Article Identifier
DOI: 10.22032/dbt.58873
URN: urn:nbn:de:gbv:ilm1-2023isc-028:4

60th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 4 – 8 September 2023
URN: urn:nbn:de:gbv:ilm1-2023isc:1

MULTISTABLE SETUPS COMBINING MAGNETIC SHAPE MEMORY ALLOYS WITH RELUCTANCE COUNTERFORCES

Marco Hutter[1], Daniel Holder[2], Thomas Maier[2], Bernd Gundelsweiler[1]

[1]Insitute for Design and Production in Precision Engineering, IKFF, University of Stuttgart
[2]Institute for Engineering Design and Industrial Design, IKTD, University of Stuttgart

ABSTRACT

Systems with the ability to hold a given position without consumption of energy, i.e. multi-stability, can be employed in a variety of applications. Apart from the most commonly friction-based systems, smart materials are an option to create multistability. Here, the ability to create a multistable system from magnetic shape memory alloy (MSM) in a magnetic field, combined with a reluctance counterforce is discussed. For the approach the necessary design process is described, as well as the experimental characterization of a demonstrator system. With the multistable range of the stroke at 0.82 mm and an average resistance to disturbance of ±10 N, two key parameters of the multistable properties are determined. As an outlook, potential applications in the design of adaptable interfaces is discussed.

Index Terms **–** Magnetic Shape Memory Alloy, multi-stability, system design

1. INTRODUCTION

Magnetic shape memory (MSM) alloys have been researched for a number of actuator concepts, usually used in a cuboid shape called stick. The basic principle used is magnetically induced reorientation (MIR), during which martensitic variants in the lattice structure change their orientation under influence of a magnetic field yielding a macroscopic shape change. [1]
Occurrence of MIR is connected to a combination of the exciting magnetic field, mechanical load on the alloy and internal resistance and can be modelled by establishing stress inequations on boundaries between areas with a dominant variant. Movement of these boundaries i.e. reorientation of variants happens, when the absolute of the difference between mechanical stress σ_{mech} and magnetically induced stress σ_{mag} exceeds the twinning stress σ_{TW}. The twinning stress is defined as the threshold for twin boundary movement and is a property of the alloy, influenced for example by defects in the lattice. The inequation describing the prerequisite is given below. [2]

$$\left|\sigma_{mech} - \sigma_{mag}\right| > \sigma_{TW} \tag{1}$$

Since the twinning stress affects elongation and compression of the MSM-stick, its stress-strain-relationship is characterized by a hysteresis. While this puts more demands towards control of MSM-based actuator systems, it also enables creation of multistable systems. In the context of this work multistability is defined as the ability of the material to retain a given stroke without excitation field even under a limited amount of external force without displacement.

Multistable functionality can on the one hand be advantageously used in systems where MSM-sticks are used to create motion, as in a stationary state no magnetic field might be required to hold a given position, therefore possibly negating energizing of coils.
On the other hand, systems in which the MSM-stick is exclusively used as a holding element are possible. There is a number of options to create these. One is the use of a passive MSM-stick, i.e. the stick is not excited by a magnetic field [3]. Therefore, elongation and compression are generated solely by exterior mechanical forces, that need to be transferred to the MSM-stick. An advantage of this type of setup is the lack of any excitation circuit. Disadvantageous is the mechanical interfacing of the MSM-stick for transfer of tension. Clamping, gluing, and welding have all been shown [3–5], while interlocking designs have been discussed but require specialized processing. All of these methods affect the materials properties by either reducing the active length and thus maximum stroke and/or negatively impact fatigue behavior. There has also been recent research into the formation and propagation of cracks within the material under tensile load [6].
The need for transmission of tensile forces can be circumvented by employing elongation of the MSM-stick by magnetic excitation. For these configurations the MSM-stick is placed into a magnetic circuit that will achieve elongation as the default state. To achieve a multistable system, a suitable counterforce needs to also be employed. One approach here is to use two MSM-sticks working alternately against each other [7]. The counterforce is to be designed in a way that its force-distance-characteristic lies within the arms of the MSM-stick-hysteresis. The actuation force necessary to change elongation of the system is then defined by the difference between hysteresis and counterforce. From the shape of the hysteresis it is apparent, that counterforce needs to decrease with distance. For this work, reluctance force is employed as counterforce, as it has an advantageous force-distance-characteristic.
In all cases described above, the multistable behavior can be characterized by two important properties. The first is the multistable range, the second is the resistance to deformation by disturbances, i.e. the holding force. Both can be affected by the MSM-stick geometry, as a longer stick has a larger stroke and therefore a larger potential for the multistable range, while the holding force is dependent on the twinning stress and cross-section of the MSM-stick. For systems with active strain and counterforce, the force-distance-characteristic of the counterforce is just as important and needs to be carefully designed.

