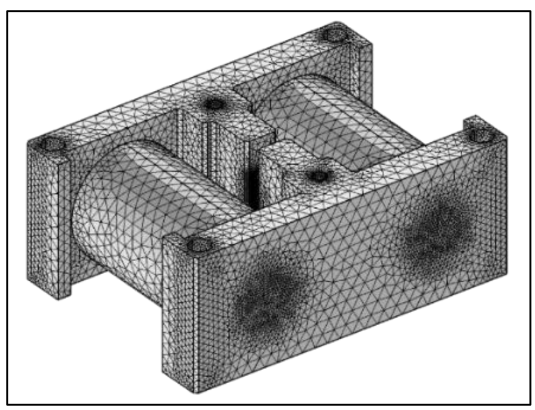

Figure 8 Mesh of the actuator model

3. Simulation Process

The simulations of this MSM actuator model are analyzed iteratively with individual magnetostatic simulations. After every simulation step the results have to be interpreted and the model have to be adapted to the new situation given by the orientation of the slices. An automatic evaluation and remodeling of the actuator would be possible by programming an external script. The focus of this work is to evaluate the possibility of modeling the physics of MSM alloys in a 3D-FEM model.

3.1 Evaluation of the iterative results

Regarding chapter **2.4** all stresses in the actuator have to be taken into account for this simulation. Each of the five slices is assigned with a random twinning stress value taken from measurements. For the first simulation step every slice is oriented by the hard axis in magnetic field direction. This is in accordance with the initial state for MSM sticks. During simulation the current and thus the magnetic field H is increased stepwise using:

$$\sigma_{\mathrm{x}}^{\mathrm{mag}}\left(\sigma_{\mathrm{max}}^{\mathrm{mag}}, H\right) + \sigma_{\mathrm{x}}^{\mathrm{ext}} > \sigma_{\mathrm{t}} + \sigma_{\mathrm{y}}^{\mathrm{ext}} + \sigma_{\mathrm{y}}^{\mathrm{mag}}\left(\sigma_{\mathrm{max}}^{\mathrm{mag}}, H\right) \qquad (9)$$

This equation is a condition which has to be evaluated after every simulation step. $\sigma_{\mathrm{x,y}}^{\mathrm{mag}}$ describe the magneto-stresses in x- and y-direction. One can determine in every simulation step and for each individual slice, whether this slice will switch the axis orientation or not [6]. This switching behavior occurs when the stress in x-direction is larger than in y-direction. In this simulation model only one external stress σ_y^{ext} occurs. Here, this is the stress of the spring on the MSM stick which is summed up to the twinning stress σ_t. In this case the magneto-stress $\sigma_{\mathrm{x}}^{\mathrm{mag}}$ has to be larger than $\sigma_t + \sigma_y^{ext} + \sigma_{\mathrm{y}}^{\mathrm{mag}}$. Fig. 9 helps to interpret this case. In the initial state all slices are oriented having the easy axis not in magnetic field direction. Increasing the current the magneto-stress $\sigma_{\mathrm{x}}^{\mathrm{mag}}$ raises depending on the magnetic field. Reaching the state the magnetic field and thus the magneto-stress $\sigma_{\mathrm{x}}^{\mathrm{mag}}$ become larger than the twinning stress σ_t, the magneto-stress $\sigma_{\mathrm{y}}^{\mathrm{mag}}$ and the external mechanical stress of the spring σ_y^{ext}, the slice will exchange the hard and the easy axis. Now, the relative permeability μ_r and magnetic field H of this slice increase significantly. Exchanging the orientation of a slice it elongates with a strain of $\varepsilon_0 = 6$ %.

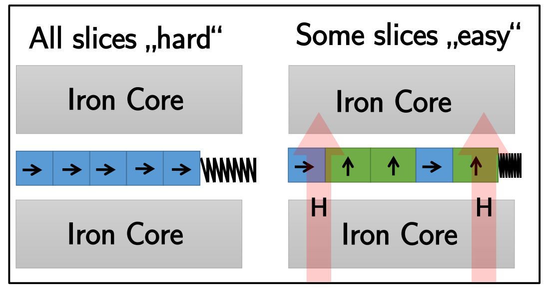

Figure 9 Geometry change of MSM element in an actuator & rotation of magnetic easy axis

For this MSM stick the slice elongates about Δl (10). In this case one slice elongates 0.18 *mm*.

$$\Delta l = \varepsilon_0 \cdot \frac{l_{stick}}{n_{slices}} \qquad (10)$$

Decreasing the current and thus the magnetic field the relation between the stresses changes. During compression of the stick the twinning stress is summed up to the magneto-stress $\sigma_{\mathrm{x}}^{\mathrm{mag}}$. To reorient the slices in the initial state the external mechanical stress of the spring σ_y^{ext} and the magneto-stress $\sigma_{\mathrm{y}}^{\mathrm{mag}}$ have to be larger than the twinning stress σ_t and the magneto-stress $\sigma_{\mathrm{x}}^{\mathrm{mag}}$. The values for the magneto-stress $\sigma_{\mathrm{x,y}}^{\mathrm{mag}}$ are obtained using field-force dependencies of the MSM material. This allows determining the magneto-stress as a function of the external magnetic field H. The values for the magnetic field H are taken from five point along the length (5 mm) of the slice (Fig. 10, red points along long edge of the stick). The arithmetic average of this values are taken into account to analyze the magneto-stress $\sigma_{\mathrm{x,y}}^{\mathrm{mag}}$.

