Effects of Varying Permeability of Magnetic Shape Memory (MSM) Alloys on Design and Performance of Actuators

Nikita Gabdullin, Sanowar H. Khan, *Member, IEEE*

City University London, London EC1V 0HB, UK, Nikita.Gabdullin.1@city.ac.uk

Magnetic Shape Memory (MSM) alloys, which change shape under magnetic field, have enormous potential to be used in actuators, sensors and other electrical devices due to their “smart” properties and large strain output that can be controlled magnetically. Maximum magnetic field induced strain varies from 6 to 12% of the MSM element’s length depending on its microstructure. The dependence of MSM magnetization and resistance on strain allows designing self-sensing actuators. At the same time, variations of MSM properties with strain complicate their performance modelling and analysis. In this paper we show how varying MSM permeability affects the performance of MSM actuators. The effects of non-homogeneous MSM microstructure on the applied field is analysed by modelling and computation of magnetic field distribution using the finite element method (FEM). This allows design optimization of actuators in terms of geometric parameters and power consumption.

***Index Terms*—Actuator design, magnetic shape memory alloys, non-homogeneous permeability, smart materials.**

I. Introduction

MAGNETIC shape memory (MSM) alloys are relatively new “smart” alloys that produce enormous strain and a considerable stress output when subjected to magnetic fields or mechanical stresses. The Ni-Mn-Ga alloys are the most studied MSM alloys which exhibit up to 12% magnetic field induced strain depending on microstructure [1]. Moreover, a multibillion cycle operation without malfunction is reported in [2]. Strain (change of shape) in MSM alloys occurs due to reorientation of martensitic twin variants and propagation of twin boundaries [3]. When a MSM element is not fully contracted or elongated, its variants form a lamellar structure. Since variants differ by orientation of “easy” magnetization axes, properties of MSM element vary along its length and also depend on strain. This complicates the performance prediction of MSM actuators and, hence their design optimization. It is still common for designers to neglect this phenomenon assuming that MSM permeability is constant [4], [5]. In this paper we show how the performance evaluation of an actuator can differ if a more accurate approach is used in order to take into account varying MSM permeability.

II. Modelling Approach

In our previous study we applied a simplistic model of MSM behaviour assuming that twin variants were magnetically connected in parallel [6]. However, a more detailed field analyses showed that such a simplistic model was not valid. In this paper we use an alternative approach first suggested in [7] with twin distribution described in [8]. This approach allows taking local effects into account that occur due to non-uniform field distribution in MSM alloys. However, we also consider each twin variant as non-homogeneous by assigning different properties for “hard” and “easy” magnetization axes. A more detail description of the approach and its validation will be published elsewhere.

The curves in Fig.1 published in [9] allow evaluating a stress-strain combination produced by a MSM element for a given magnetic field. These curves are used for the calculation of output characteristics of MSM actuators in this study. Since the curves are measured with a sensor placed close to the surface of the MSM element, a field solution in an air gap region is of main interest. However, the overall field distribution depends on the properties of all regions of the magnetic circuit including the MSM element. The problem is solved by modelling the entire magnetic circuit of MSM actuator using finite element method (FEM) in order to obtain an accurate solution.

III. Results and Discussions

The magnetic field distribution in the MSM actuator used in this study is shown in Fig. 1. Here the magnetic circuit consists of a coil of 200 turns, a ferromagnetic core and an air gap containing a $10 \times 1 \times 2.5$mm MSM element. The total air gap width is 1.2mm. The core material is high-permeable steel. The results are obtained by solving static magnetic problems in FE models using magnetic scalar potential (MSP) formulation in ANSYS Multiphysics software package. Average flux density is measured in the air gap at a distance of 0.02mm from the surface of the MSM element.

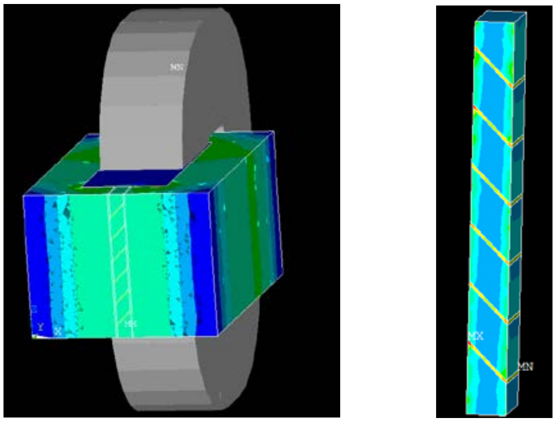

Fig. 1. Magnetic field distribution in the magnetic circuit of a MSM actuator studied (left) and its MSM-element regions (right). The MSM element has 6 “easy” variants resulting in a very non-uniform field distribution. Surrounding air is hidden.

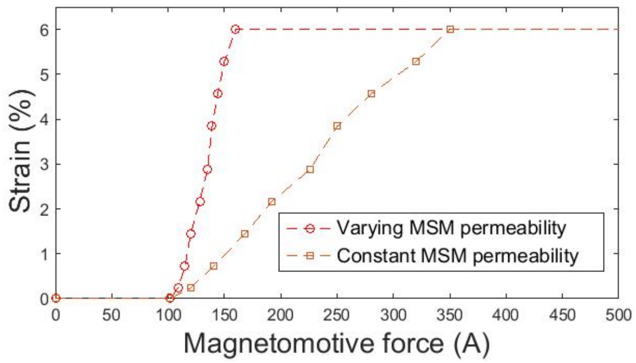

Fig. 2. Variation of output strain of the MSM actuator studied with magnetomotive force (mmf) under 0.5MPa load.