2. SYSTEM OVERVIEW

From the properties of magnetic shape memory alloys, systems that allow for multistable positioning are feasible. This work focusses on a system using an active MSM-stick, that is by default fully elongated in a permanent magnetic (PM) circuit. A second PM circuit is used to create a reluctance counterforce, that can be fitted to the shape of the hysteresis. The armature of this circuit is connected to a rod, that transfers the counterforce to the MSM-stick and acts as interfacing to exterior parameters. This system design is depicted schematically in Figure *1*.

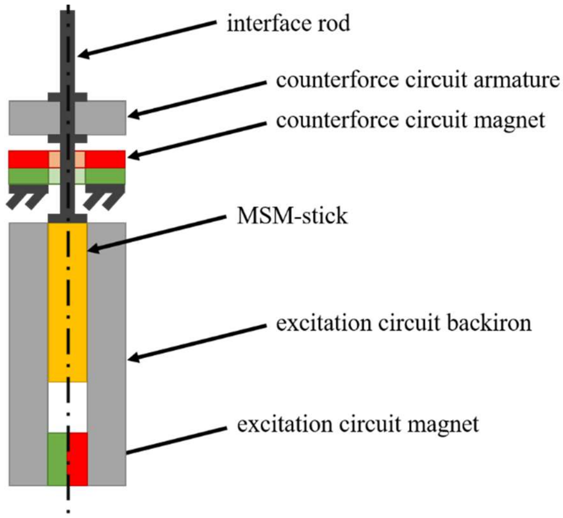

Figure 1: schematic depiction of the proposed multistable system, with the excitation and counterforce circuits connected by the interface rod

For the design shown here, MSM-sticks with dimensions of 3x5x20 mm² are used as a starting point. For the given NiMnGa-alloy a theoretical maximum strain of 6 % suggests a maximum stroke of 1.2 mm. Twinning stress for this type of alloy is expected to be at around 0.5 MPa [8]. The entire system is designed as rotationally symmetric, with the excitation circuit consisting of a steel tube for flux guidance, into which the MSM-stick and the magnets are set, while armature and magnet of the counterforce circuit are both rotationally symmetrical as well. The interface rod can easily be guided by polymer bushings.

More detail into the design process for the excitation circuit, counterforce circuit and design details as individual subsystems is given in the following sections.

3. MAGNETIC EXCITATION CIRCUIT

The proposed system is fundamentally based on a stick exhibiting as large a stroke as possible, since the maximum multistable range is defined by the stroke. Therefore, sufficient magnetic excitation is the first step in designing the whole system. From the field-stroke-characteristic (see Figure 2) the necessary excitation can be determined with regards to mechanical preload. For this study, a flux density goal of 700 mT in the MSM-stick is desired, resulting in a full elongation under small mechanical loads.

