FEM-Simulation of Magnetic Shape Memory Actuators

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***Abstract*—It is known that Magnetic Shape Memory Materials can be simulated with the focus on proper magneto-mechanical representation of the material itself. The target of this work was to simulate complete actuators based on Magnetic Shape Memory Alloys in order to work out design key parameters and finally to increase performance of the complete actuator. It is shown that internal and external stresses should be taken into account by using numerical computation tools for magnetic fields in an efficient way.**

***Index Terms*— Electromagnetic analysis, Electromagnetic coupling, Shape memory alloys.**

I. INTRODUCTION

Electromagnetic actuators are a well known field where finite element simulations are applied. Force and motion of individual components of the actuators like the armature can be calculated based on the Maxwell equations.

Magnetic Shape Memory (MSM) actuators represent a new type of smart electromagnetic actuators where the MSM material elongates and contracts in a magnetic field. The MSM material typically is a monocrystalline NiMnGa alloy [1], which has the ability to change its size or shape many million times repeatedly. Some alloys are known, which are able to achieve a magnetic field induced strain of up to 10% [2]. Using today´s standard FEM tools it is not possible to simultaneously calculate magnetic field, mechanical stress and resulting shape change in MSM actuators, because integrated magneto-mechanical material models are not available. Although several approaches have been established in order to simulate the magneto-mechanical behaviour of MSM materials [3]-[5] at the moment existing simulation concepts of complete MSM-based actuators are still insufficient, and therefore the designs are inefficient. This is an important roadblock for the commercialization of MSM actuators.

The ability of MSM material to change its size, shape and magnetization curve causes several effects on the complete actuator like a change of the inductance or the magnetic resistance. Since in practical applications actuators should be small and efficient these circumstances have a huge impact, considering that small actuators produce only a limited amount of magnetic energy.

Target of this research is to propose a simulation approach for MSM actuators based on established engineering FEM tools and to gain the ability to simulate and optimize a complete MSM actuator for practical applications.

II. SIMULATION MODEL

A. *Magnetization curve*

Magnetization curves have been measured [6] using bulk samples of 2×3×15 mm³ [7]. Figure 1 shows the magnetic anisotropy of a MSM sample. The curves are measured in compressed and elongated state of the sample and can be identified with the easy and hard axis magnetization. During elongation, easy and hard axes exchange their orientations. This behaviour is taken into account in the FEM model by using a magnetization curve which corresponds locally to the switching status of the MSM element.

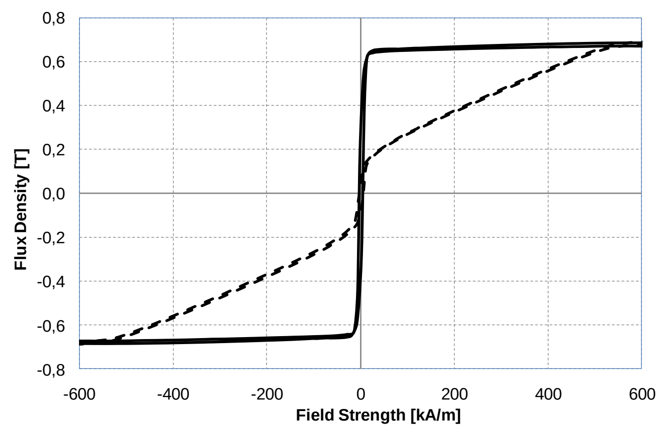

Fig. 1. Magnetization curves of a Ni-Mn-Ga element measured along magnetic easy (continuous) and hard axis (dashed)

B. *Material structure*

In an actual MSM element the twin boundaries, i.e. the boundaries between differently oriented slices, are tilted by 45° with respect to the sample edges. This structure is represented in the FEMM [8] simulation (Fig. 2) by slices with a statistically distributed width. The width distribution is taken from [9]. During the iterative simulation process, these slices reorient at certain local field strengths. The width and length of the complete element will then change accordingly.

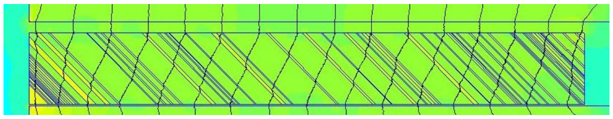

Fig. 2. MSM element in FEM simulation (FEMM) [7].

C. *Stress based approach*

Inside an actuator, the MSM element can be affected by several types of stress which can be divided into internal and external stresses [5]. The internal stresses can be subdivided into magneto-stress and twinning stress σ_t. The maximum magneto-stress $\sigma_{\max}^{\mathrm{mag}}$ is caused by an external magnetic field and depends on the magnetic anisotropy constant 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 [5].

$$\sigma_{\max}^{\mathrm{mag}} = K_1/\varepsilon_0 \tag{1}$$

The magneto-stress is the maximum stress, which each martensitic twin (i.e. each slice in the FEM model) can generate under an applied magnetic field. The twinning stress hinders the reorientation of the martensitic twins and favourably is as low as possible.