Figs. 2 and 3 illustrate the output characteristics calculated using 0.5 and 2.5MPa load (external) curves [9] as functions of the total excitation coil current (magnetomotive force, mmf).

The considerable difference in results obtained by different approaches can be seen in Fig. 2. It shows that the mmf required for a certain strain calculated using an accurate approach that takes varying MSM permeability into account is much lower than the one calculated with the assumption that the permeability does not depend on strain. This means at least two possible effects on a MSM actuator. Firstly, a lower current is required for operating an actuator, which may result in overshoot at small strains. Moreover, larger current means larger energy consumption and losses. The difference in the values of current calculated for achieving a 6% strain by these two approaches is 1A. This results in an additional electrical power loss of about 2W. This can have significant negative effects on magneto-thermal stability of the actuator.

Secondly, a lower mmf means a smaller number of coil turns required for a given excitation current. At present, in MSM-based actuators excitation coils are relatively large and contribute considerably to the overall size. Table I below shows how coil and actuator sizes vary with coil turns. Here the excitation current is 3A.

TABLE I
EFFECTS OF THE ADOPTED APPROACH ON THE SIZE OF ACTUATORS

Approach	Number of coil turns	Coil size (mm^3)	Overall actuator size, (mm^3)
μ=const.	150	5x25x17.5	10x25x22.5
μ=variable	50	5x15x7.5	10x15x12.5

However, there is just a small difference in output characteristics calculated for 2.5MPa load. This is primarily due to the saturation of "easy" variants. This effect is not so apparent in the magnetic field required for operation under 0.5MPa load where "easy" variants' contribution to the overall permeability is bigger. Conversely, a MSM element with saturated "easy" variants acts similar to the one with all "hard" variants if the applied field is sufficiently strong.

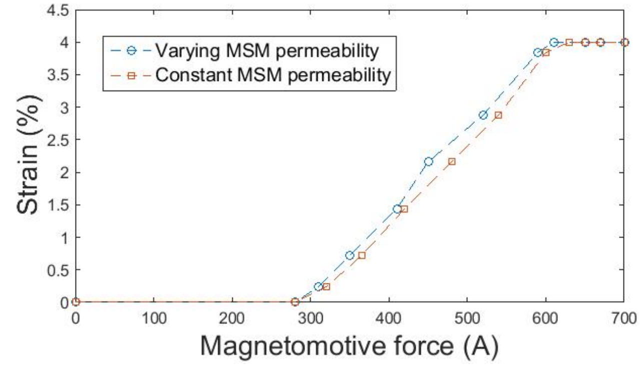

Fig. 3. Variation of output strain of the MSM actuator studied with magnetomotive force (mmf) under 2.5MPa load.

IV. CONCLUSIONS

Magnetic field distribution in MSM alloys is very non-uniform due to twinned microstructure of the MSM element used in actuators. This has a significant effect on the parameters of its magnetic circuit. The contribution of "easy" variants in the MSM element also depends on the applied load. This effect cannot be taken into account accurately if the MSM element is treated as a single homogenous body. Thus, an advanced computational technique is needed which allows modelling complicated MSM geometry and taking into account its non-homogeneous properties. The FEM is essential for addressing this problem also allowing modelling the entire magnetic circuit of MSM actuators and evaluating their output characteristics. It is especially important to use an accurate approach adopted in this study for medium and weak fields when the contribution of "easy" variants is the most significant. This has a significant effect on the design optimization of MSM actuators for size and power consumption.

V. REFERENCES

[1] A. Sozinov, N. Lanska, A. Soroka, and W. Zou, "12% magnetic field-induced strain in Ni-Mn-Ga-based non-modulated martensite," *Appl. Phys. Lett.*, vol. 102, no. 2, pp. 021902-1–021902-5, 2013.

[2] I. Aaltio, Y. Ge, H. Pulkkinen, A. Sjöberg, O. Söderberg, X.W. Liu, and S-P. Hannula, "Crack growth of 10M Ni-Mn-Ga material in cyclic mechanical loading," *Phys. Procedia*, vol. 10, pp. 87-93, 2010.

[3] H.E. Karaca, I. Karaman, B. Basaran, Y.I. Chumlyakov, H.J. Maier, "Magnetic field and stress induced martensite reorientation in NiMnGa ferromagnetic shape memory alloy single crystals," *Acta Mater*., vol. 54, pp. 233-245, 2006.

[4] H. Schmidt, "Magneto-Mechanical Energy Conversion in Magnetic Shape Memory Alloys," *J. Phys. Conf. Ser*., vol. 303, p. 012078, 2011.

[5] K. Wegener, P. Blumenthal, and A. Raatz, "Development of a miniaturized clamping device driven by magnetic shape memory alloys," *J. Int. Mat. Syst. and Struct.*, vol. 0, pp. 1-7, 2013.

[6] N. A. Gabdullin, S. H. Khan, "Application of change in permeability of magnetic shape memory (MSM) alloys for optimization of magnetic circuit in actuators," *9th IET Conference on Computation In Electromagnetics (CEM 2014)*, pp. 1-2, 2014.

[7] T. Schiepp, M. Maier, E. Pagounis, A. Schlüter, M. Laufenberg, "FEM-Simulation of Magnetic Shape Memory Actuators," *IEEE Trans. Mag*., vol. 50, no. 2, Feb. 2014.

[8] E. Pagounis, M. Maier and M. Laufenberg, "Properties of large Ni-Mn-Ga single crystals with a predominant 5M-martensitic structure," *3rd International Conference on Ferromagnetic Shape Memory Alloys*, 2011.

[9] E. Pagounis, P. Müllner, "Recent Developments in Magnetic Shape Memory Actuation," *Proc. Actuator*, pp. 86-91, 2014.