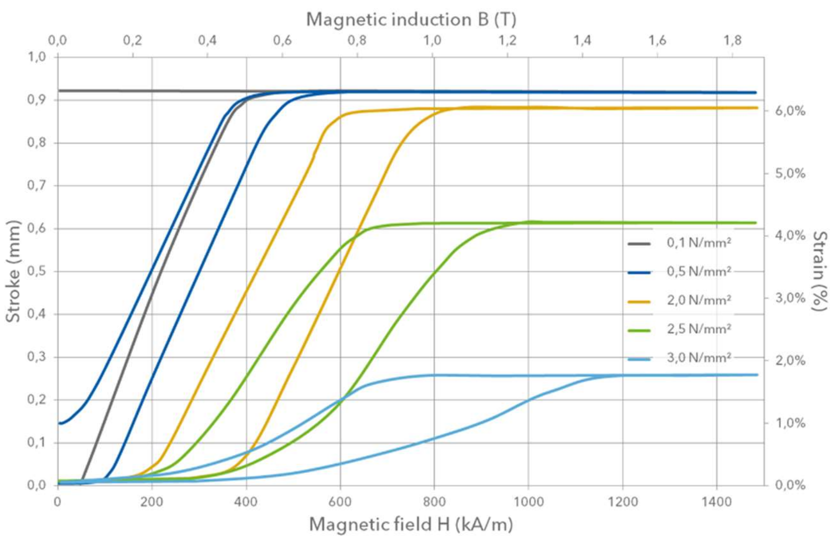

Figure 2: Field-strain-characteristic for the used MSM-alloy for given mechanical preloads [8]

Here, excitation is to be achieved by permanent magnets. Two of these are to be placed right by the MSM-stick with a ferromagnetic sleeve around this assembly, acting as a flux guidance. The magnets in use have dimensions of 5 x 5 x 20 mm³ and a magnetization of N42. For these an FEA simulation-based verification is conducted. Results, as calculated by Ansys Electronic Desktop, are displayed in Figure 3 as a section through the core of the setup. Displayed as a ring is the steel tube, that serves as a flux guidance here, as well as the two magnets and the MSM-stick in the middle. Flux density is indicated by color.

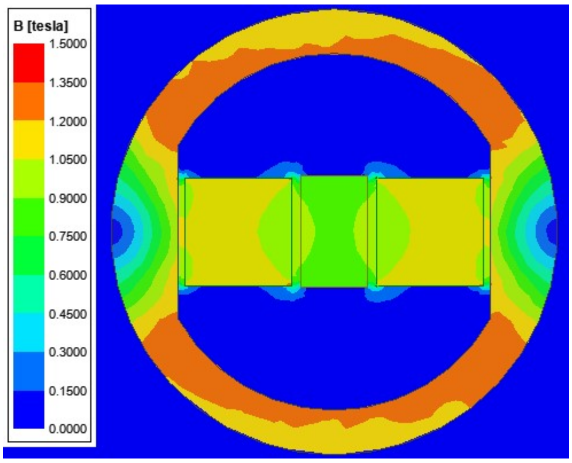

Figure 3: FEA-simulation results for the excitation circuit, depicting the MSM-stick in the middle, excitation magnets on either side and the surrounding flux guidance

As can be seen, the flux density within the MSM-stick is at least 750 mT for the entire cross section, therefore fulfilling the requirement of 700 mT for the circuit. The expectation of full MSM-stick elongation is verified by experiment. An MSM-stick is placed into the circuit after manufacturing and assembly and the resulting stroke measured to be 1.06 mm. This is close to the maximum elongation of 1.09 mm of elongation that has been recorded for this stick before.

4. COUNTERFORCE CIRCUIT

After design of the excitation circuit, a suitable counterforce needs to be implemented. As reluctance forces show a force-characteristic decreasing with distance and are compact to implement, this approach is used here. To maximize the multistable range of the system, the counterforce needs to be well adjusted to the force-stroke-hysteresis of the MSM-stick. Therefore, the hysteresis of the MSM-stick within the excitation circuit is determined via experiment. For this, the MSM-stick is placed within the circuit and compressed by external actuation. Stroke is monitored using a triangulation sensor (micro epsilon ILD1420-50), while force is measured by a force sensor (AST KAP-E/D, 50 N), during compression and subsequent relaxation of the stick. Results are displayed in Figure 4.

The measured hysteresis gives a target for design of the counterforce-characteristic. To create this an axially polarized ring magnet (19 mm outer diameter, 9.5 mm inner diameter, 6.4 mm height, N42) is chosen, in line with the overall cylindrical design of the system. The magnet is placed into a circuit consisting of an armature and flux guidance encasing the magnet. To adjust the force-distance-characteristic of this setup, thickness of flux guidance and armature can be varied, as well as the initial air gap. The design process is again done by FEA-simulation, and the resulting characteristic for a thickness of 2.5 mm and an initial air gap of 0.6 mm is superimposed on the MSM-hysteresis in Figure 4.