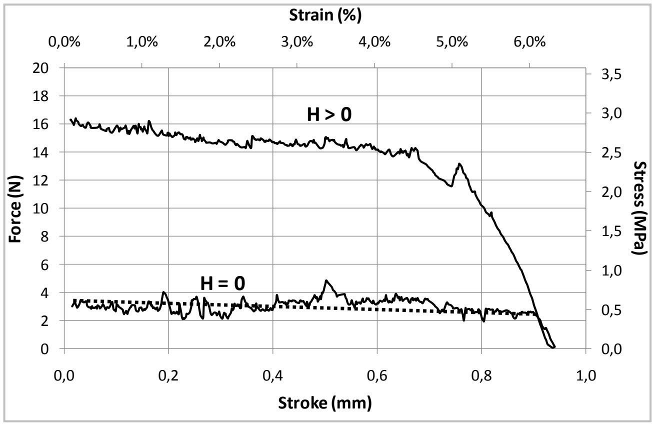

Fig. 3. Measurement of twinning stress (indicated by dotted line).

D. *External stress*

The external stresses $\sigma_{x,y}^{\mathrm{ext}}$ in *x*- and *y*-direction can be from a spring, a pneumatic pressure or due to friction effects that can all act on the MSM element. Depending on its direction it will support or suppress a reorientation of twins and therefore the macroscopic strain of the MSM element.

III. SIMULATION RESULTS

All stress contributions are coupled and magnetic simulations with FEMM are realized. The twin structure of the MSM element is represented by hundreds of slices. Each of them is assigned with its own (statistically distributed) twinning stress value, slice width, and orientation of easy and hard axis. Finally, the magnetic circuit of the complete actuator is included into the simulation, too.

During simulation the current in the actuator coils and thus the magnetic field *H* is increased stepwise. Using

$$\sigma_{\mathrm{x}}^{\mathrm{mag}}\left(\sigma_{\max}^{\mathrm{mag}}, \mathrm{H}\right) + \sigma_{\mathrm{x}}^{\mathrm{ext}} > \sigma_{\mathrm{t}} + \sigma_{\mathrm{y}}^{\mathrm{ext}} + \sigma_{\mathrm{y}}^{\mathrm{mag}}\left(\sigma_{\max}^{\mathrm{mag}}, \mathrm{H}\right) \tag{2}$$

where $\sigma_{x,y}^{\mathrm{mag}}$ are the magneto-stresses in *x*- and *y*-direction, respectively, it is determined in every simulation step for each slice, whether this slice reorients or not.

The highest positive stress of all slices, which are not yet reoriented, is taken and divided by the MSM element cross-section in order to calculate the resulting MSM element force. After each simulation step the FEM model of the MSM element is rebuilt based on the same slice pattern, but switched slices will exhibit a shape change of 6% and a reorientation of magnetic easy and hard axis.

Figure 4 shows that the measured current-stroke characteristics of a prototype actuator are in good agreement with the results based on the FEMM simulation. This demonstrates that the presented approach is appropriate for simulation of complete MSM actuators.

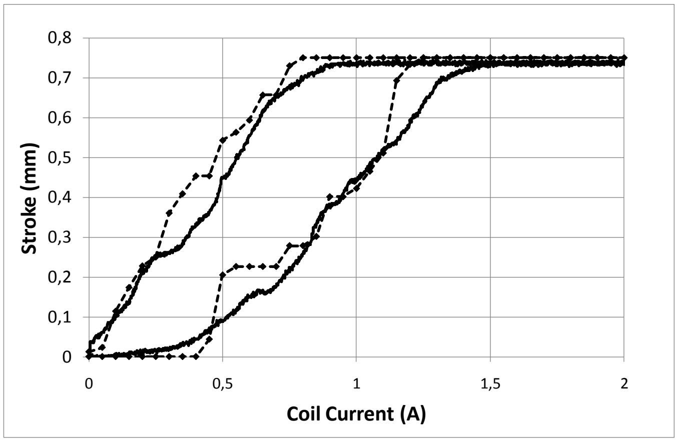

Fig. 4. Current-stroke curve of a simulated (dashed) and measured (continuous) MSM actuator.

IV. CONCLUSION

The material behaviour of MSM can be described adequately with a stress-based approach using standard FEM simulation tools for electromagnetic fields. Also complete actuators can be investigated on an engineering level and designs can be improved for practical applications.

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