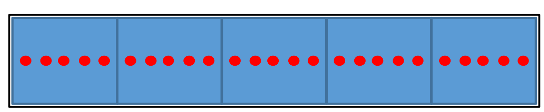

Figure 10 Measurement of magnetic field $\boldsymbol{H}$ in the MSM stick (red points)

Fig. 11 shows a plot of the magnetic flux density B in the actuator having two slices oriented in easy direction. On the right section of this figure it is possible to see the effect of having several slices oriented in different axis. The red arrows of the volume arrow plot show how their factorized size and the magnetic flux density B changes stepwise between two slices having different directions. The slices which are oriented in easy axis generate significant more flux density than the slices oriented in hard axis.

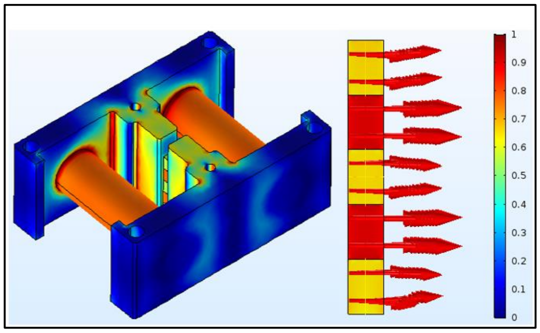

Figure 11 Plot of magnetic flux density ***B*** having two slices oriented in easy axis

The results of all simulations steps are visualized with the current-elongation diagram on Fig. 12. The results of the 3D-FEM simulation with COMSOL® are compared with the real measurements and the existing 2D-FEM simulations. This diagram shows that the measured and 2D-FEM current-elongation characteristic of a prototype actuator are generally in agreement with the results of the 3D-FEM simulations. The effect of hysteresis can be simulated.

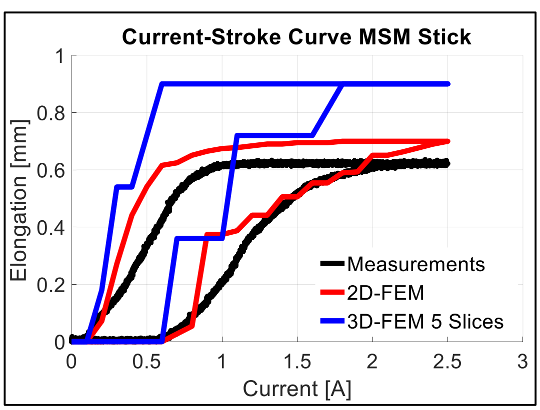

Figure 12 Current-stroke-curve of MSM stick

The elongation section, i.e. the lower branch of the hysteresis shows that the MSM stick in this actuator elongates with full strain of 6 %. The full compression of the stick can be achieved with the 3D-simulations, too. A first view suggests that the quantitative results of the 3D-FEM simulations are generally poorer.

3.2 Discussion of the results

The reasons for the divergence between the 3D-FEM simulations with COMSOL®, the measurements and the 2D-FEM simulations can be explained with several arguments. Simulating only five slices in the 3D-model results in poorer results because only 25 data points are taken from the model where the existing 2D-FEM-models include more than 150 slices with five probing points. Increasing the number of slices raises the quality of this model. With an additional model simulating 15 slices with 75 data points this explanation can be confirmed. With this improvement the simulated hysteresis curve approximates the measured curve (Fig. 13).

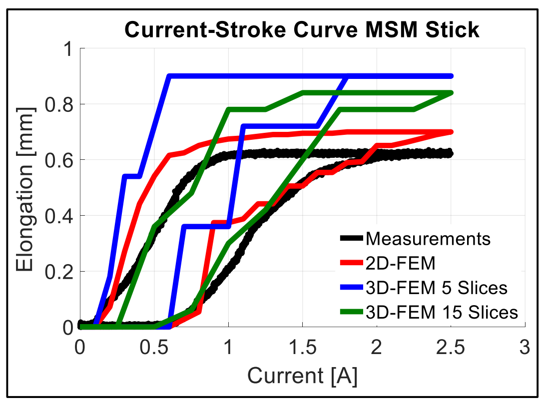

Figure 13 Current-stroke-curve of MSM stick improved

In the upper branch of the hysteresis where the currents are above $\approx 1.5\ A$ the divergence of the results in both models increase clearly. During the simulation some problems occur. Reaching the point when the induced current results in exchanging the orientation of several slices and thus their permeability values μ_r, convergence problems in the solver occur. Regarding the $\mu_r(B)$-curve of the material shows the reason for these problems. Reaching the point when a slice changes its orientation, the relative permeability μ_r undergoes a tenfold change. Then, the difference between the energy of a slice with lower and one with higher permeability gets very large. This energy step can be interpreted as a singularity for the solver. This effect has occurred in 2D-FEM simulations, too. A strong refinement of the mesh and an increase of the solver tolerance improve this behavior. The adaption of the solver tolerance generates more inexact results what can be interpreted as reason for the divergence between the different current-elongation curves. Increasing the number of slices again would generate much better results but also means a large increase of simulation and evaluation expense.

4. Conclusion and Outlook

3D-FEM simulation results using COMSOL® are presented that demonstrate a simple way of designing MSM actuators based on an adapted approach of existing models. Taking into account the anisotropic behavior of MSM materials as well as an appropriate representation of the martensitic twin structure, the magnetic field within the magnetic circuit of an MSM actuator is analysed. From the simulation results the stroke and force-behaviour of the actuator are derived. The results generally agree with experimental data and 2D-FEM simulation results. Implementing more slices in the representation of the MSM material together with an adaptive and automated evaluation procedure would increase the precision and efficiency of the simulation approach. A next step could be the implementation of coupled magneto-mechanical tools with Multiphysics applications to simulate and visualize the strain of the MSM stick directly in COMSOL®.

5. References

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