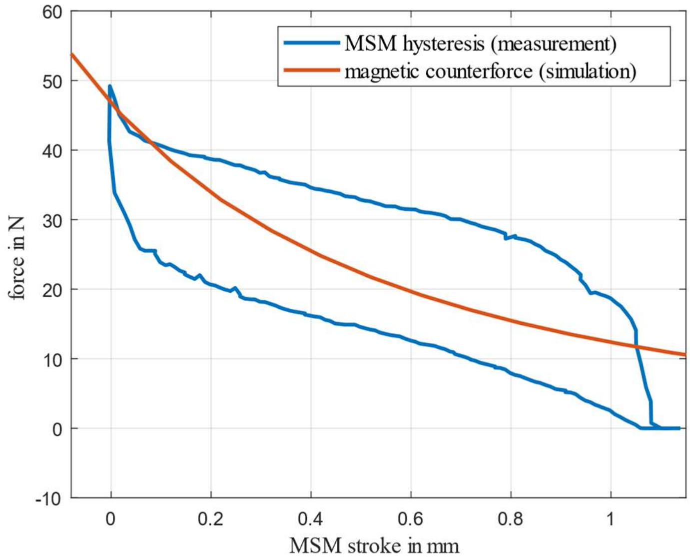

Figure 4: Measured force-stroke-hysteresis of the active MSM-stick within the excitation circuit and simulated force-distance-characteristic of the magnetic counterforce circuit.

From the results, the close to full elongation of 1.06 mm can again be seen. With the setup, the force-distance-behavior of the counterforce-circuit is positioned well within the hysteresis. From this depiction, expectations towards multistable range and resistance to disturbances can be deduced. The multi-stable range is estimated to be at around 0.9 mm, while the resistance to disturbances varies depending on stroke and direction, peaking at around 12 N. The variation however is wide but can be reduced by adjusting the counterforce characteristic. For the prototype setup presented here, more importance is placed on the multi-stable range.

5. SYSTEM CHARACTERIZATION

Combining the two subsystems described above, the overall system is created in which the magnetically induced and mechanical stresses cancel each other out, producing a multi-stable system. Transfer of the counter-force onto the MSM-stick is achieved by a rod that is guided by two bushings and also acts as interface to the exterior of the system. The whole assembly is encased by an aluminum sleeve and has a length of 65 mm and a diameter of 26 mm. Exploded views of the final design of the entire system and the excitation circuit are displayed in Figure 5. In the setup the MSM-stick is held by a mounting of polymer flexures of the type described in [9].

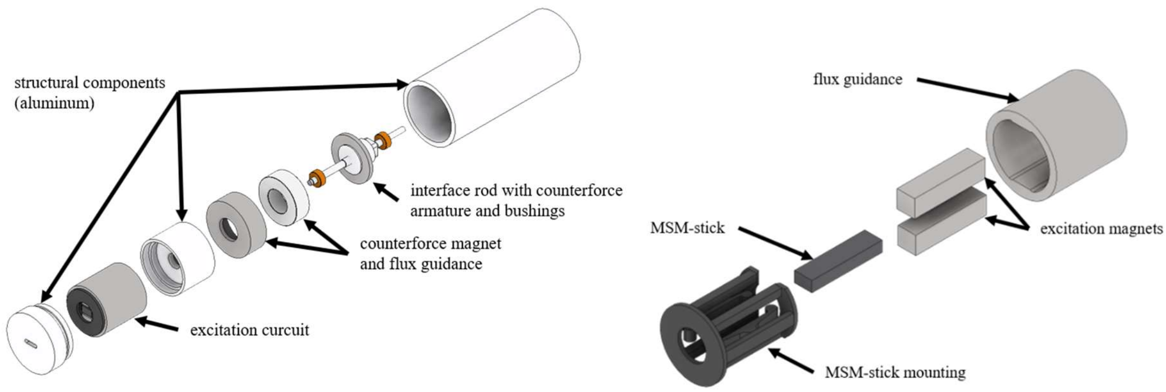

Figure 5: Exploded view of the entire system (left) and the excitation circuit (right)

Starting the verification process, the force necessary for adjustment of the MSM-stroke is measured, which gives an indication of the maximum disturbance the system can experience without being displaced. This measurement also provides insight into how well the characteristics of MSM-hysteresis and counterforce circuit are fitted to each other. The prototype design employed here, allows for an adjustment of the initial counterforce air gap to improve the fit if necessary. For the measurement the stick is displaced using a micro screw, while the exhibited force is recorded using a force sensor and the position is monitored using a laser triangulation sensor. Results are displayed in Figure 6 in comparison to the values found by simulation of the counterforce, as shown in Figure 6.

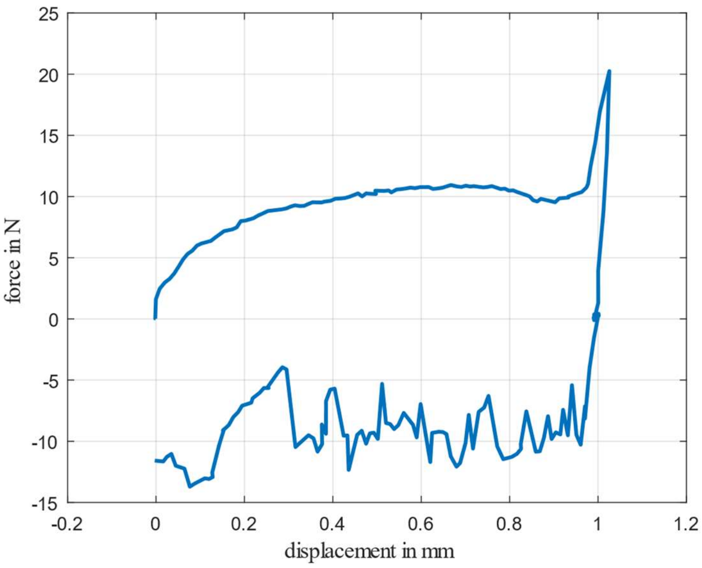

Figure 6: Measurement of the actuation force necessary for displacement of the interface rod of the multi-stable system

The result is a hysteresis, showing a high degree of symmetry around the x-axis, with only minimal adjustment. In the direction of compression (upper arm of the hysteresis) measurements indicate a smooth behavior, while in elongation (lower arm) the trace is more jagged. This is attributed to two causes. The first is aging effects in the MSM-stick, that under elongation needs to follow the rod which can be “jerky” for older sticks. The second is imperfections in the guidance of the interface, resulting in a stick-slip behavior which may also cause higher forces when compared to the estimations from Figure 6. Apart from this, the force levels of necessary actuation are at around ±10 N for a wide section of the available stroke. From the way the measurements were set up, backlash and influence gravitational forces are possible causes for measurement error. The influence of backlash can be seen at the zero force crossing at 1 mm, but is very small, while gravitational influence is estimated to be small as well, since the overall weight of the respective components is at below 100 g. Therefore, both of these influences are not expected to significantly affect system performance.

For measurement of the multistable range and short-term stability, the MSM-stick is set to its maximum elongation by moving the rod connected to the counterforce circuit. This rod is then again actuated by a micro screw in successive steps of about 0.2 mm. After each step, the screw is retracted and the MSM-position monitored for roughly 300 s by a laser triangulation sensor. Results for this procedure are depicted in Figure 7.

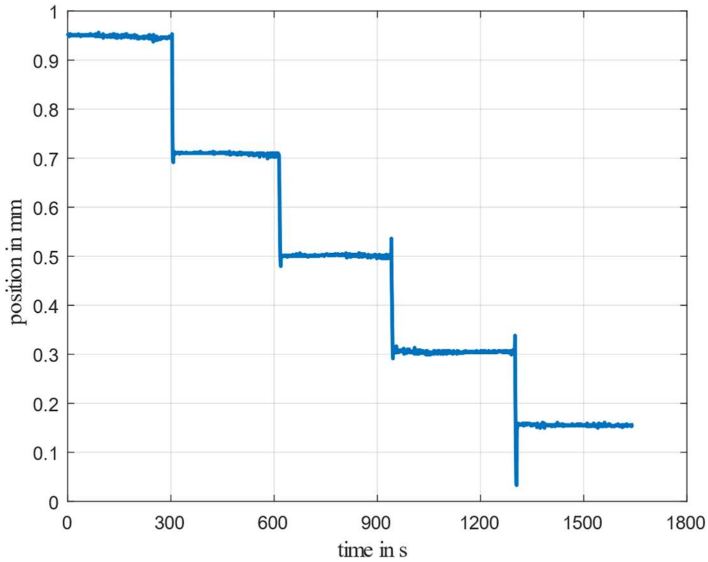

Figure 7: Experimental results for multi-stable range and short-term stability of the entire system

Results indicate a multi-stable range of 0.82 mm as the first position is at a lower elongation than the maximum stroke and the last step is not held at its end position but rather shifts back to a stable point, at which (1) is fulfilled. The true effective multistable range is close to the one estimated from Figure 4, with differences likely caused by friction in the interface rod movement. During each holding interval, deviations are small at below 12 µm which is close to the uncertainty of the sensor at 3 µm. Larger deviations at either end of the intervals are caused by elastic deflections.

The stability of the position is also measured over longer times. The setup is similar to the one described above. In preliminary tests over a 10 h time span it is found, that deviation occur by shape of a declining exponential characteristic with hardly any change after 3 to 4 hours. Observation of three levels of stroke over a 4 h time span is depicted in Figure 8.

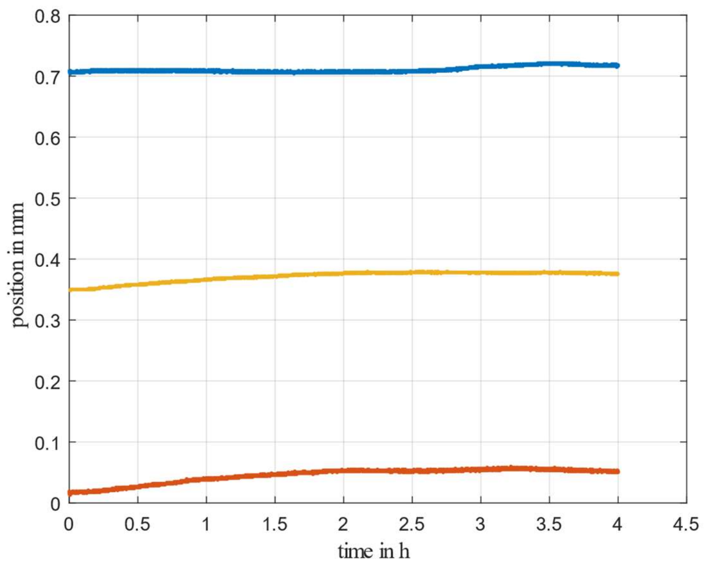

Figure 8: Long-term stability test of the setup

Over the longer measurement period, deviations in stroke are more obvious. The maximum deviation reached within the 4 h period is at 39 µm. The declining nature is also visible, however at the upper end of the multistable range, there is a secondary displacement, that could for example be caused by a change in temperature.

6. POTENTIAL FOR APPLICATION IN INTERFACES

The ability to hold different intermediate states without energy and over a longer period of time and the option to measure the operating distance suggest the application of this type of system in interface design. Linear control elements with the ability to continuously adjust different intensities or machine openings with variable end positions are possible applications. Additionally, use in multi-functional control elements is promising, as the necessary adaptation of the actuating characteristic due to changing operating scenarios is feasible. These adaptations may include continuous actuation, ratcheting or actuations with return to the operating elements initial position. Other anthropometric requirements may be accounted for by adaptation of the actuation force characteristic to the needs of different users. Due to the ability to precisely design a stable actuation characteristic of MSM-based multistable systems, they are also suitable for application in fine-motor operating tasks. [10]

7. CONCLUSION

In this paper, a setup for an MSM-based multistable system has been proposed. The system employs active, i.e. magnetically excited, MSM-sticks, therefore foregoing the need to facilitate the transmission of tension to the MSM-stick. For a given MSM-stick a suitable excitation circuit has been designed using FEA-simulation and verified by determining MSM-stick elongation in the circuit. To make use of the multistable properties, a second magnetic circuit is designed exhibiting a counterforce based on reluctance force. The combined setup is then evaluated concerning its multistable properties. These properties are an actuation force of about ±10 N with a large near-constant range, a multistable range of 0.82 mm out of the 0.9 mm of stroke and a maximum deviation of 39 µm over 4 h (with basically no further change in position after that) indicate the ability of this type of system as a multistable component. Furthermore, an introduction into the possible use of this type of system in design of interfaces was given, where adjustability and adaptability open up potential use in different kinds of control elements, especially in the context of human-machine-interfaces, that are going to be looked at in more detail in the future.

8. REFERENCES

[1] K. Ullakko, J. K. Huang, C. Kantner, R. C. O'Handley, and V. V. Kokorin, "Large magnetic-field-induced strains in Ni 2 MnGa single crystals," *Appl. Phys. Lett.*, vol. 69, no. 13, pp. 1966–1968, 1996, doi: 10.1063/1.117637.

[2] L. Riccardi, "Position Control with Magnetic Shape Memory Actuators," Dissertation, 2014.

[3] Julius Happel, Emmanouel Pagounis, René Schnetzler, Jonas Heider, Markus Laufenberg, "Multistable proportional valve: An energy efficient approach for high temperature passive magnetic shape memory applications," in *GMM-Fb. 98: ACTUATOR 2021: International Conference and Exhibition on New Actuator Systems and Applications GMM Conference, February 17-19, 2021, Online Event*, 2021.

[4] M. Raab, M. Hutter, A. Kazi, W. Schinkoethe, and B. Gundelsweiler, "Magnetically Levitated Linear Drive Using an Active Gravity Compensation Based on Hybrid Shape Memory Actuators," *IEEE/ASME Trans. Mechatron.*, vol. 26, no. 3, pp. 1380–1391, 2021, doi: 10.1109/TMECH.2020.3019369.

[5] M. Chmielus, I. Glavatskyy, J.-U. Hoffmann, V. A. Chernenko, R. Schneider, and P. Müllner, "Influence of constraints and twinning stress on magnetic field-induced strain of

magnetic shape-memory alloys," *Scripta Materialia*, vol. 64, no. 9, pp. 888–891, 2011, doi: 10.1016/j.scriptamat.2011.01.025.
[6] Glen D'Silva and Constantin Ciocanel, "Phase field modeling of fracture in Ni2MnGa magnetic shape memory alloys (Conference Presentation)," in *Behavior and Mechanics of Multifunctional Materials XVII*, 2023, PC1248402.
[7] J. Gauthier, A. Hubert, J. Abadie, C. Lexcellent, and Chaillet N., Eds., *Multistable actuator based on magnetic shape memory alloy*, 2006.
[8] ETO Magnetic, *Magnetoshape.* [Online]. Available: http://etogroup.com/MAGNETOSHAPE.html
[9] M. Hutter and B. Gundelsweiler, "Analysis of the impact of mechanical guidance on active MSM-stick elongation behavior," in *ACTUATOR 2022; International Conference and Exhibition on New Actuator Systems and Applications*, 2022, pp. 1–4.
[10] S. Bagnara, *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018): Volume IX: Aging, Gender and Work, Anthropometry, Ergonomics for Children and Educational Environments*. Cham: Springer International Publishing AG, 2019. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=5485659

CONTACTS

Marco Hutter — email: marco.hutter@ikff.uni-stuttgart.de
ORCID: https://orcid.org/0000-0001-6945-9168

Dr.-Ing. Daniel Holder — email: daniel.holder@iktd.uni-stuttgart.de
ORCID: https://orcid.org/0000-0002-3088-1182

Prof. Dr.-Ing. Thomas Maier — email: thomas.maier@iktd.uni-stuttgart.de

Prof. Dr.-Ing. Bernd Gundelsweiler — email: bernd.gundelsweiler@ikff.uni-stuttgart.de
ORCID: https://orcid.org/0000-0002-7524-5438

